Photoniques

N°101

LIGHT AND APPLICATIONS | EOS & SFO JOINT ISSUE

NEWS
Partner news
& scientific highlights

BIOGRAPHY
Gustav Mie:
the man, the theory

BUYER'S GUIDE
Spatial
light modulators

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New products in optics
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Editorial

NICOLAS BONOD
Editor-in-Chief

Focus on THz technologies: Covid-19 & Photonics

The Terahertz spectral domain is a fertile wavelength range for spectroscopy because THz radiations stimulate the vibrational modes of biomolecules. For this reason, THz technologies have attracted a keen interest to develop devices capable of probing and sensing viruses, proteins, and antibodies. This choice of focus, decided long before the Covid-19 epidemic hit the headlines, sounds very timely today. Along with THz technologies, the entire photonics research and industry will have a key role to play in the fight against epidemics, not only in understanding them and preventing them, but also in diagnosing and curing diseases.

This pandemic stresses further the crucial role of research, innovation and scientific expertise. Europe has developed an ambitious research policy with very effective funding programs, but with severe economic constraints expected in the near future and major choices to be made in terms of budgetary policies, this crisis should convince decision-makers of the necessity to maintain Europe's scientific excellence and prioritize the funds allocated to research and innovation.

The biographical section of this issue is dedicated to the German physicist Gustav Mie and discusses how an outstanding physicist, passionate about teaching experimental physics, ensured his place in the history of science with an outstanding theoretical work. Motivated by the understanding of the structural colours of gold colloids, Mie developed a complete electromagnetic theory that truly reached prosperity decades after its initial publication. This article could have been called "The Brilliance of a Hidden Gem" since Gustav Mie himself did not foresee the importance of this major work and was far from anticipating the huge impact that his theory would have several decades after its publication.

The Buyer's Guide is devoted to Spatial Light Modulators (SLMs). The article introduces the basics of this optical component which is nowadays widely used to tailor the properties of light beams, explains its operating principles and main categories (transmission, reflection) and provides a list of suppliers. Beam-shaping is at the core of many classical and quantum technologies and the range of applications of this optical component is steadily growing.

The success of previous annual issues has motivated the edition of two international issues this year. The publication of two such issues per year would not be possible without the strong support of EOS, SFO and EDP Sciences, whom I warmly thank for their partnership and support in the edition and distribution of this issue.

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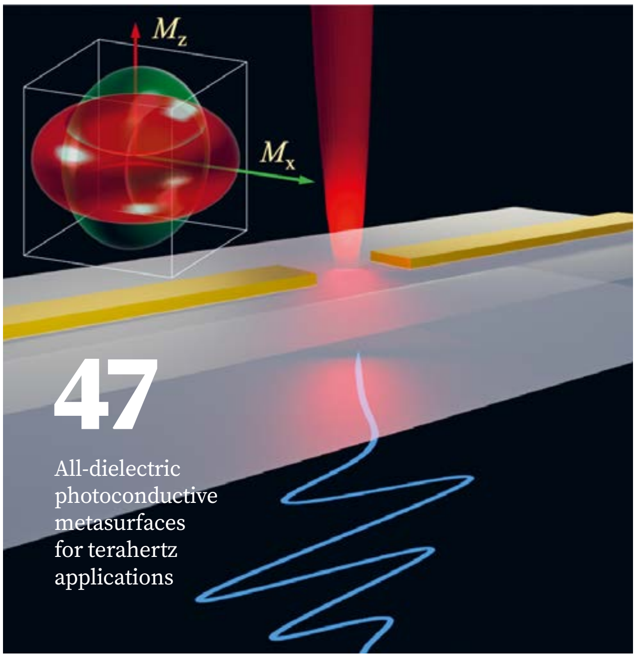

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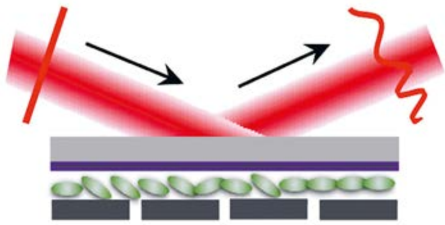

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EOS/SFO forewords

PHILIPPE ADAM
President of the French Optical Society

The PHOTONIQUES magazine is an opened window on the activities of the French optical community: it reflects its dynamism and vitality. The French Optical Society (SFO) also wishes to ensure the spreading towards other communities and to strengthen the influence of this community in a broader framework than the simple national scale. These are the goals of that publication, with a half-year period, for the special international issue of PHOTONICS.
The European Optical Society entrusted to France the organization of EOSAM (EOS Annual Meeting) for 2021 (EOSAM 2020 will take place in Porto / Portugal). It is a great responsibility to be assigned the organization of this event; it is also a great sign of trust and we will do all our best to ensure the success of this congress, one of the flagship meetings of our community in Europe.
Still in the direction of promoting our scientific activities in the field of R&D, is our involvement in the operations of EOS: the SFO takes care to propose French candidates for each Fellows campaign; it has already provided a substantial number of these EOS-Fellows and of course wishes to continue to contribute to this important committee with annually renewed proposals.
Finally, in this somewhat destabilizing period, it is clear that the usual links and friendliness are put to the test : many events will be cancelled or postponed, and activities delayed or the necessary times for many of our activities considerably lengthened. On the other hand, we can clearly realize that research is a key activity, nationally and as well as internationally. This unprecedented crisis could help us to refocus, because of the pressure of events, on what makes our strengths and weaknesses, in order to better contribute in the current needs and to participate more efficiently in the construction of the future.
Despite the current situation, which could be also time consuming, I hope we could find some little times to read about Physics and Optics. The main topic of PHOTONIQUES about THz is a nice opportunity. Have a pleasant and interesting time while reading this special issue of PHOTONIQUES.

HUMBERTO MICHINEL
President of the European Optical Society

As president of the European Optical Society (EOS), I am pleased to write once more an editorial for a new European special issue of "Photoniques", a journal which is a beautiful example of the strength of SFO, the French branch of EOS. This European special issue is devoted to a very promising optical technology, such as THz photonics, which has attracted a great deal of interest from the optical community in the last years, mainly due to its potential use in many hot fields, from biomedical applications and security to communications and nanotechnology, among many others. This fast growing field gathers a multidisciplinary community, joining physicists, engineers and electronics experts, in a technological melting point that will generate many exciting applications in the years to come.
In line with this, I would like to emphasize in these days of uncertainty because of the global crisis due to the spread of the coronavirus pandemic, that the commitment to excellent research, such as that represented by the French optical community, is without a doubt the best weapon that humanity has in the face of threats like the one that currently plagues us. It is evident that Optics and Photonics, in combination with other technologies, have a lot of potential as efficient tools in the fight against the virus, either by contributing to the development of faster and more reliable tests, or by improving the precision and quality of other existing techniques. I hope that once the crisis has passed, decision makers in Europe will not forget that it is essential to maintain support for researchers who contribute to the development European technology and science. From here I finally want to congratulate the entire French optical community, represented by SFO, for their excellent contribution and encourage them to persevere in their continuous search for excellence in photonics research, which is an example for all of us. Their vitality, not only in the field of THz technologies, but in all Optics and Photonics disciplines, is periodically reviewed in each issue of "Photoniques", a nice window to the progress in French Optics.

NEW MEMBERS

PHOTONICS FRANCE NOW HAS 157 MEMBERS! WELCOME TO:

- AERODIODE
- CEDRAT TECHNOLOGIES
- CMP
- DISTRAME
- IRIDESCENCE
- JENOPTEC
- OBS FIBER
- SATT SAYENS,
- TERATONICS
- PHASELAB INSTRUMENT
- ENSSAT
- MBTEC
- VISIONAIRY

AGENDA

- **France Pavilion**
  May 12-14, CLEO, San Jose (US)
- **General Assembly / Photonics France Congress**
  June 4, BPifrance Le Hub, Paris
- **France Pavilion, SPIE Astronomical Telescopes + Instrumentation 2020**
  June 14-19, Yokohama (JP)
- **Photonics Pavilion, Global Industrie,**
  June 24-26, Villepinte, Paris
- **French Photonics Days: Special optical fibres and future applications,**
  Sept. 17-18, Perros-Guirec
- **France Pavilion, OPTATEC**
  Nov. 17-19, Frankfurt (DE)
- **3rd Journées Sécurité Optique et Laser au Travail (JSOL),**
  Dates tbc, Grenoble (FR)
- **LALS2020 Partnership,**
  Spring 2021, Nancy (FR)

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SAVE THE DATE

FRENCH PHOTONICS DAYS
On 17 & 18 September in Perros-Guirec. Do you have the fibre of innovation ?

Photonics France, SupOptique and Photonics Bretagne are co-organizing the 2nd edition of the French Photonics Days in Perros-Guirec (22) on the theme "Special optical fibers and future applications". This two-day seminar, designed for a technical but non-specialist audience, will include presentations (overview, news on new special fibers, training and needs of the industry), conferences including those of Marko Erman, Scientific Director of Thales and Hervé Lefèvre, Scientific Director of iXblue, as well as a round-table discussion to allow stakeholders to reaffirm the issues at stake and debate the industry's priorities, and presentations by local political figures.
Programme & registration to come. Attention, places are limited to 150!

Free for the members of the organizing entities, except for the evening (participation of 30€ HT/36€ TTC). Non-member rate, including the evening: 130€ HT/ 156€ TTC.

RECRUITMENT AND TRAINING

Photonics France collaborates with the State to attract talent in the technologies of the future!

Photonics France has initiated a process with the cabinets of the Ministries to strengthen the representation and support of photonics in order to make it recognized as a strategic sector. The federation proposes solutions to certain problems, such as training and the lack of qualified personnel.
Photonics France signed a project (EDEC) on Employment and Skills Development with the Ministry of Labour on November 12, 2019. This project in photonics and electronics with a budget of 521k€ is financed by the State and the UIMM for a period of 3 years. Four axes are developed: the diagnosis and identification of jobs and skills in voltage (March to September 2020), the reinforcement of continuous training and its promotion, the development of work-study programs and the link between the industry and the actors of training, and the implementation of a plan to develop the attractiveness of jobs. Various works are undertaken with the Ministry of National Education, Pôle Emploi and ONISEP.

More information on www.photonics-france.org

OPTIQUE DIJON
is postponed to welcome you when the health crisis is overcome

You are cordially invited to attend and participate in the 8th Congress of the French Optical Society SFO, which will take place in Dijon, France. OPTIQUE Dijon, initially planned from July 7 to July 10, has been postponed. Several date options are being studied to organize this congress in the best sanitary conditions. We will keep you informed as soon as possible.
OPTIQUE Dijon will cover a wide range from the fundamental to the applied research, industrial developments and pedagogical innovations. An exhibition area for photonics industry, including start-ups, will be set up at the heart of the congress. This congress provides fertile ground for beneficial exchanges between the actors of optics and photonics.
Professor Gérard Mourou, Nobel Prize in Physics 2018, will deliver the keynote opening plenary speech in this congress. OPTIQUE Dijon also includes plenary sessions led by guest speakers renowned internationally for their expertise, several thematic conferences and poster sessions.

OPTIQUE Dijon Prizes, to promote optics and photonics research

To recognize excellence, the SFO awards three Scientific Prizes during this congress: Léon Brillouin, Fabry-de Gramont and Arnulf-Françon. OPTIQUE Dijon welcomes for the first time the awarding of the Jean Jerphagnon Prize.

Women in Physics committee, to promote parity in Optics

In symbiosis with the commission "Women and Physics, achieve parity in optics" the congress pays a special attention to the number of women working in optics, at all responsibility levels and tends to parity on invited conferences.

PhD students are welcome in OPTIQUE Dijon

Our goal is to allow all PhD students to participate once in the congress during their thesis. 200 students are expected in this congress.

Dijon host the 8th edition of SFO biennial congress

The local organizing committee orchestrated by Guy Millot is very happy to host the SFO Congress. They do their utmost to welcome hundreds of participants in the best conditions. The congress facilities at Faculty of Sciences of Dijon are well located and easy to reach. During our networking program, you will get to know this exciting city in all its aspects.

We sincerely hope you will continue to participate. We are very grateful for your support.
Welcome to OPTIQUE Dijon in the best health conditions!

Renewal of the SFO Education Commission –
« Société Française de l'Optique » (French Society of Optics), a new team willing to promote Education in Optics!

On Feb. 11th, a meeting was held at the SFO gathering current members of the Commission and voluntary contributions which were answering the Call for Expression of Interest recently launched in scientific magazine Photoniques. The main goal of this kick-off meeting? To present an overview of the previous actions, to share the know-how on the dedicated tools available and to discuss the specific commission's tasks regarding Education that might pave the way for the next steps. Both participant took part in making it a smooth handover for this enthusiastic team: Bruno BOUSQUET (University of Bordeaux), Lola COURTILLAT (Systematic Paris-Region), Christophe DAUSSY (Sorbonne Paris Nord), Christophe FINOT (University of Bourgogne), Fabienne GOLDFARB (IUT of Orsay) and Claire MICHEL (University Côte d'Azur).

This new team proactively identified key actions the sector might benefit from, namely:

- To have an **established network of contacts** with an identified, qualified and up to date referent for each French establishment where optics is taught;
- To increase visibility to teachers and **share best practice and experience** among this network in order to foster both levels' homogenization and lessons' attractiveness;
- **To improve relations between academics and industry** leading to a better employment rate after graduation;
- To promote access to scientific contents by **revitalizing the open access database**;
- To implement and support activities to **increase public awareness** such as the International Day of Light.

Key actions strongly aligned with the main assignments of this Commission: Triggering, supporting and highlighting all types of actions aimed at promoting Optics' Education in France thanks to teachers, researchers and industrialists.

Want to know more? Contact: Christophe DAUSSY (christophe.daussy@univ-paris13.fr).

EPIC GOES ONLINE

organising new online technology meetings, webinars and networking sessions

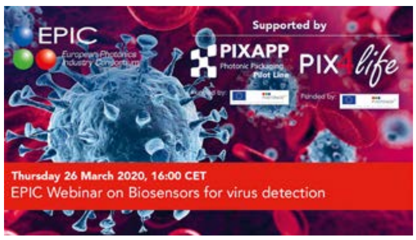
EPIC – European Photonics Industry Consortium – is in its core a networking facilitator, hosting events to bring key enablers within the photonics industry together. The outbreak of this new coronavirus has also meant for us that many of our networking and technology meetings had to be postponed. Fortunately, we have a great team coming up with new ideas and opportunities to continue adding value to our members and facilitating networking.

The COVID-19 virus is also impacting the businesses of our members. To support them in this difficult time, we have organised the **EPIC Members Online Meeting on Coronavirus Impact & Possible Concerted Actions**. Over 50 EPIC members from 15 countries joined the meeting to join the conversation. The meeting gave the attendees the opportunity to share experience and discuss and identify follow-up actions, related to how this coronavirus is affecting their business, from manufacturing and supply chains to HR and marketing.

We followed-up with **EPIC Members Webinar on Working from Home & Managing Remote Teams**. Here we shared our experiences of managing 13 employees spread across 8 countries. We discussed the benefits of having employees working from home, setting up your work environment, and managing collaboration among teams. We had 36 attendees and we discussed best practise tips, shared experience and networked. It is great to see how everyone played a role and actively was sharing their experiences. Thank you to all those who attended!

In light of current events, a meeting showing how photonics is helping to face and defeat viruses like the COVID-19 could of course also not be missing in this line-up. Supported by the EU-funded MedPhab*) Pilot Line, we organised the **EPIC Webinar on Towards a Prototype of an Anti-virus UVC-LED-based Respiratory Mask**. This webinar showed the developments of an innovative respiratory mask capable to killing the virus. The exhaust of the mask is equipped with an UVC-LED string, exposing the incoming as well as the outgoing airflows to the suitable amount of light to kill the virus.

Besides technologies designed to protect us from pathogens, we also had a meeting about technology helping to quickly identity viruses like this new coronavirus in a cost-effective, real-time and user-friendly way. Providing fast diagnosis can prevent further spread of a disease in big groups. During the **EPIC Webinar on Biosensors for Virus Detection** different alternatives and European capabilities were presented for the development of Photonic Integrated Circuit based biosensors for virus detection including chip design, fabrication, packaging and biofunctionalization of the sensor surface. This meeting was supported by the EU-funded Pilot Lines PIXAPP* and PIX4Life*.



MedPhab, PIXAPP and PIX4Life have received funding from the European Union's Horizon 2020 research and innovation programme. To view details of the grant agreements, please visit www.photonics21.org

AGENDA

■ **Upcoming EPIC Events**
To continue to facilitate networking and creating business opportunities, EPIC is organising dedicated Online Technology Meetings. These meetings will bring together component suppliers, system integrators and end-users to efficiently discuss real business opportunities. Each meeting is dedicated to specialised photonics topics such as femtosecond lasers, quantum sensors, fibre sensing, hyperspectral imaging, LIDAR, micro-optics, packaging, freeform optics, biosensors and more. Do you have an innovative idea or product and you would like to contribute? Then please register on our website www.epic-assoc.com

■ **EPIC Online Technology Meeting on Microwave Photonics**
17 April 2020

■ **EPIC Online Technology Meeting on Blue and UV Laser Diodes**
20 April 2020

■ **EPIC Online Technology Meeting on Micro-optics Manufacturing**
22 April 2020

■ **EPIC Online Technology Meeting on Photonics Packaging and Testing**
24 April 2020

■ **EPIC Online Technology Meeting on Surface Structuring**
27 April 2020

■ **EPIC Online Technology Meeting on Freeform Optics for AR/VR**
29 April 2020

■ **EPIC Online Technology Meeting on Hyperspectral Imaging**
06 May 2020

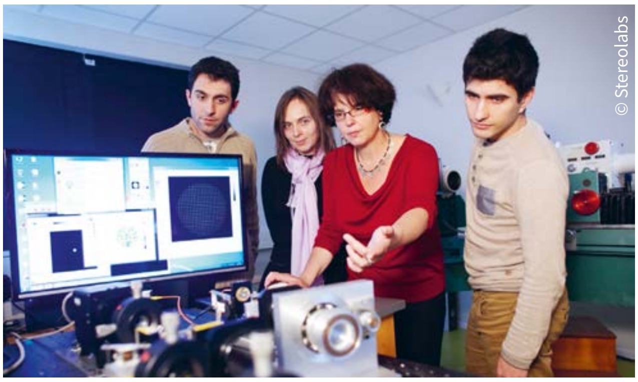
■ **EPIC Online Technology Meeting on Photonics for New Space**
08 May 2020

■ **EPIC Online Technology Meeting on Biosensors**
11 May 2020

INSTITUT D'OPTIQUE GRADUATE SCHOOL

Key partner of the Photonics industry

The Institut d'Optique Graduate School is a world leader in training, research and innovation in optics and photonics. With a vast array of interests, from optical instrumentation and lasers to quantum physics and from biophotonics to nanotechnologies, it has become, over time, a key actor of its economic and academic sector. As a century old institution, privately held but recognised as being of public utility, it contributes to the global efforts of the field.
Several schemes and collaborations are developed to ensure that the Institut d'Optique remains in close link to the industrial needs in terms of training and research while staying at the cutting edge of the scientific and technological advances.



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Apprenticeship track at Institut d'Optique

Institut d'Optique was the first engineering training institution in France to open an apprenticeship track in 1997, with the same requirements of knowledge and skills and leading to the same degree as the rest of the cohort.
For companies, the ability of our apprentices to contribute concretely to the success of the projects entrusted to them is noted by all. It is also a way for the employer to attract future collaborators from the outset, who will be perfectly operational once they graduate.
This success is confirmed by over a hundred companies that regularly hire apprentices and that have already relied on the programme to source and train future engineers in photonics.

For more information about hiring apprentices, please contact:
caroline.rayer@institutoptique.fr

Entrepreneurship track at Institut d'Optique

Over the three years of their engineering studies, the Entrepreneurship track or FIE (Filière Innovation-Entrepreneurs) trains students to undertake and innovate through project-based pedagogy where they develop photonics-based projects. Students who choose this course have 550 hours (out of 1800 hours of the standard engineering training) to develop their project over 3 years.
Entrepreneurship projects are either submitted by laboratories or by companies that wish to test, in real life, an idea or a technology. Coached by technological and marketing tutors, hosted in our entrepreneurship and innovation centres and FabLabs (11.000 m^2 of facilities) with 35+ companies on premises, best practices in terms of confidentiality are enforced to allow for the most secure setting in case there is a patent or a patent pending. Over 20 companies have been created and the FIE has been granted 120+ national and international awards since its creation in 2008.

To submit an idea, please contact:
david-olivier.bouchez@institutoptique.fr

Continuing education at Institut d'Optique

As part of its mission to be of service in photonics, the Institut d'Optique offers comprehensive training tailored to the industry's needs in optics and photonics.
Continuing education is organized within a solid and extremely dynamic ecosystem that enables us to offer concrete and, if necessary, tailor-made solutions to our industrial customers: 150 practical work benches, a FabLab, several computer rooms equipped with the latest softwares used today in the fields of photonic engineering, a media library and, above all, recognized experts, researchers or engineers, with expertise in a wide range of topics related to optics and photonics.
Training sessions target a wide variety of audiences, both fairly specialized technicians and systems engineers within our wide range of expertise: from lighting to space and astronomy, from sustainable development to transport, from fibers and telecommunications to medical or pharmaceutical equipment, from virtual and augmented reality to industrial vision. We also offer training courses on the fundamentals of photonics as well as on computer-assisted optical design, optical components and systems, lighting, light-related quantum technologies, or the sustainable development of photonics.

For more information, please contact:
emilie.ericher@institutoptique.fr

Please consider supporting Institut d'Optique

French based companies can help Institut d'Optique Graduate School while devoting their mandatory apprenticeship tax (taxe d'apprentissage in French) to our outstanding teaching facilities. This contribution will help improve experimental work facilities (lab work) as well as the hiring of non-permanent faculty comprising prominent experts from the industry.

Please contact: annie.keller@institutoptique.fr

Photonics Bretagne members joined forces at Photonics West

Last February, Photonics Bretagne attended Photonics West in San Francisco, in collaboration with Business France, Photonics France and other french regional clusters (ALPHA-RLH, Minalogic, Systematic and Optitec), on a co-organised French Pavilion branded “Choose France”. As every year, Photonics Bretagne exhibited at this world’s largest exhibition in photonics alongside a growing number of members (21): Bktel, Cailabs, EXFO, iXblue, Kerdry, Le Verre Fluoré, Lumibird, Oxxius, ALPhANOV, Amplitude, Eldim, GLOphotonics, Irisiome, Laser Components, Leukos, Novae, Optosigma, Polytec, Qiova, SEDI-ATI, Thales. Our local R&D CNRS labs, such as Foton Institute and ISCR, and some our of industrial members took also the occasion to present their last scientific breakthrough at the conference. In a nutshell, our network has been able to demonstrate again this year its dynamism and excellence both at Scientific and business level! See you next year in San Francisco with more innovation and new products!

AGENDA

■ **Meeting R&D lab/SME,**
June 3, Lannion, France

■ **Breizh4Good,**
Lannion, France
The aim of this event is to build tech projects responding to societal and environmental issues. June 17: inspiring conferences and creativity workshops. October 2 & 3: new Innovation “Tech4Good” Challenge (30h-2 creativity days) for everyone, with expert coaches and prizes. Projects, ideas, or skills can be submitted on the Breizh4Good collaborative platform. Mandatory registration before 14th of September. More information on : www.breizh4good.bzh.

■ **French Photonics Days,**
September 17-18,
Perros-Guirec, France
Photonics France, SupOptique Alumni, and Photonics Bretagne organize this year in Perros-Guirec the French Photonics Days on the topic « Specialty Optical Fibers and future applications ». The agenda will cover scientific presentations, invited conferences (Marko Erman, Scientific Director of Thales and Hervé Lefèvre, Scientific Director of iXblue), training in Photonics, round table on challenges and priorities of the field, and networking breaks (cocktail, social event on the evening, visits of local photonics companies).
Free for members of organizing structures (except diner: 30€ HT). 130€ HT, including diner for non-members.
Registration coming soon (limited 150 attendees !).

NEW CAMPUS OF EXCELLENCE
"Digital and Photonics" based in Lannion

On the 6th of February, the Ministry of National Education and Youth rewarded our local Campus with a seal of Excellence and a national funding in the framework of the Investments for the Future Programme (PIA) “Teaching & Innovation Territory” (4,2M€ over 5 years). Brittany and Lannion in particular have a rich and attractive ecosystem gathering research laboratories, companies and schools in the field of digital and photonics. With an international dimension and a national ambition, this new regional Campus of Excellence “Digital and Photonics” will open up wonderful prospects for young people interested in photonics. In particular, one major aim will be to match student skills and company needs by improving or setting up new training in these two fast-growing sectors.

Cailabs and BridgeComm, Inc. are partnering up

Their shared intent is to propose joint offerings that will integrate solutions from both enterprises into systems that will significantly improve laser communications between space, airborne and terrestrial optical wireless communications solutions. This agreement with BridgeComm is a new confirmation of the market interest for Cailabs solutions and a new milestone on the US market for the company.

The European Clusters Alliance
elected its Board of Directors

On 28 February 2020, Antonio Novo Guerrero, chairman of the Spanish federation Clusters.es, was elected as president. Hervé Floch, AFPC (French Competitiveness Clusters Association) - and CEO of ALPHA-RLH cluster - and Krzysztof Krystowski, Polish Clusters Association, were nominated both as vice-presidents.

The European Clusters Alliance was launched in 2019. It is a bottom-up initiative that gathers 13 national cluster associations (from Bulgaria, Czech Republic, Finland, France, Hungary, Latvia, Lithuania, Poland, Portugal, Romania, Slovakia and Spain) and represents more than 740 clusters all together.

Its main mission is to give Europe´s clusters a common voice and promote the inter-cluster collaboration at international level. By facilitating their collaboration and strengthening their bonds, the European Clusters Alliance aims to position clusters as key agents in the European innovative ecosystem for the development and growth of the economy.

AGENDA

- **European Microwave Week (EuMW)**
  September 13-18, 2020
  in Utrecht (The Netherlands)

- **INPHO Venture Summit**
  October 22-23, 2020
  in Bordeaux (France)

The ALPHA-RLH cluster
partner of a major European project in the field of nanotechnologies

The European project NewSkin (H2020) aims to create an Open Innovation Test Bed to provide technologies, resources and services to companies in the nanotechnology field. It brings together 36 partners from 12 European member states.

ALPHA-RLH will be involved in this European project in piloting dissemination actions, assistance to companies for the development of their business plan, their business model and their commercial strategy. NewSkin will provide a single point of entry to a set of expertise and testing facilities.

ALPHA-RLH will work with inno TSD for the creation and management of the platform and with ALPhANOV for surface texturing using a continuous "roll-to-roll" laser process. ALPhANOV has developed a unique laser technique to add new functionalities to various kinds of surfaces without altering the physical-chemical properties of the material (see photo).

The project, with a budget of almost €16 million and a duration of 4 years, should start in the first half of 2020, upon signature of the Grant Agreement by the 36 partners.

TWO NOBEL PRIZE WINNERS IN PHYSICS
AT THE HEART OF A "PHOTONICS & ENERGY" EVENT

On February 17th, 2020 the ALPHA-RLH cluster organized at the Palais de la Bourse in Bordeaux an event dedicated to innovative technological solutions for the energy of the future. It brought together nearly 150 participants: academic, industrial and institutional players.

During conferences and a roundtable, experts discussed the contribution of photonics and laser technologies in the energy field, with a focus on photovoltaics, thermodynamic solar, self-consumption and the storage of intermittent energies.

ALPHA-RLH was pleased and honored to welcome two distinguished guests: the French physicist Gérard Mourou and the Canadian Donna Strickland, winners of the 2018 Nobel Prize in Physics for their invention of the Chirped pulse amplification (CPA) technique. It consists in amplifying an ultrashort laser pulse up to the petawatt level, with the laser pulse being stretched out temporally and spectrally, then amplified, and then compressed again. They gave their vision on the relationship between laser physics and energy and proposed several applications for the future (nuclear transmutation of wastes, desorbitation of space debris).

The European PIMAP project
on the way to phase 2

PIMAP+ is a COSME (ESCP-4i) European collaborative project that has reached the stage of Grant Agreement preparation with the associated funding early February. ALPHA-RLH is leading the project involving 5 other clusters: Triple Steelix/IUC Dalarna AB (Sweden); Produtech (Portugal); Moravian Aerospace cluster (Czech Republic); Associazione Fabbrica Intelligente Lombardia (Italy) and Business Joensuu Oy (Finland).
The PIMAP+ consortium has been set up to support those 6 leading European clusters, their SMEs and regional ecosystem actors to strengthen cross-sectoral cooperation in the fields of photonics, advanced manufacturing, metalworking and aerospace industry.
The PIMAP+ project is a follow-up of the successful activities implemented in the previous PIMAP Partnership project/Strand 1. After two years of action oriented project implementation and a solid internationalization strategy with 3 MoU signed off, the partners seek to move to another level and accelerate access to international markets for SMEs and to support the development of business agreements and B2B cooperation. Four country markets will be targeted: The United-States, Canada, China and Japan.

Solidarity to fight the COVID-19

Through its commitment in the Association française des pôles de compétitivité (AFPC) and in the European Clusters Alliance (ECA), ALPHA-RLH has been involved in several European initiatives in order to fight the COVID-19 crisis and help finding solidarity-inspired solutions. DG GROW (European Commission) has launched with the help of all the national cluster organizations an inventory of all the 3D-printing resources all over Europe in order to proceed to a production effort for 3D-printing of medical masks and/or end-caps, valves… for respirators. A similar initiative has been launched by the Nouvelle-Aquitaine Region with the setting up of a dedicated platform.
At the national level, ALPHA-RLH and ASPEC (Association pour la prévention et l'étude de la contamination) have appealed for donations of COVID-19 protection equipment and consumables that may be available in high-tech, medtech or biotech research institutions and companies. This initiative has allowed to collect several hundred thousand masks in a quick manner.

Briefly

Systematic in figures :

- €3.18 billion for R&D
- 625 innovation projects
- Over 620 listed products and services, built on collaborative R&D

FOCUSING ON OPTICS & PHOTONICS AND HOW TO IMPACT THE AGRO-FARMING AND AGROFOOD SECTOR

As the Paris Region Government has set agro-farming & agrofood as a key element of the regional strategy.

Indeed, the Optics and Photonics Hub of Systematic is involved in the FoodPackLab project (COSME programme stage 2 starting in May 2020) which aims at fostering cross-border and cross-sectorial collaboration of clusters and business networks in the strategic field of food security by supporting the implementation, testing and further development of the European Strategic Cluster Partnership – Going International "ESCP-4i" (FoodPackLab strand 1, funded under the previous 'Cluster Go International' call COS-CLUSINT-2016-03-01) through the implementation of its planned actions towards selected third countries beyond Europe. It connects clusters from four different sectors (agriculture, food processing, packaging and deep tech) and 5 European countries (Belgium, Denmark, France, Italy and Spain) in order to support European SMEs to access new global value chains and ensure their position as global leaders of innovation in targeted industries. By providing a framework for cross-border and cross-sectoral collaboration, FoodPackLab 2.0 will not only strengthen innovation potential and international competitiveness of the European SMEs but will also contribute to the development of emerging industries.

https://foodpacklab.eu/

Systematic Paris-Region

European cluster gateway for DeepTech innovations

Systematic Paris-Region, the innovation and technology cluster, brings together and promotes an ecosystem of excellence in deep tech and digital technologies with over 900 members. This network gathers about 600 SME & start-ups, 150 major corporate companies, 140 Universities & Research Institutes. Their key activities include connecting stakeholders and boosts innovation through collaborative R&D projects, boosting SME's development, facilitating market entry and access to finance on an international level, and providing an efficient business sourcing, across a range of strategic economic sectors.

The cluster's innovation strategy is organized and conducted, throughout 2019-2022, around two strong and complementary themes: innovation in backbone technologies and the digital transformation.

- Innovation in backbone technologies, or DeepTech, built on technological breakthroughs, inspired Systematic's creation of 6 hubs: Data Science & AI, Cyber & Security, Digital, Infrastructure & IoT, Digital Engineering, Optics & Photonics, Open Source.
- The digital transformation, enabled by these technological breakthroughs, has given rise to 3 issue groups, focusing on economic and societal concerns: Transformation of territories, Transformation of industry and services, Transformation of society.

www.systematic-paris-region.org/fr/hub-optics-photonics

AGENDA

- **What's on ?**

June 18th 2020, at Polytec,
come and visit our member to discover, among others, their innovative drone solution for hyperspectral remote sensing for agricultural and environmental protection.

More about Polytec : www.polytec.com/uk/

Want to join the Optics & Photonics Hub of Systematic ? Don't wait any longer and contact :

Lola Courtillat, Hub Coordinator :
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Dual-use fact-finding mission to the United Arab Emirates

KETs4Dual-Use (K4DU) partnership has carried out its second fact-finding mission to the United Arab Emirates (UAE) between 13 and 15 January 2020.

The country ranks among the top 15 defence spenders in the world and the defence expenditure as a proportion of GDP has remained comparatively high in recent years in response to various threats and events in the region. UAE's 2016 defence expenditures stood at approximately $23.4 billion, while it is projected that the country's defence expenditure will grow at a compound annual growth rate (CAGR) of 6.5% to value $31.8 billion by 2021.

In November 2019 the UAE authorities launched EDGE, a government-owned company meant to position the country as a global player in advanced technology that can address the threat of hybrid warfare and streamline the local defense industry. With combined annual revenue of $5 billion, EDGE employs more than 12,000 individuals, and it will consolidate 25 national subsidiaries in the field of defense, focusing on five principal areas: platforms and systems, missiles and weapons, cyber defense, electronic warfare and intelligence and mission support.

K4DU delegates have held meetings with Tawazun Holding as well as Emirates Defense Companies Council (EDCC) representatives in order to discuss how European dual-use SMEs could contribute to EDGE initiatives as well as about future collaboration opportunities, notably in form of participation at the UAE flagship defense exhibitions UMEX and IDEX.

The agenda also included meetings with ATOS UAE office, with focus on possible involvement of European dual-use SMEs in the local supply chains, as well as with French and Danish military attachés.

This fact-finding mission has enabled the K4DU partnership to establish initial contacts with the UAE defense & security ecosystem, which will be further pursued during the UMEX exhibition (February 2020) and EXPO 2020 hosted by Dubai (October 2020 – April 2021).

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DUAL-USE FACT-FINDING MISSION TO THE UNITED STATES AND CANADA

KETs4Dual-Use (K4DU) partnership has carried out its first fact-finding mission to the United States of America (USA) & Canada between 14 and 18 October 2019.

The North America region with the USA and Canada is clearly one of the priority destinations for the consortium given the size of its defence & security market.

During the first leg of the trip to Washington, K4DU partnership joined forces with the Alliance partnership. The two delegations participated in the Annual Meeting & Exposition of the US Army and met with the US National Defence Industry Association (NDIA). The K4DU delegates also met with the Regulatory Affairs team of the International Society for Optics & Photonics (SPIE) in order to discuss the current dual-use technologies landscape in the US and collaboration possibilities with US entities, notably from a regulatory perspective.

After a two-day stay in Washington, the K4DU delegation than moved on to Ottawa where it participated in the SME Day organised by Canadian Association of Defence and Security Industries (CADSI).

The last destination was Montreal. Hosted by Quebec's Ministry of Economy and Innovation and photonics cluster Optonique, the delegates met with various stakeholders of the Quebec's ecosystem active in the defence and security domain such as Department of Canada's Defence Ministry in charge of innovation programme IDEaS and companies such as IBM, Excelitas and Cysca Technologies.

This fact-finding mission has enabled the K4DU partnership to establish initial contact with US & Canadian associations in order to discuss possibilities of future collaboration and to identify opportunities for creating partnership synergies between SME members.

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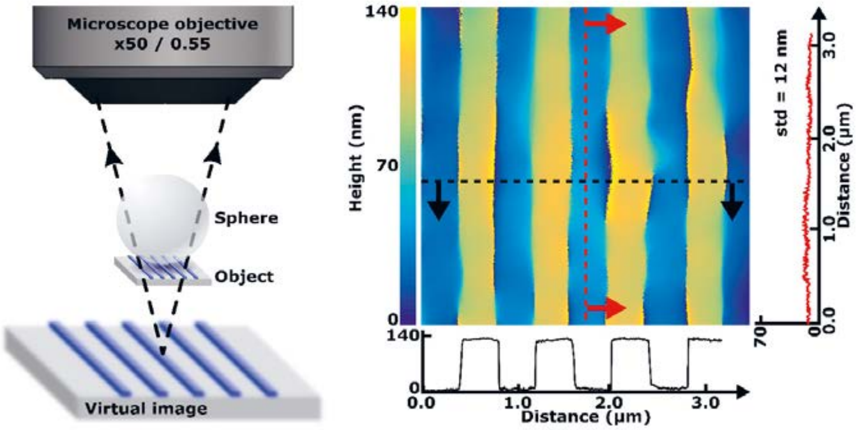
Microspheres for super-resolution
3D reconstructions in interference microscopy

In classical optical microscopy, an aberration-free objective allows the lateral resolution to reach λ/2 in air where λ is the wavelength of the illumination light used. However, the performance in interference microscopy is not only limited by the diffraction of light, but also by the ability to reconstruct the topography distribution, usually leading to resolving powers larger than 1 μm. Researchers in the Photonics Instrumentation and Processes team at the ICube Laboratory (UMR 7357) in Strasbourg have developed a super-resolution full-field interference microscope using glass microspheres. By introducing two similar 30-μm-diameter microspheres in the arms of an interferometer, the lateral resolution is increased by a factor of 3, with compensated optical aberrations compared with the use of a single microsphere alone. This innovative combination of coherent interferometry with microsphere-based microscopy has made it possible to reconstruct 300-nm-groove standard gratings and 250-nm-diameter transparent nanodots in air with a nanometre-scale axial sensitivity and higher lateral resolution compared with interferometry alone. The technique allows straighter sidewall measurements together with accurate height distributions to be retrieved. Currently, researchers are working on the fabrication of high-quality microspheres to improve measurements even further, together with the development of a microsphere positioning system to perform more practical contactless measurements.



Characterization of a 800-nm-period standard grating using microsphere-assisted interference microscopy compensated by two 50-μm-diameter microspheres. The height profiles along the black-dashed and the red-dashed lines allow the straight features and the axial sensitivity of the imaging system to be retrieved, respectively.

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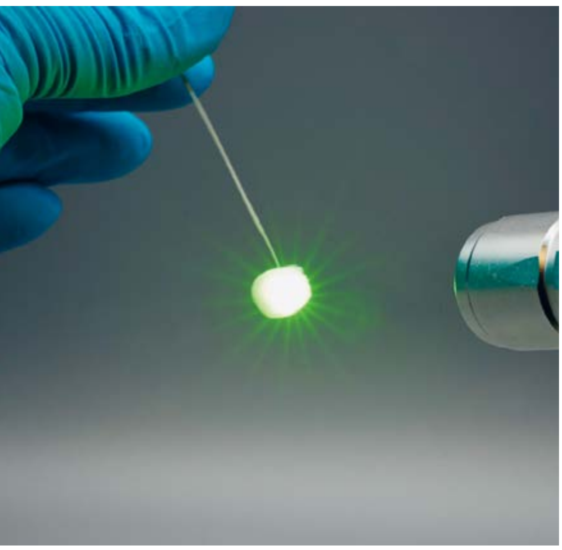
ARTIFICIAL SOLID FOG MATERIAL CREATES PLEASANT LASER LIGHT



Researchers from Kiel University (Germany) have devised a nanostructured light diffuser based on hexagonal boron nitride – able to efficiently convert directional and high intensity laser light beams into a homogenous white light source, useful for applications that require high-brightness light sources, such as projectors and automotive headlights. With a porosity of more than 99.99% the foam-like material, called Aeroboronitride, has a density similar to that of air. It is made of a semi-transparent web of randomly arranged and interconnected hollow microtubes that are dispersed at low density – similar to a fog, but in a solid form. When irradiated with a laser, the directed light penetrates deeply into the structure, where it is strongly scattered multiple times by the nanoscopic walls of the microtubes, before it leaves the structure again, creating a homogenously emitting laser-based light source. The extremely strong scattering can not only be used to mix different laser colours, but also strongly reduces the speckle contrast, a typical problem of laser-based light sources, to values well-below the threshold of the human eye.

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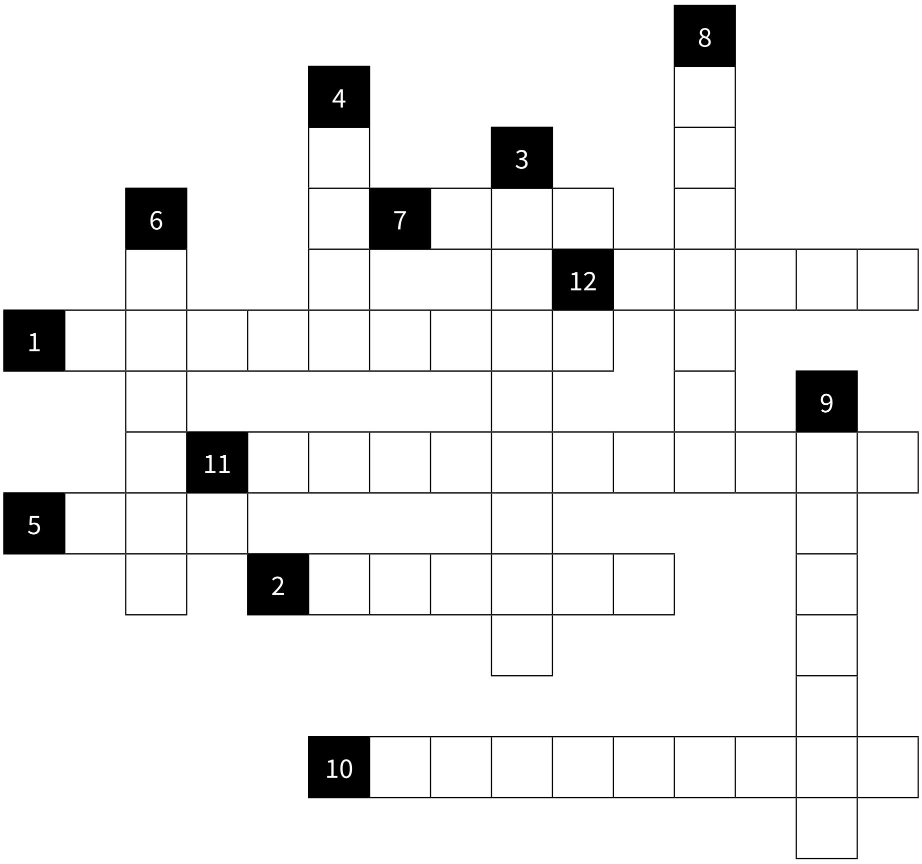
CROSSWORD PUZZLE ON LASERS



1 the strongest one
2 under the sea
3 beautiful blue color
4 the oldest one
5 the largest one
6 for telecommunications
7 a cascade of IR light
8 to improve eyesight
9 used for lidar
10 what a cool laser!
11 for hair removal
12 everywhere nowadays

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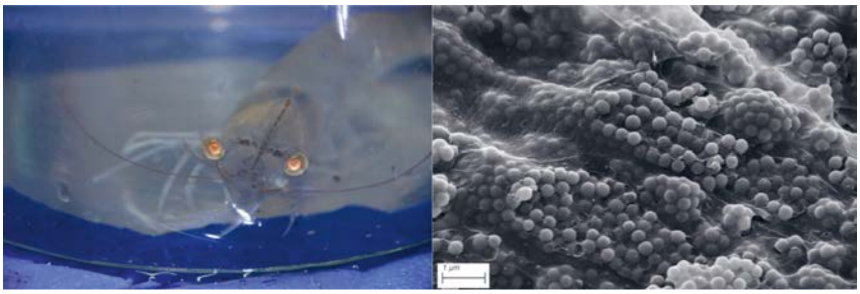
Nature's Design for Birefringent Photonic Crystals



Three dimensional photonic crystals are not uncommon in the animal kingdom, from butterfly wings to chameleons, but the one found in the tapetum (the reflective layer underlying the retina) of some shrimp species pushes this technology one step further. In their recent work [citation], researchers at Weizmann Institute and Ben Gurion University unraveled the role of birefringent building blocks in dramatically enhancing the backscattering of light from the thin tapetum layer, providing a significant advantage to these deep-dwelling marine species. The photonic crystal in the shrimp eye is made from crystalline isoxanthopterin, a layered organic material exhibiting nearly 30% birefringence, with an in-plane refractive index of about 2. Isoxanthopterin nanoplatelets are organized in a spherical arrangement to form spherically symmetric birefringent shells (spherulites) with a diameter of about 300nm, which are assembled into an opal structure. The researchers found that backscattering from this structure is much stronger and more broadband than from an equivalent structure made from an optically isotropic material. The shrimps thus use a unique geometry which harnesses the advantages of birefringence yet obviates the need for orienting the nanoparticles relative to one another. These structures are said to have significant potential as ultrathin scattering layers and as structural paints.

REFERENCE

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ADVERTORIAL

LUMIBIRD
MORE THAN LASERS

With 50 years of experience and expertise, LUMIBIRD (formerly the Quantel-Keopsys group) designs and manufactures high performance lasers for the industrial, scientific, medical and defense markets. Key technologies include solid-state lasers, fiber lasers and diode lasers for various applications, including LiDAR, ADAS, ophthalmology and laser pumping.

LUMIBIRD's dynamic capabilities are reflected in the number of new lasers released this year. A few examples are shown below:

Unveiled at Photonics West exhibition last February in San Francisco, the Q-smart 1200 & 1500 are new flashlamp-pumped Nd:YAG lasers reaching up to 1.5 J at 1064 nm. Using an all new and proprietary oscillator-amplifier design, they include all of the renowned features of the Q-smart laser series, such as plug and play harmonic generators, automatic phase-matching, best-in-class beam quality and detachable cables and coolant lines.

In diode-pumped nanosecond solid-state laser technology, Lumibird expands its range with the release of the Falcon, an ultra-compact diode-pumped eye safe laser at 1.57 µm. Extremely rugged, portable and designed for battery operation, the Falcon series is built for demanding applications (LIBS, ranging, sensing ...) and unpredictable extreme environments where temperature and vibration eventually destroy most commercial lasers.

Lumibird's fiber lasers and laser diodes ranges also continue to evolve, providing their users with ever more advanced features and specifications. Our Pulsed Erbium Fiber Lasers (PEFL) are now available in a MIL-STD 810G vibration compliant platform for integration into obstacle warning systems in helicopters, and our QCW diodes stacks are offered coupled with optical fibers for enhanced flexibility.

Thanks to the expertise of the LUMIBIRD team and the complementary laser technologies, LUMIBIRD is the ideal partner for your laser projects. ●

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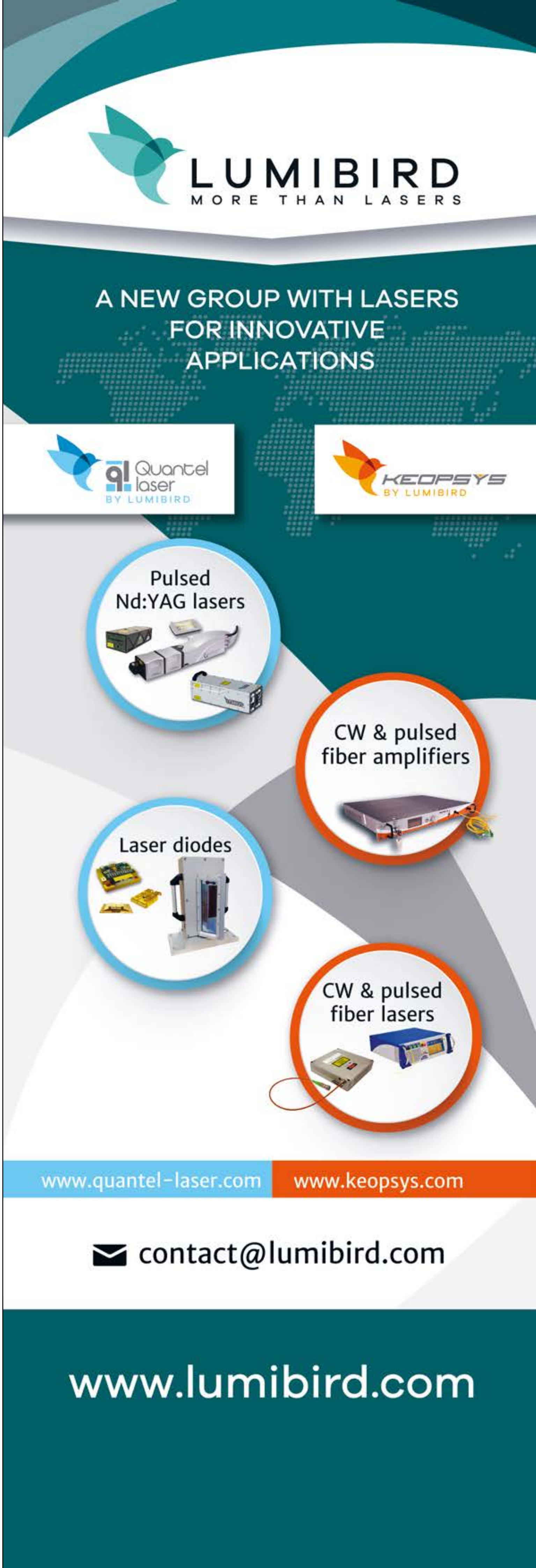
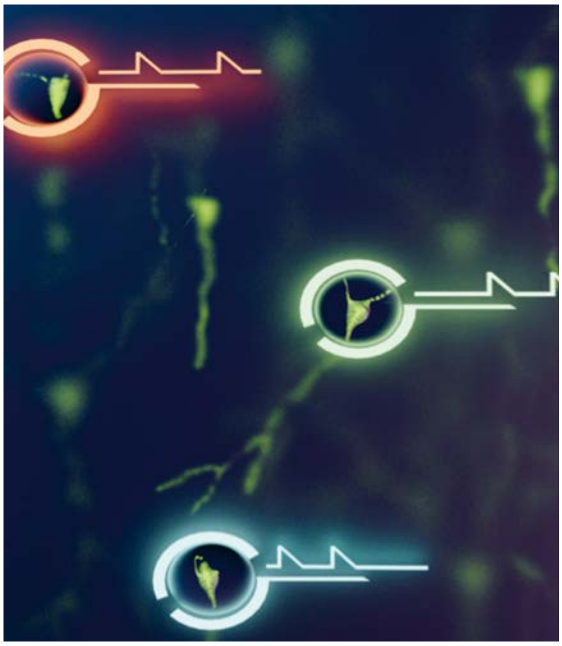


A computational approach
to optical readout of ultradeep neurons activity

Optogenetics has revolutionized neurosciences, allowing to observe (and ever control) neuronal activity with light, thanks to fluorescent markers. Yet, observing the activity of neurons at depth is very challenging, due in particular to light scattering by tissues, that prevents separating contributions from multiple neurons. In a proof-of-principle experiment, where neurons are emulated by fluorescent beads that are excited in such a way as to reproduce typical signal from in-vivo brain activity, researchers at Kastler-Brossel Laboratory in Paris, have shown that the activity from individual neurons may be retrieved, even when observed through a mouse skull, that strongly scatter light. This « unmixing » was done by using a computational approach based on matrix factorization algorithms. These results open important perspective in neuroscience and beyond, and more generally show that multiple scattering of light, despite strongly perturbating and mixing the information carried by light, did not destroy this information, which could be retrieved thanks to signal processing.



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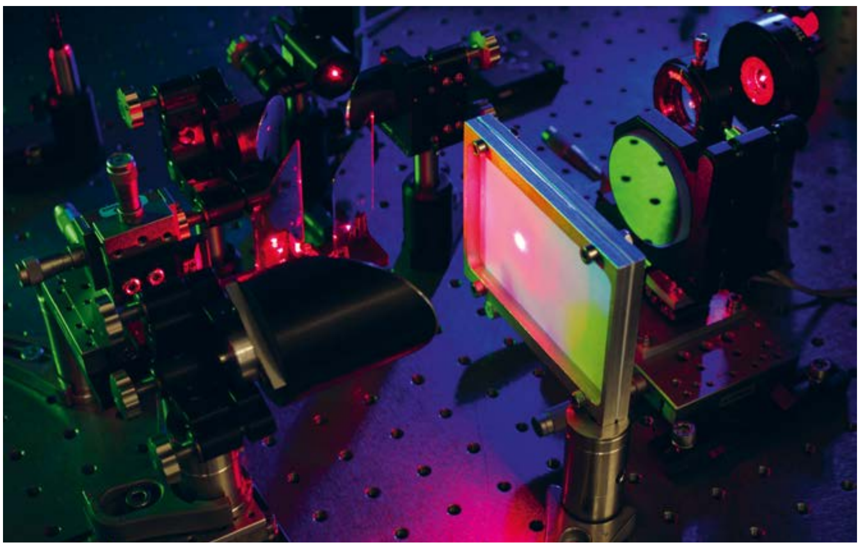
https://doi.org/10.1038/s41566-020-0612-2

Terahertz quantum sensing

The terahertz spectral region is highly attractive for applications ranging from fundamental solid-state physics to industrially relevant non-destructive testing of dielectric materials. Unfortunately, due to the low photon energy of terahertz waves detecting requires either cooled bolometers or experimentally demanding coherent detection schemes. Here, cost of equipment and ease of use are far beyond what one is used to from silicon-based camera devices used in every smartphone. Quantum sensing might be the solution: Sample information is gained in the terahertz spectral region and transferred via biphoton correlations into the visible spectral range, for which highly sensitive detectors are available. Georg von Freymann and coworkers from Fraunhofer ITWM and Technische Universität Kaiserslautern, Germany, report in a recent Science Advances paper on the first demonstration of quantum sensing in the terahertz frequency range in which the terahertz photons interact with a sample in free space and information about the sample thickness is obtained by the detection of visible photons. Layer thickness measurements with terahertz photons based on biphoton interference are demonstrated. The photon pairs are created in a periodically poled LiNbO-crystal from continuous wave visible laser radiation and all information is collected with a commercial uncooled CMOS camera.



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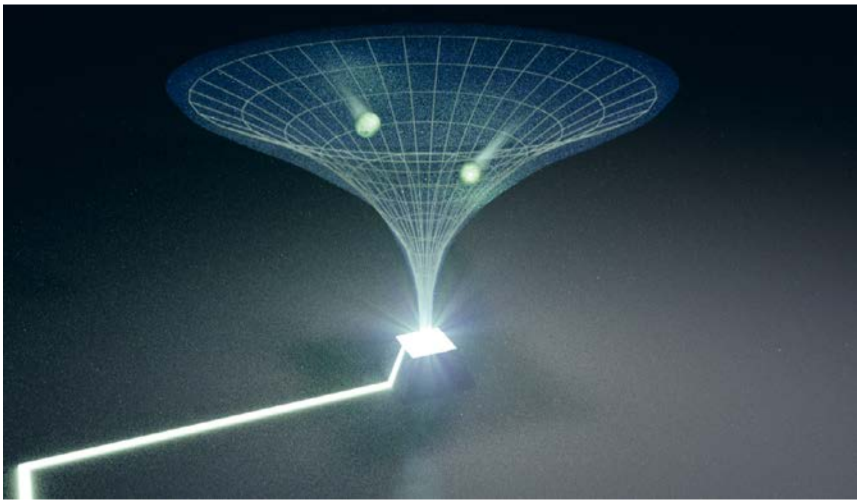
https://doi.org/10.1038/s41566-020-0612-2

A light funnel from topology



Dissipation is ubiquitous in almost every physical system, but mostly considered a nuisance. However, in recent years numerous beneficial effects were demonstrated like an enhanced sensing. In a recently published work, dissipation was used to create a photonic lattice with effective nonreciprocal coupling. This paved the road to experimentally explore new topological features, which are exclusive to non-Hermitian systems. The current work concerns the so-called non-Hermitian skin effect, which is related to a topological winding number of the complex spectrum. It characterizes the unique sensibility of this system with regard to edges or interfaces, because as soon as an edge or a topological interface is introduced, the whole spectrum collapses at the interface, thereby making the notion of a bulk compared to an edge questionable. The researchers from the University of Rostock together with their partners from the University of Würzburg demonstrated this effect for the first time by utilizing the robustness of the topological interface state to build a funnel for light. Any light field, regardless of its shape and distance from the interface, is transported towards the interface and remains confined, like an optical funnel. This concept opens up new possibilities for an effective and topological robust collecting of light.

REFERENCE
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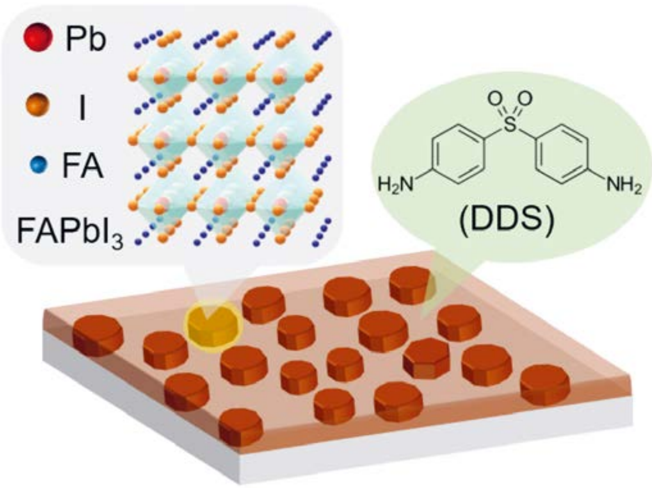
https://doi.org/10.1126/science.aaz8727

PEROVSKITE LEDS MADE STABLE BY MOLECULES

Light-emitting diodes (LEDs), a type of devices converting electricity into light, are widely used in modern society, such as lighting, displays, medical devices, etc. Metal halide perovskites are promising light-emitting materials that have aroused the interest of scientists around the world. They have excellent optical and electronic properties, and they are both easy and cheap to manufacture. The efficiency of perovskite LEDs has increased considerably in recent years, and for some colors the efficiency has reached that of mature technology. They are, however, not stable enough for practical use. In a recent paper published in Nature Communications 2020, 11, 891, Wang et al have found a way forward and brought them one step closer. The perovskite which consists of lead, iodine and formamidinium was in-situ embedded into an organic molecule matrix to form a perovskite-molecule composite thin film. This molecule with two amino groups at its ends helps the other substances to form a high-quality perovskite crystal structure and makes the crystal stable. Based on such a film, they have achieved a perovskite LED with both high efficiency and long operational lifetime. Considering the huge library of molecular semiconductors, more functional and new combinations of different perovskites and organic molecules are expected for the development of practical perovskite LEDs with various colours for low cost and energy efficient lighting and display applications.



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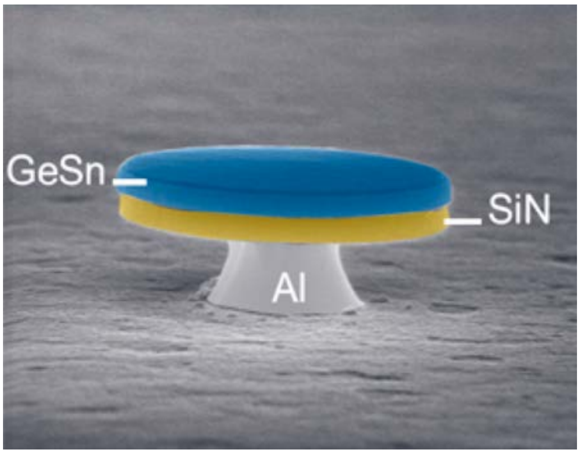
NEWS

First ultra-low threshold
continuous-wave lasing in Germanium-Tin

Germanium-Tin alloys (GeSn) are promising for realizing light emitters as it is compatible with Silicon and can be fully integrated in the CMOS fabrication chain.
Today, the main approach consists in introducing as much tin as possible in the GeSn alloy (around 10-16%). The obtained compound provides direct alignment of the band structure, which makes it possible the laser emission. However, due to the lattice mismatch between the Germanium (strained relaxed) substrate on silicon and the Sn-rich GeSn alloys, a very dense dislocation defects network is formed at the interface. It thus takes extremely high pumping power densities (hundreds of kW/cm^2 at cryogenic temperature) to reach the laser emission regime.
Using a different approach based on specific material engineering, a team of researchers at the Centre de Nanosciences et de Nanotechnologies – C2N (CNRS/Université Paris-Saclay), at the Forschungszentrum Jülich (FZJ) and at STMicroelectronics, obtained a laser emission in a microdisk of GeSn alloy fully encapsulated by a stressor layer made of dielectric Silicon Nitride (SiNx). They demonstrated for the first time the laser emission in the alloy able to operate under continuous-wave (cw) excitation. Laser effect is reached under cw and pulsed excitations, with ultra-low thresholds compared to the current state of the art. Their results are published in Nature Photonics.



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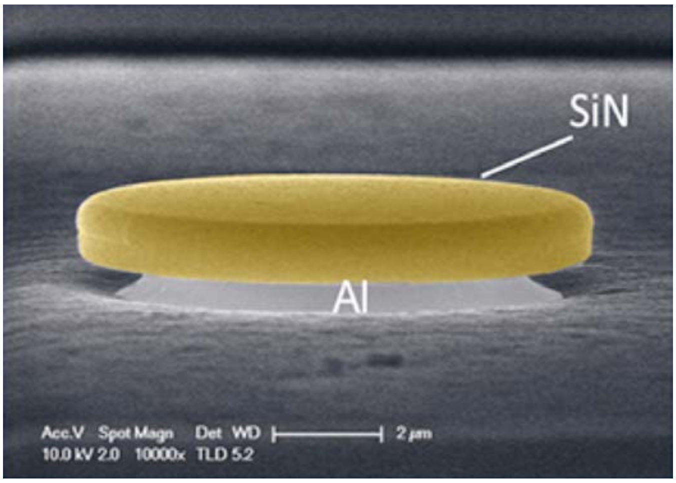

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Gustav Mie: the man, the theory

By Brian STOUT* and Nicolas BONOD
* brian.stout@fresnel.fr

Gustav Mie was a German scientist who published a rigorous electromagnetic scattering theory by a spherically shaped particle in 1908, but which only began to attract attention some fifty years later. How then did Gustav Mie, who was initially attracted to science by his interest in mathematics and mineralogy, publish a 'hidden gem' that now shines so brightly over physics?

https://doi.org/10.1051/photon/202010122

Were you asked to name famous 20th century physicists, it is rather unlikely that Gustav Mie would be near the top of your list. Nevertheless, starting from the late 1940's, Mie's 1908 opus [1] on the scattering of light scattering by a spherical particle has played an important role in physics and technology. So who was Gustav Mie and how did a single publication authored by him in the early 20th century, treating a 19th century problem, become an entire methodology, most often referred to simply as 'Mie theory', with literally tens of thousands of citations in the 20th and 21st centuries?

Gustav Mie (Sept. 29th 1868- Feb. 13rd 1957) grew up in Rostock, a German city along the coast of the Baltic sea, in a family of protestant pastors. Although initially set to follow the family tradition, his interests turned to the natural sciences and mathematics during his high school years. His university education was carried out between his native city of Rostock and Heidelberg with a noted emphasis on mathematics and geology with physics and chemistry falling rather to the background of his formal education.

In 1890, Mie passed the State Examination for Mathematics and Physics that grants access to

BIOGRAPHY

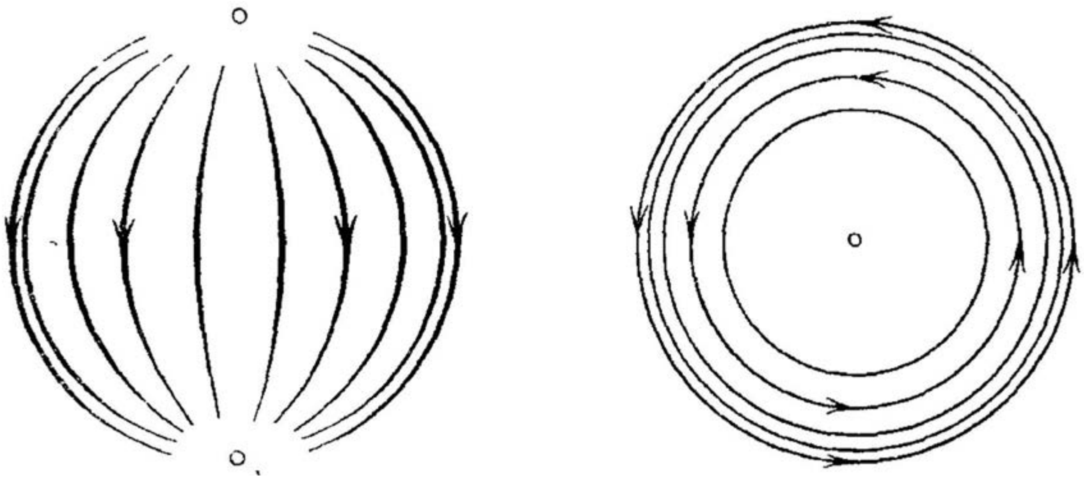
1868:	1901:	1902-1917:	1908:	1957:
Birth at Rostock, Germany	Wedding with Berta Hess	Professor at the university of Greifswald	Publication of his theory on light scattering	Passing at Freiburg

the higher teaching profession. Mie spent weeks preparing his dissertation in physics and his examinator, Otto Lehmann, was highly impressed by Mie's developments on induction and the construction of dynamo electric machines, but this left him only 24 hours to write his entire dissertation in mathematics which was evaluated with quite less praise. After his doctoral thesis, defended in Karlsruhe in 1891, "On the fundamental Principle of the Existence of integrals of Partial Differential Equations", his prospects for a scientific career seemed slim and in the summer of 1892, Mie accepted a teaching position in a private school at Dresden. A turning point in Mie's life came when he sent his dissertation to his former examiner, Otto Lehamn, a German physicist and crystallographer, considered as the first physicist to have studied liquid crystals. Otto Lehman offered Mie an assistantship at the Technical University of Karlsruhe which embarked Mie on a career as a distinguished physics professor that spanned two world wars and considerable social upheavals.

Since mathematics and mineralogy were Mie's preferred university subjects, his physics education was largely auto-didactic, and he made good use of his first years of teaching a practical physics course in Karlsruhe to improve his mastery of experimental techniques. Henrich Hertz's renowned experiments on the propagation of electromagnetic waves, performed

MORE THAN MIE

Although Mie learned of and cited Maxwell Garnett's (1904 and 1906) work on metal colloids [5], it appears that he was unaware of Lorenz's 1890 (non-electromagnetic) theory of light scattering by lossless spheres [6]. In 1890, Maxwell's equations were not yet as enshrined as they are today, and Ludvig Lorenz based his theory on a 'model-free' set of equations, which, for non-magnetic media, were mathematically equivalent to Maxwell's light propagation formulas. There are certain similarities here to Augustin Fresnel's reflection-transmission coefficients which were also derived on general principles for lossless media, but which were later readily generalized to include dispersive media in the context of Maxwell equations. Since L. Lorenz's expressions for the renowned scattering coefficients in the context of dispersionless scatterers are the same as those obtained by Mie in his study of dispersive scatterers, a number of modern authors now refer to 'Lorenz-Mie' theory in the interest of historical justice. In 1909, Peter Debye published a work on light scattering which included analytical expressions for the optical forces on the sphere, so one also encounters references to 'Lorenz-Mie-Debye' theory.



at TU Karlsruhe only a few years earlier, likely influenced Mie's [2] choice to specialize on the theoretical and technical applications of electrodynamics, culminating in his habilitation, "Draft of a general Theory of the Energy Transmission" in July 1897. Despite Mie's accomplishments in the practical and experimental domains, he provided a detailed mathematical solution of the Lecher line problem in 1900 that considers two parallel lines acting as a wave-guide to measure the wavelength of radio waves. This theoretical work played a pivotal role in establishing Mie's reputation as a theoretical physicist.

Figure 1.
Lines of the electric fields deduced from the expressions derived in Mie's seminal paper [1] for electric (left) and magnetic (right) dipoles. Adapted from Figs.[3-4] in Ref. [1].

Gustav Mie married Berta Hess in 1901, and shortly thereafter he obtained a special (extraordinarius) position of professor at the university of Greifswald, (1902-1917), another Hanseatic city in northeastern Germany. This period is the most productive of his career [2,3]. In particular, he made

FAME OF MIE

One reason for the enduring popularity of Mie's theory is that it supplies exact solutions to a highly non-trivial physics problem without forcing us to delve into the full details of its derivation. The famed 'Mie' coefficients a_n and b_n have relatively simple expressions in terms of what we now call the 'spherical Bessel functions', but which are hardly more difficult for a computer to calculate than the far better known sine and cosine functions (of which they are a generalization). The a_n coefficients describe the 'electric multipole modes' of the sphere while the b_n coefficients (denoted p_n by Mie) describe its 'magnetic multipole modes' (the index $n = 1$ stands for dipole, $n = 2$ quadrupole, etc.).
These 'Mie' coefficients determine the entire field dynamics of any scattering process and mathematical manipulations *à la Lorenz and Mie*, and can extract information in terms of simple formulas. For example, the scattering cross section, σ_s, for light of wavelength λ by any spherical particle can be calculated as:

$$\sigma_s = \frac{\lambda^2}{2\pi}\sum_n (2n+1)[|a_n|^2 + |b_n|^2]$$

Given the vast range of applications of such simple formulas, it is no surprise that a host of extensions and generalizations have been proposed over the years to extend its range of applications as reviewed in box below: After Mie.

AFTER MIE

Entire fields of study have formed around extensions of Mie theory. Quite naturally enough, Mie theory has been generalized to a wide class of special cases: spheroidal and cylindrically shaped particles, radially inhomogeneous spheres, chiral and anisotropic spheres, etc. Of particular note is the 'T-matrix' theory which uses Lorenz-Mie multipolar 'basis functions' to describe scattering by particles of arbitrary shapes, in which 'Mie theory' appears simply as a special case characterized by diagonal T-matrices [7]. Combining the T-matrix formulation with 'addition formulas' [8] and further analytic considerations [9], one can now solve multiple scattering solutions for finite clusters of particles on a computer, while other extensions add planar interfaces. Yet another domain of extensions has come to be called 'Generalized Lorenz-Mie theory' [10] (GLMT) since it 'generalizes' the incident plane waves of the initial Lorenz-Mie formulations to a host of exotic beam types which nowadays include localized sources, like atoms, modelled as electric or magnetic point-like multipolar emitters [11].

important contributions to problems related to the Poynting vector and energy transmission. He also developed a model of the interaction forces of atomic gases which was both a precursor and a more generalized form of the famed Lenard-Jones potential. Furthermore, Mie maintained an active correspondence with other renowned German physicists, notably with Max Planck on dispersion theory and later with Albert Einstein on questions of field theory.

The enduring success of the "Mie" theory stems from its savant use of rigorous mathematical analysis to produce simple and powerful practical formulas which have found a vast array of applications, from atmospheric aerosols to nano-optics.

Mie's interest in the theory of light scattering was clearly motivated by the Austrian-Hungarian chemist Richard Zsigmondy's work on the ultramicroscopic investigations of colloids for which he received the 1925 Nobel Prize in Chemistry. Gustav Mie set one of his students, Walter Steubing, to study the remarkable color effects observed in gold colloids. The results of these experiments, published separately, led Mie to develop his multipolar electromagnetic theory of light scattering by a spherical particle, humbly entitled

"Contributions on the Optics of Turbid Media, particularly colloidal metal solutions".

In his theoretical work, G. Mie correctly explained the gold colloid colors as being due to what would come to be called, many decades later, structural colors based on localized surface plasmon resonances. Remarkably, and after thorough and technical mathematical derivations, G. Mie concludes his 69 long pages article with clear and didactic conclusions on the color of suspensions of colloidal gold particles, *e.g.* "The gold particles have in fact a very sharp maximum in the absorption capability in the green, and secondly a maximum in reflection capability in the yellow red. Very small particles reflect weakly and absorb strongly, consequently they make the solution ruby-red. Large particles reflect strongly, at the same time the pure absorption curve for them becomes lower and flatter, so they make the solution blue."

Although applications of Mie theory to plasmonics are important and continue to this day, its fame is also due to its host of successes in other domains, with the aerosol and rainbow problems being some of the best known. Issues of historical precedence aside, Mie's work 1908 was remarkable for being self-contained and mathematically extensive, with developments of asymptotic expansions for large spheres and numerical algorithms permitting the (laborious) calculation of the electromagnetic field distributions. Given the wealth of detail of this article and its orientation toward applications, it is of little wonder that when computers began to alleviate numerical burdens in the 1940s, it was to Mie's electromagnetic scattering formulation that so many turned, and in so doing, rendering multipolar scattering theory nearly inseparable from his name.

Mie's foray into scattering theory ended however in 1908. Keeping in mind that this was only three years after Einstein's 'Annus Mirabilis', it is hardly surprising that Gustav Mie turned his mathematical talents away from a specific '19th' century problem to more general studies in field theory which embarked him on an ambitious program that attempted to formulate a unified theory of matter and radiation including ideas from both the burgeoning quantum mechanics and relativity. Mie's investigations along these lines are well documented, but are nowadays generally considered to be only of history interest. Mie's reputation was hardly tarnished by the failure of his unified matter-field program however, as he was an accomplished lecturer and well known for his experimental studies and thesis supervisions. Between 1917 and 1924, he occupied a professor position in experimental physics at the university of Halle. He spent the last part of his academic career at the university of Freiburg (1924-1935), in southwest Germany, where he remained after retirement. Mie carried out significant investigations on the unit problem where he developed a system of units (now fallen to disuse), and he authored a widely appreciated textbook on electricity and magnetism, the last of its multiple editions being authored by Mie when he was eighty years old [4].

The enduring success of the "Mie" theory stems from its savant use of rigorous mathematical analysis to produce simple and powerful practical formulas which have found a vast array of applications, from atmospheric aerosols to nano-optics. Gustav Mie passed away in 1957, three years after his beloved wife Berta. Neither Mie nor his contemporaries had considered his scattering paper to be of particular importance. However, given that he lived long enough to see the dawn of the computer era, he may well have remarked that one of his nearly forgotten publications, written nearly 50 years earlier, had begun its ascension to being crowned the 'hidden gem' of his long career.

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TERAHERTZ SPECTROSCOPY USING QUANTUM-CASCADE LASERS

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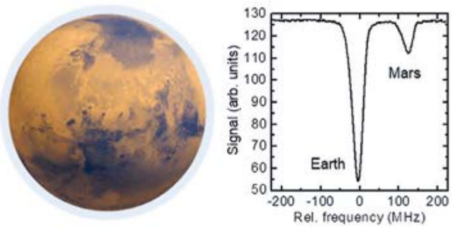

Terahertz (THz) quantum-cascade lasers (QCLs) provide powerful, narrow-band, and frequency-tunable radiation, which makes them ideal sources for high-resolution molecular spectroscopy. A first application of a THz QCL has been as local oscillator in a heterodyne spectrometer for astronomy on board a Boeing 747. For laboratory spectroscopy, QCLs close the so-called THz gap and enable new research topics.

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High-resolution terahertz (THz) spectroscopy is a very important technique for the detection of molecules and atoms, since they exhibit characteristic absorption or emission spectra in the THz spectral region due to transitions between rotational states of molecules and fine-structure transitions within a multiplet of orbital angular momentum states in atoms. For example, molecules and atoms such as the hydroxyl radical OH and atomic oxygen can be detected in space or in the atmospheres of the Earth and other planets. The hydroxyl radical plays a key role in the chemistry of the stratosphere. It has rotational transitions at about 2.5 and 3.5 THz. Atomic oxygen, which is important for the chemistry and energy balance of the mesosphere and lower thermosphere, can be detected through its fine-structure transition at about 4.7 THz. Furthermore, THz spectroscopy allows for the investigation of the structure and energy levels of molecules and atoms as well as for the determination of Doppler and pressure broadening.

Until the realization of THz quantum-cascade lasers (QCLs) in 2002 [1], high-resolution THz spectroscopy with a resolving power of 10^6 or better was very difficult to achieve due to the lack of suitable radiation sources. Because of the very high spectral brightness of THz QCLs, which is typically on the order of several mW per MHz, they became important for high-resolution molecular spectroscopy [2]. THz QCLs have been implemented in heterodyne as well as in absorption spectrometers. Heterodyne spectrometers are mostly used for remote sensing in astronomy and in atmospheric science. In this case, a very weak signal on a low-power background has to be detected. In a heterodyne spectrometer, the QCL serves as a local oscillator. In absorption spectroscopy, the goal is to detect a small fractional change of a relatively large amount of power. Although both applications are different, the requirements regarding the QCL are similar. Additional advantages of THz QCLs, covering at present the emission frequency range of about 1 to 5 THz, are compactness and optical output powers of typically several mW. A challenge is still the necessary cryogenic operation. However, mechanical coolers, which are free of cryogenic liquids, can be used.

TERAHERTZ QUANTUM-CASCADE LASERS: PHYSICS AND TECHNOLOGY

The radiation of QCLs, which were invented by F. Capasso and his coworkers more than 25 years ago [3], is emitted by intersubband transitions within the conduction band rather than by transitions across the energy gap. The optically active regions, which contain the laser levels, are connected by extractor/injector stages forming a cascade structure as shown in Figure 1. The carrier transport through the structure relies on resonant tunneling between adjacent quantum wells and on carrier scattering between subbands. In order to achieve population inversion, a well-balanced interplay of scattering processes and stimulated emission has to be established. Both, the scattering rates and the emission wavelengths, can be tailored by varying the thickness of the individual layers.

THz QCLs are based on two main design types: bound-to-continuum and resonant-phonon designs [4]. A combination of these two types, the *hybrid design* (Fig. 1), is often preferred for continuous-wave operation. The rather complex heterostructures consist of a single period with typically 6 to 20 layers, which is repeated about 100 times. The thicknesses of the layers vary between a few nm and about 20 nm resulting in a total thickness of the QCL structure of typically about 10 µm. For the modeling of THz QCLs, which is necessary in order to develop advanced designs and to exploit new frequency ranges, several theoretical approaches have been employed. The complexity of the methods increases starting from most straightforward and fast rate equation systems over full density matrix models and Monte Carlo simulations to non-equilibrium Green's function theories with increasing physical insight, but also with significantly increasing numerical costs [5].

THz QCLs are mainly based on $GaAs/Al_xGa_{1-x}As$ heterostructures with $0.1 \leq x \leq 0.25$, which are grown by molecular beam epitaxy with a very good stability of the growth parameters over up to 20 hours. In order to achieve the necessary long-term stability, in-situ growth rate control methods are employed. To form a laser waveguide, the wafers are processed using wet chemical or dry etching. Edge emitting Fabry-Pérot ridge lasers represent a straight-forward and robust approach. For single-mode operation, distributed-feedback lasers, two-section cavity lasers, or very short cavities are used. Examples for the waveguide and resonator configurations are presented in Figure 2.

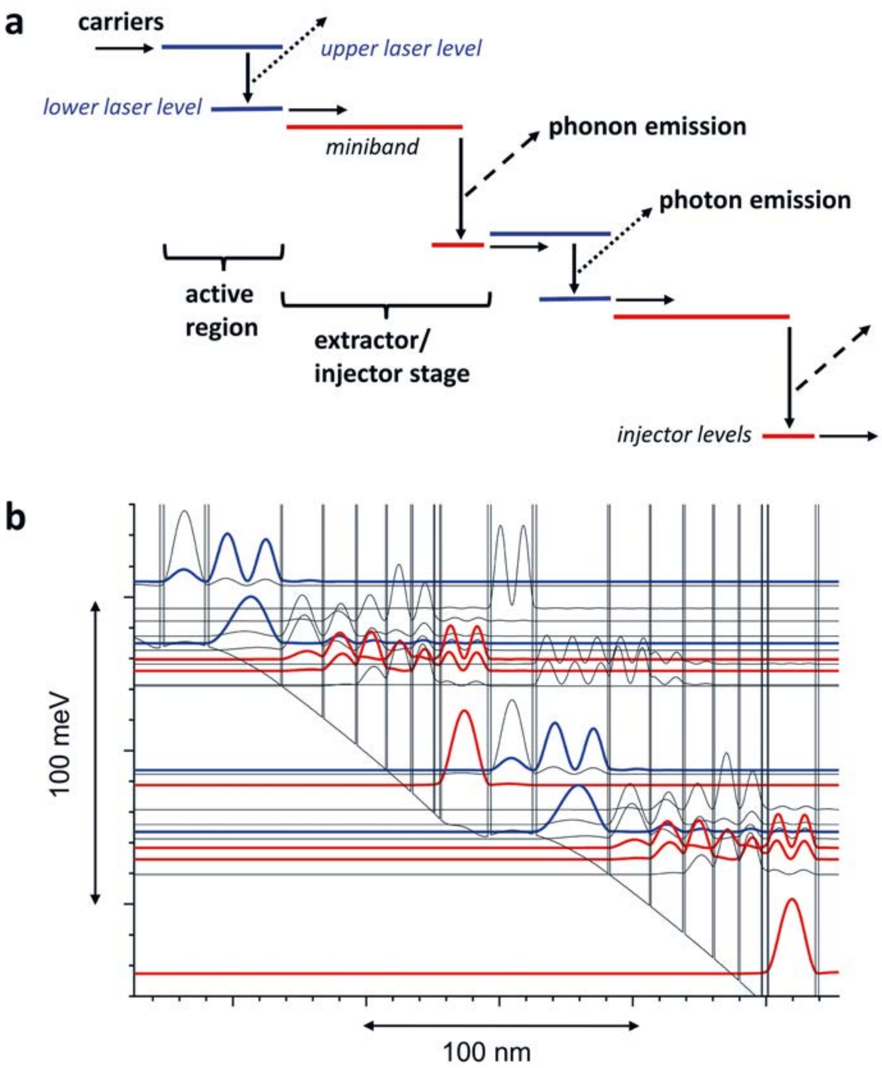


Figure 1.
(a) Schematic representation and (b) subband structure (envelope functions) of a hybrid design for a QCL at 4.7 THz. The carriers (electrons) are injected from the left into the upper laser level. The emission of a THz photon is connected with the transition of a carrier to the lower laser level, which is coupled to a miniband (*bound-to-continuum* transition). After transport through the miniband, the electron emits a longitudinal optical phonon due to a transition resonant to the longitudinal optical phonon energy (*resonant-phonon* transition) and is injected into the upper laser level of the following period of the cascade. In the *bound-to-continuum* design, the transition resonant to the phonon energy is not present, while there is no miniband in the *resonant-phonon* design.

Typical dimensions of the laser ridges are widths of 15 to 200 µm and lengths of 0.5 to 7.5 mm.

For continuous-wave operation in mechanical miniature cryocoolers, the wall plug efficiency of the lasers has to be sufficiently large for the limited available cooling power. For this case, we developed GaAs/AlAs THz QCLs, which exhibit an up to three times higher wall plug efficiency than GaAs/$Al_{0.25}Ga_{0.75}As$ QCLs with an almost identical active-region design. Currently, QCLs based on this alternative materials system are available for frequencies between 3.3 and 5.0 THz (Fig. 3) [6].

HIGH-RESOLUTION SPECTROSCOPY WITH TERAHERTZ QUANTUM-CASCADE LASERS

THz heterodyne spectroscopy is the first example where THz QCLs found a unique application in astronomy. One particularly important example is the detection of atomic oxygen. It can be traced by measuring the emission from its fine-structure transition at 4.7 THz. THz heterodyne spectroscopy is the only technique which provides the required spectral resolution of around 1 MHz.

In a heterodyne spectrometer, a weak THz signal is detected by generating an intermediate frequency, which is the difference frequency of the signal radiation and the radiation from a local oscillator. The intermediate-frequency spectrum, which is a one-to-one replica of the THz spectrum, is recorded by a digital fast Fourier transform spectrometer (Fig. 4). Above about 3 THz, QCLs are the only radiation sources which comply with the requirements of a local oscillator with respect to an output power of several mW, the transformation of the beam profile into an approximately Gaussian shape, and a well-defined, stable as well as tunable frequency. Since 2014, a THz QCL local oscillator [7] has routinely been used in the German Receiver for Astronomy at Terahertz Frequencies (GREAT) on board the Stratospheric Observatory for Infrared Astronomy (SOFIA) for the observation of the atomic oxygen emission (Fig. 4). The QCL has a lateral distributed feedback grating, which is optimized for 4.745 THz and allows for single-mode emission over most of the driving current range of the laser. Frequency stabilization on the order of 1 MHz is achieved by a high-precision control of the driving current and heat sink temperature of the QCL. Besides for SOFIA, further QCL local oscillators are currently under development for future balloon or spaceborne missions.

In contrast, high-resolution absorption spectra are acquired by tuning the frequency of the QCL across the absorption line. The linewidth of the QCL radiation has to be significantly smaller than the absorption feature to be measured. The typical width of a Doppler-limited molecular rotational transition is a few MHz. With a sufficient temperature and driving current stabilization, the linewidth of a free running QCL is about 1 MHz, although this is still far above the fundamental quantum limit, which is on the order of several 10 Hz [9]. To improve the frequency stability and linewidth of the QCL, its radiation can be locked to a molecular reference line, to a reference source such as a microwave oscillator whose emission frequency is multiplied to the THz range, or to a frequency comb. With the latter two techniques, phase-locking has been demonstrated [10,11]. Very high frequency precision can also be obtained by injection locking to a telecom wavelength frequency comb [12]. Furthermore, if the frequency or wavelength of the QCL is modulated and the first or second harmonic is measured instead of the direct absorption signal, a minimum detectable absorption of better than 10^{-5} can be achieved.

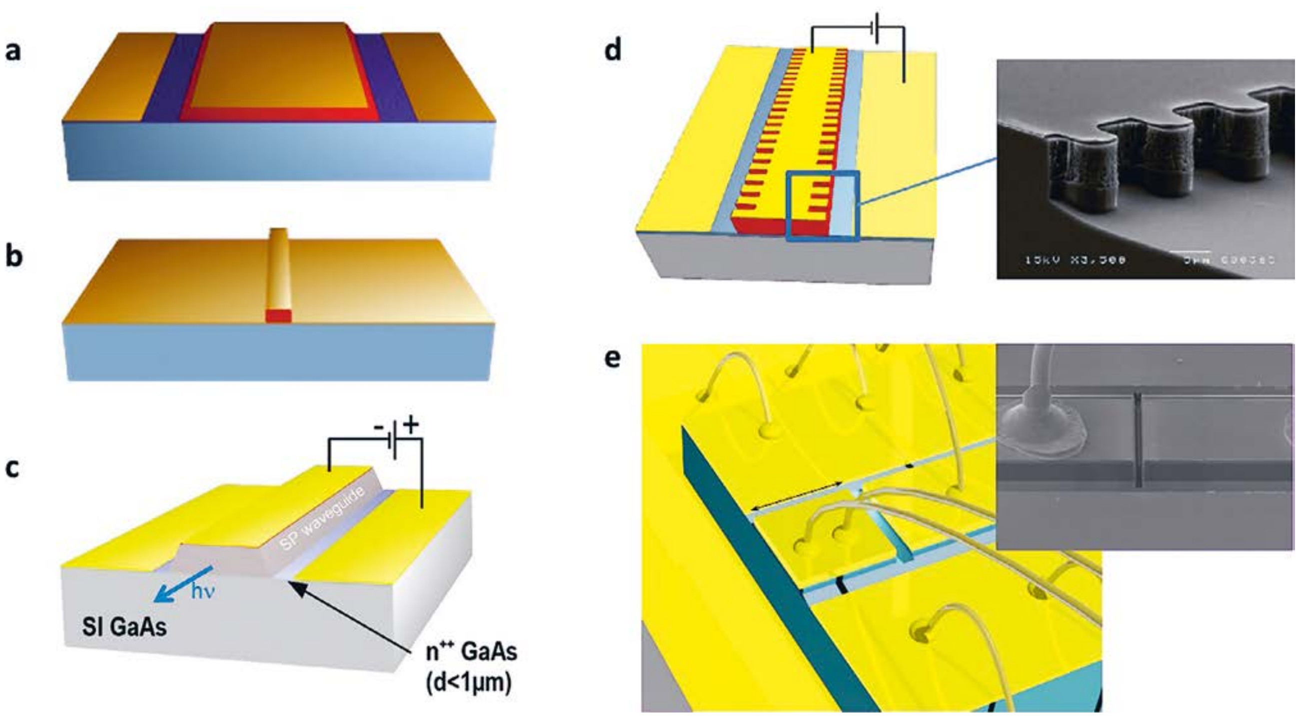
The straightforward approach for frequency tuning is to change the driving current or operating temperature of the QCL, which allows for a •••

frequency tuning of several GHz. For larger tuning ranges, several techniques such as micro-optomechanical cavities, electronic frequency tuning in multi-terminal and multi-section QCLs, as well as tuning by gas adsorption have been demonstrated. However, all of these methods have particular shortcomings, which have prevented their use in high-resolution spectroscopy. Recently, frequency tuning has been demonstrated by illuminating the substrate below the active medium of the QCL with near-infrared radiation so that an electron-hole plasma in the vicinity of the back facet of the QCL is generated [13], which changes the optical length of its cavity. A tuning range of 40 GHz has been achieved [14]. This method is rather straightforward, and its potential has been demonstrated by high-resolution spectroscopy of CH_3OH [14] (Fig. 5). THz QCLs have also been employed for Lamb-dip spectroscopy, which requires the saturation of the transition, as well as for techniques based on optical feedback, which changes the QCL frequency as well as its terminal voltage. While in the first case the spectroscopic precision can be increased significantly, the latter allows for a much simpler spectrometer design, because the external detector can be omitted. Figure 5 shows a Lamb dip with a sub-Doppler linewidth of 170 kHz for a rotational transition of HDO in a collinear pump-probe configuration [15]. The feedback technique has been demonstrated with a mixture of D_2O and CH_3OD [16] as shown in Figure 5 by placing the absorption cell between the QCL and a mirror so that the radiation is reflected back into the QCL.

OUTLOOK

In the past few years, THz QCLs have reached a level of maturity which enables routine operation in various types of spectrometers. In particular, QCLs for local oscillators at frequencies above 3 THz are currently unrivaled for heterodyne receivers in airborne instruments for astronomy and atmospheric research. Similar systems are now being developed for balloon-borne instruments and future space missions. For absorption spectroscopy using THz QCLs, many techniques as well as key performance parameters, which have already been established for other frequency ranges, have been ●●●

Figure 2.
Schematic representations of (a) a *single-plasmon* waveguide, in which the optical mode is confined between a top metal contact and a highly doped (contacting) layer underneath the cascade structure, and (b) a *metal-metal* waveguide, in which the radiation is confined between two metal layers. While metal-metal waveguides exhibit a larger mode confinement factor than single-plasmon waveguides and are preferred for high-temperature operation, single-plasmon waveguides allow for a better beam profile and larger output powers for rather straightforward resonator designs and are often preferred for practical applications. (c) Schematic layout for a THz QCL based on a single-plasmon waveguide. Since in this case the laser mode penetrates into the substrate, semi-insulating substrates are used so that the bottom contact formed by the highly doped layer is also accessed from the top. (d) and (e) present schematic views and scanning-electron micrographs of laser stripes with a lateral distributed-feedback grating fabricated by dry etching and a two-section resonator fabricated by focused-ion beam cuts, respectively, for single-mode operation.



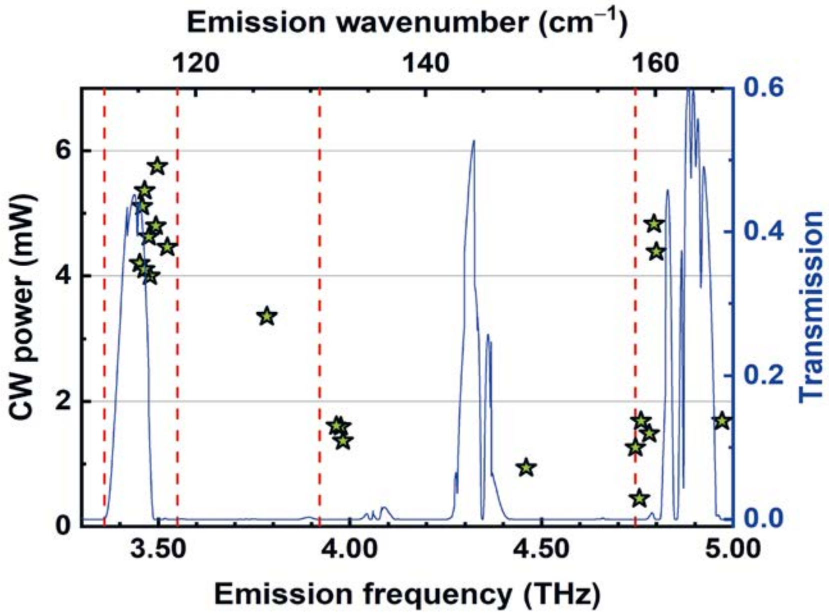
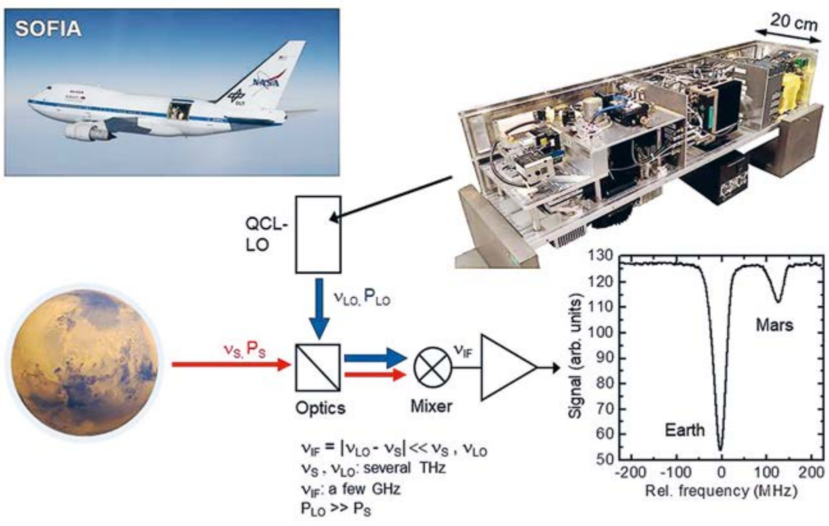


Figure 3.
Compilation of the optical properties of 21 GaAs/AlAs THz QCLs based on the *hybrid* design. The asterisks depict the maximum output power for continuous-wave operation as a function of the center emission frequency (wavenumber) measured at a heat sink temperature of 30 K. The vertical dashed lines indicate target frequencies of 3.36, 3.92, and 4.75 THz for fine-structure transitions of Al, N^+, and O atoms/ions, respectively, and 3.55 THz for OH detection. The blue solid line depicts a simulated transmission spectrum of air based on the HITRAN database for ambient conditions and an optical path length of 10 m, exhibiting maxima at 3.43, 4.32, and 4.92 THz (adapted from Ref. [6]).

Figure 4.
GREAT heterodyne spectrometer aboard the airborne observatory SOFIA. The radiation from the QCL local oscillator is mixed with the 4.7-THz signal from the atmosphere of Mars and down-converted to a GHz frequency band as shown on the right. In the spectrum, an absorption feature due to atomic oxygen in the atmosphere of Mars appears together with one due to absorption in the mesosphere and lower thermosphere of the Earth. Due to the relative velocity of Mars and Earth, the absorption in the atmosphere of Mars is shifted by 140 MHz from the absorption in the atmosphere of the Earth at 4.7448 THz (rel. frequency: 0 MHz) (spectrum adapted from Ref. [8]).



demonstrated paving the way for further applications. In the years to come, THz QCLs are expected to enable exciting discoveries in molecular spectroscopy as well as in astronomy and atmospheric science.

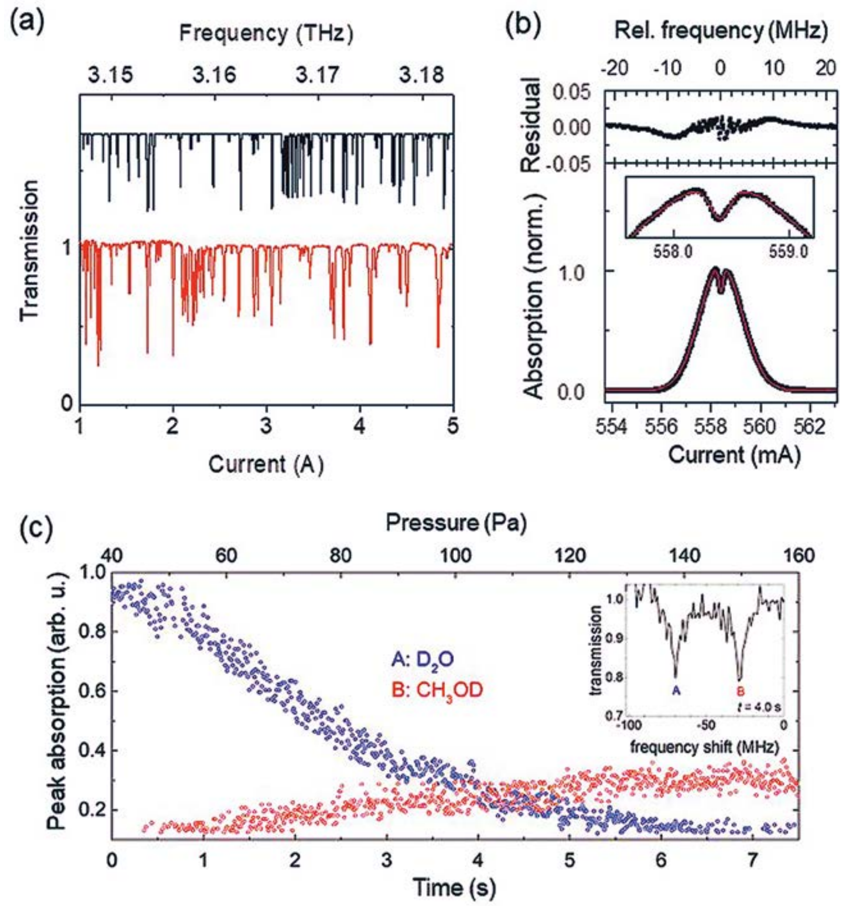


Figure 5.
(a) Absorption spectrum of CH_3OH at 3.3 THz (red line) measured by tuning the frequency of the QCL by illumination of its back facet with a near-infrared laser. The black line indicates a calculated spectrum using the HITRAN data base (adapted from Ref. [14]). (b) A 170-kHz-wide Lamb-dip (full width at half maximum) of a transition in HDO which amounts to three times the theoretical value. The spectrum has been measured within only 200 ms at a gas pressure of 2.5 µbar (adapted from Ref. [15]). (c) Peak absorption of D_2O (blue dots) and CH_3OD (red dots) as a function of time obtained from the absorption spectra recorded by the optical feedback technique. Each 100-MHz wide spectrum, which covers one transition from both species (inset), takes 10 ms to be measured. Initially, the absorption cell contained only D_2O, while CH_3OD was added slowly (adapted from Ref. [16]).

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THz SPECTROSCOPY FOR FUNDAMENTAL SCIENCE AND APPLICATIONS

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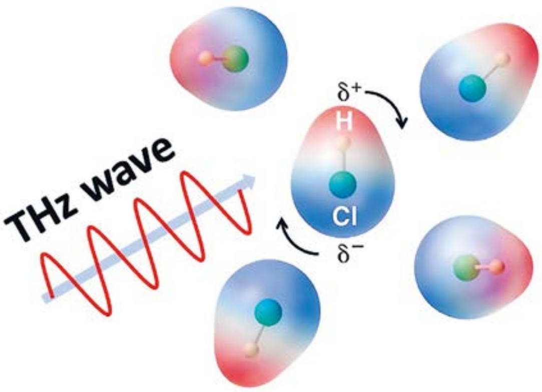

Many elementary process in matter, such as the interaction of electrons, spins and phonons as well as rotational modes of molecules possess resonances frequencies in the THz spectral range (1 THz = 10^{12} Hz) and dynamics on (sub)-picosecond time scales. Therefore, THz spectroscopy has become an exciting technique for probing and characterizing a variety of low-energy physical phenomena [1], which makes it very attractive for a wide range of disciplines including physics, chemistry, astronomy, and medicine.

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THz SPECTROSCOPY EXPERIMENTS

THz spectroscopy is based on the interaction between the electromagnetic field and the electric or magnetic dipoles contained in matter. These interactions with matter affect the propagation of THz waves, which yield a spectral signature that permits to identify matter and to understand its properties (Fig. 1). The majority of THz spectroscopy systems can be divided into three types: time-domain, frequency-domain systems and interferometric techniques.

TIME-DOMAIN SPECTROSCOPY

THz time-domain spectroscopy (THz-TDS) measures the time-resolved electric fields of THz radiation propagating through a medium and compared to a reference beam. These systems are based on ultrafast optical lasers that provide a set of femtosecond (fs) pulses centered around 800 nm. The pulse train is split in two optical beams (Fig. 1a). One optical beam is focused onto a photoconductive antenna or a nonlinear crystal (the THz emitter). The optical excitation gives rise to transient current or optical rectification that results in the emission of THz pulses. The emitted THz pulses are focused by paraboloidal mirrors onto the sample and then onto a THz detector. The second optical beam passes through a delay line (that modifies the path length) and is also focused onto the THz detector that synchronously probes the transient THz electric field. The detector is usually a photoconductive antenna or an electro-optic crystal. By delaying the timing of the optical probe pulse to the optical pulse which drives the THz emitter, • • •

the temporal waveform of the THz pulse incident on the detector is recorded with fs resolution (Fig. 1b). Both the amplitude and the phase of the THz radiation are obtained by a Fourier transform (Fig. 1c). The complex refractive index of the sample under investigation (*i.e.* the absorption and the dispersion) is then directly obtained without requiring the use of Kramers-Kronig relation [2].

Starting from this basic spectroscopic technique and exploiting its time-gated coherent nature, a set of dynamical spectroscopy experimental techniques can be implemented in pump-probe configuration, multidimensional THz spectroscopy and THz emission spectroscopy. Special set-ups were also designed to allow the measurement of small quantities of material which is useful for biosamples [3].

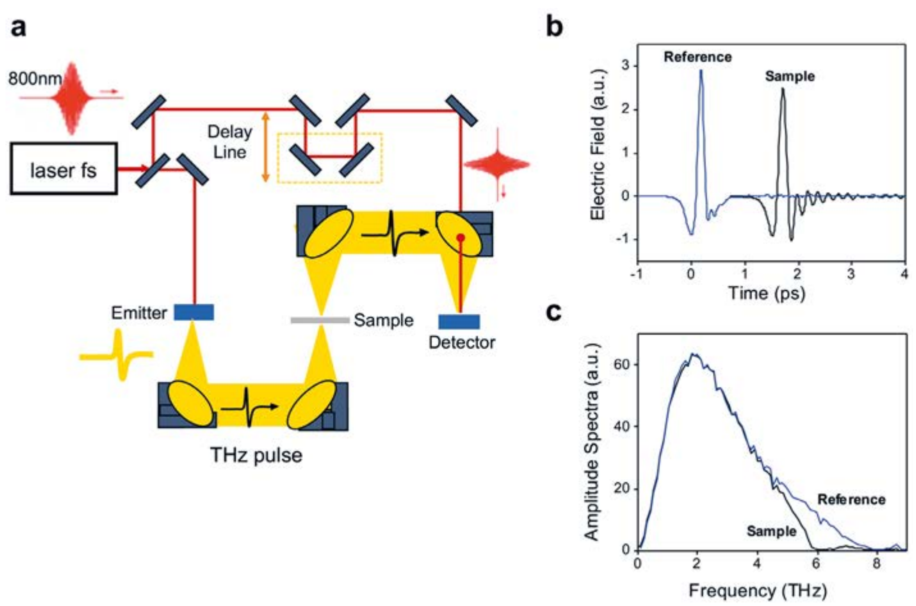
The photocurrent follows the variation of the laser light intensity induced by this beat and flows in a broadband antenna which radiates a CW THz beam in free space. This photomixing technique can be used also for the detection of the beam with the same kind of device thanks to a homodyne setup.

FREQUENCY-DOMAIN SPECTROSCOPY

In contrast to THz-TDS, frequency-domain THz spectroscopy systems do not require fs lasers but they are based on continuous-wave (CW) lasers. The CW photomixing THz spectroscopy technique relies on superimposing two continuous optical laser beams on an ultrafast photodetector for the generation of CW THz waves. The two lasers are tuned to two different wavelengths, then a beat appears at the frequency equal to the difference between the two laser frequencies. This beat is easily tunable between zero and several THz by tuning one of the lasers. The photocurrent follows the variation of the laser light intensity induced by this beat and flows in a broadband antenna which radiates a CW THz beam in free space. This photomixing technique can be used also for the detection of the beam with the same kind of device thanks to a homodyne setup. CW THz-TDS systems are usually less complex and less expensive than a typical THz-TDS setup and are used to perform high resolution broadband THz spectroscopy (the spectral resolution can be of the order of 1 MHz or less). It is well suited for narrow spectral features in gas-phase spectroscopy, but is also used for the spectroscopy of solid or liquid samples in amplitude and phase thanks to the homodyne setup [4].

More recently, THz Quantum Cascade Lasers (QCLs) have been used as powerful sources for THz spectroscopy systems. THz QCLs are compact semiconductor sources exploiting III-V quantum wells for direct laser action in the THz range [5]. Laser action arises from transitions between engineered electronic sub-bands and by 'cascading' a number of such active regions together. THz QCLs have shown remarkable performances over the 1–5 THz range, with demonstration of high peak (> 1 W) and (> 10 s of mW) average powers. These advances have permitted THz QCLs to be made commercially available, with operation recently demonstrated on Peltier coolers. QCLs are particularly interesting for astronomy where their large output powers, tunable emission and compact geometry are particularly advantageous compared to bulky CO_2-pumped gas lasers. Future developments related to QCL based spectroscopy will take advantage of recently demonstrated mode-locked QCLs where ultrafast, coherent and sensitive detection is expected using dual frequency comb spectroscopy.

Figure 1.
(a) Schematic illustration of a THz-TDS system showing the fs laser excitation source, optical delay line, THz source, THz detector and THz coupling optics. (b) Time-domain scans of a THz pulse with and without a sample of Teflon. The sample delays, disperses, and attenuates the pulse. (c) Amplitude spectra of the reference and the sample pulse calculated by Fourier transform.



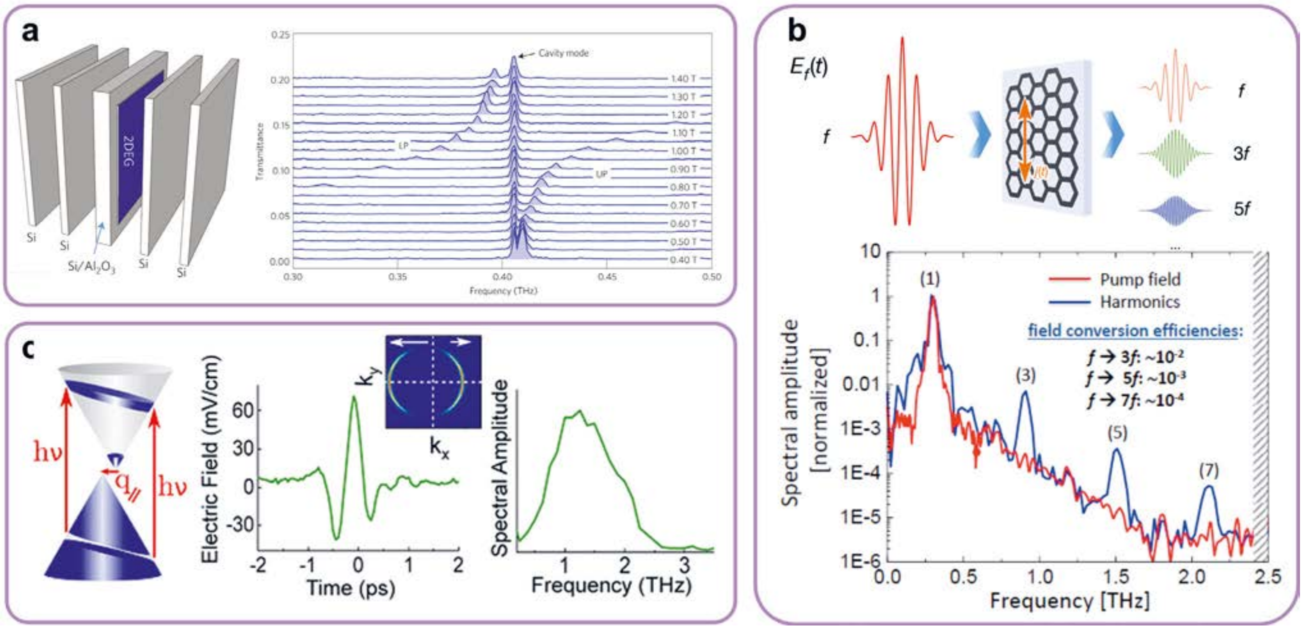


Figure 2. (a) (left) Collective non-perturbative coupling of 2D electrons gas with high-quality-factor THz cavity, from Ref [6]. (b) Extremely efficient THz high-harmonic generation in graphene by hot Dirac fermions, from Ref [7]. (c). Coherent THz emission by dynamical photon drag effect in graphene excited by fs optical pulses, from Ref [8].

The latter has revolutionized metrology in other spectral regions and has begun to be applied to the THz range, going hand-in-hand with recent developments in detector technology, such as THz quantum well infrared photodetectors (QWIPs).

INTERFEROMETRIC SPECTROSCOPY

Alternatively, THz Fourier transform infrared (FTIR) spectroscopy is a well-established method based on a Michelson interferometer providing Fourier transform of the interferogram of broadband incoherent radiation. A typical far-infrared FTIR consists of an incoherent high-pressure mercury arc lamp, a beam splitter, focusing and collimating optical beams, a motorized delay line and a thermal detector. FTIR spectrometers cover a wide frequency range from THz to visible with typically a better signal-to-noise ratio than THz TDS systems above 5 THz. In return, below 3 THz, their signal-to-noise ratio is lower by a few orders of magnitude than typical THz-TDS systems. Standard FTIR systems measure only the intensity of the THz waves and do not capture the phase information. As a result, they have the drawback over THz-TDS and CW THz spectroscopy systems to require ●●●

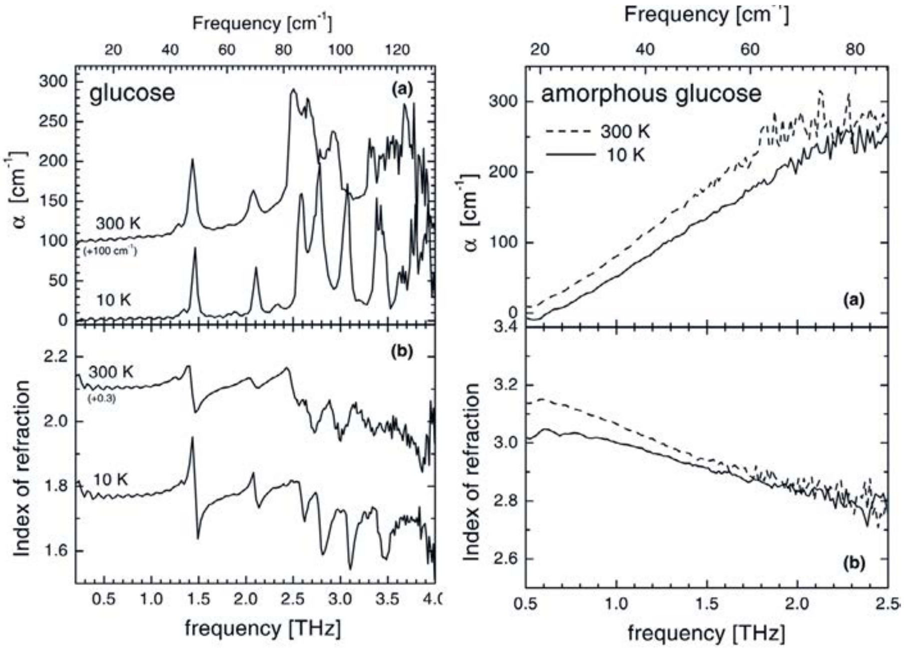


Figure 3.
(a) Absorption coefficient and (b) index of refraction of crystalline α-D-glucose (left panel) and amorphous glucose (right panel), from Ref. [9].

Kramers-Kronig analysis for extracting the complex-valued refractive index of the sample.

FUNDAMENTAL STUDIES

Over the last decade, THz spectroscopy has been investigated to explore fundamental excitations in matter. For instance, in the field of THz quantum optics and THz quantum electrodynamics, researchers have studied strong THz light-matter coupling (Fig. 2a), measured directly the spectral characteristics of vacuum field fluctuations and the squeezed states of the vacuum. Using THz spectroscopy emission schemes, several interesting works have reported ultrafast photoinduced spin currents and spin-to-charge conversion in magnetic metal multilayers as well as transient photon drag effect in graphene (Fig. 2c). Leveraging high power lasers and recent breakthroughs in THz generation, THz experiments with intense THz fields is an emerging area. This offers the possibility to perform time-resolved nonlinear studies and so to probe new fascinating physics in many materials. For example, extremely efficient generation of THz high harmonics has been demonstrated in graphene induced by the collective thermal response of background Dirac electrons to the driving THz fields (Fig. 2b). Further, the nonlinearity of transverse phonon modes has been recently explored providing insight on the interatomic potential of lithium niobate. Nowadays, ultra-broadband THz time domain spectroscopy can extend up to the mid-infrared, enlarging the field of physical phenomena that can be probed, such as the study of electronic correlations in van der Waals heterostructures. Another important recent area involves the THz near-field microscopy where individual nanostructures can be studied despite the extremely long wavelengths of THz photons. These examples illustrate the novel and unique fundamental studies that can be carried out with THz light and that will have an impact on the progress and development of future THz technologies.

APPLICATIONS

THz SPECTROSCOPY OF SOLIDS

The transparency of materials to THz waves depends critically on the polarity of the chemical bonds present in the material. It will also depend on the electrical conductivity of materials. Indeed if mobile electrons are present in the material they will oscillate under THz wave excitation and this will correspond to a loss of energy. Highly conductive metals such as copper do not allow transmission of terahertz waves, but they reflect them and can be used as mirrors. The semiconductors are more or less transparent depending on their doping, THz spectroscopy can therefore be used to probe the doping of semiconductors. Figure 3 shows an example of THz spectroscopy of a very common sugar: glucose. It shows the difference obtained between crystallized glucose and amorphous glucose. The spectrum features peaks only when glucose is crystallized, whilst in the amorphous case only a broad absorption is seen. Contrary to what happens in infrared spectroscopy that is mainly sensitive to localized vibrations between atoms and for which the two spectra would be very similar, THz spectroscopy is sensitive to low frequency vibrations of the whole crystalline structure which in this case is organised by the molecular hydrogen bonds. THz spectroscopy can also be used to identify different isomers, isotopologues or polymorphs of the same molecule and thus has applications in the pharmaceutical industry [10].

THz SPECTROSCOPY OF GAS PHASE

As early as 1955, C. H. Townes, Nobel Prize laureate in physics, stated that the use of rotational spectra of polar molecules, usually measured in the THz domain is an ideal tool for chemical gas phase analysis due to an exceptional degree of resolution (Fig. 4). The Doppler linewidths of pure rotational spectral signatures give rise to very sharp lines yielding the unrivalled degree of selectivity. As a result, many applications such as, breath analysis, environmental surveillance, food spoilage monitoring, or detection •••

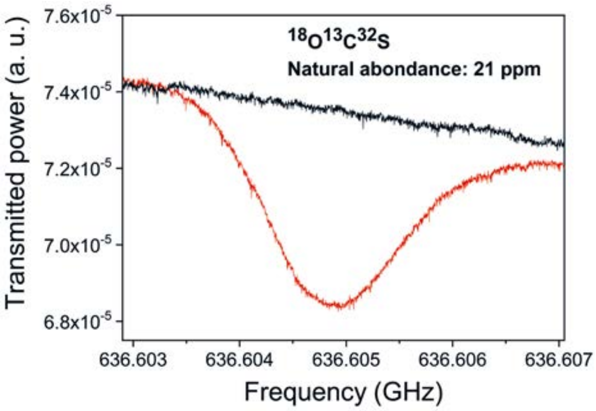


Figure 4. Absorption signature of the transition J = 56 ← 55 of the rare isotopologue $^{18}O\,^{13}C\,^{32}S$ in natural abundance at a pressure around 100 µbar in red (the black line is the base line).

of explosive taggants have been proposed. Another successful application of THz waves is the continual study of the atmosphere (terrestrial, planetary or cometary) and the interstellar medium. THz astronomy is a hot topic for which a huge number of scientific groups over the world are engaged to obtain a large amount of information on "the cold Universe" and especially on organic molecules. Many observatory stations and/or satellite platforms, such as Hershel Space Observatory, Stratospheric Observatory for Infrared Astronomy (SOFIA) and Atacama Large Milli-metre Array (ALMA), are currently operated. All those applications require very sensitive THz gas phase spectrometers to be competitive with classical chemical analysis techniques or to obtain very accurate data for an efficient astronomical observation. Basically, increasing the interaction length between target gases and THz radiation improves the sensitivity and thus significance of all these latter applications. Up to very recently, THz gas-phase spectrometers were based onto single pass cells to reach an interaction length of several meters. Multiple pass cells provide higher sensitivities but are limited by a significant attenuation and generally require large volumes to reach distances typically not exceeding one hundred meters. A superior approach is to adapt the ultrasensitive techniques developed in the infrared domain, such as Cavity-Enhanced Absorption Spectroscopy (CEAS) and Cavity Ring Down Spectroscopy (CRDS) to the THz and submillimetre domain that require a high finesse cavity. This explicit requirement was recently achieved by use of extremely low loss oversized corrugated waveguide along with very high reflectivity Bragg mirrors [1]. Typically, a finesse around 3200, corresponding to a quality factor around 6×10^6, was experimentally demonstrated corresponding to a kilometre equivalent interaction length around 600 GHz, extending greatly the possibility and scope of applications described before and also opening others too.

CONCLUSION

In conclusion, the field of THz spectroscopy is rich and vibrant, with impacts in many areas of science. Thanks to on-going progress on the different THz spectrometers, their performances (such as spatial resolution, spectral range, electric field amplitude and time resolution) are significantly improved, opening exciting perspectives for fundamental research. Besides, THz spectrometers are already adapted for industrial requirements. Indeed, last achievements offer compact, broadband THz spectrometers that are easy-to-use, turnkey and flexible, meeting the needs for integration in industrial environment. As an example, some THz spectrometers are currently implemented in nondestructive testing industry to evaluate the properties of material components (polymers, semiconductor, ceramics and glasses, organic molecules, gas spectroscopy, conductive films, liquid crystals, composites, oil & gas), without causing damage.

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BI-DIMENSIONAL MATERIALS FOR THz FREQUENCY NANODEVICES

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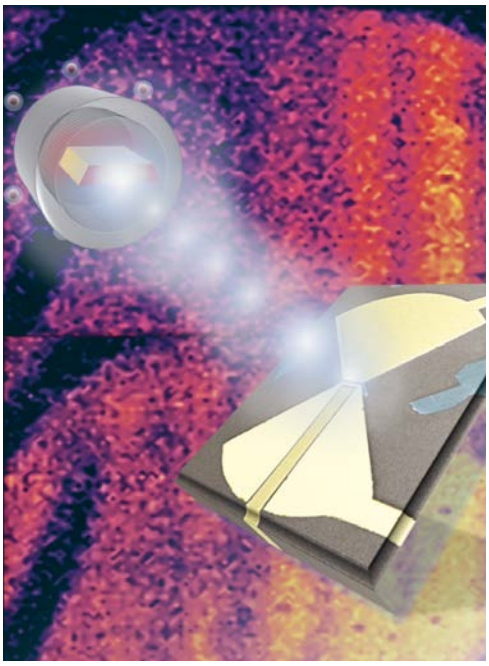

Although artificial semiconductor heterostructures have long been the core material system for the generation, detection and manipulation of carriers, at TeraHertz (THz) frequencies, the discovery of graphene and the related intriguing abilities have triggered an unprecedented interest in inorganic two-dimensional (2D) materials, as black phosphorus and boron nitride, amongst many others. They offer a unique platform for developing efficient devices, without the need of lattice matching, and with a variety of physical properties, that can be engineered from scratch, exploiting the material structures, the layer thickness or their inherent anisotropy.

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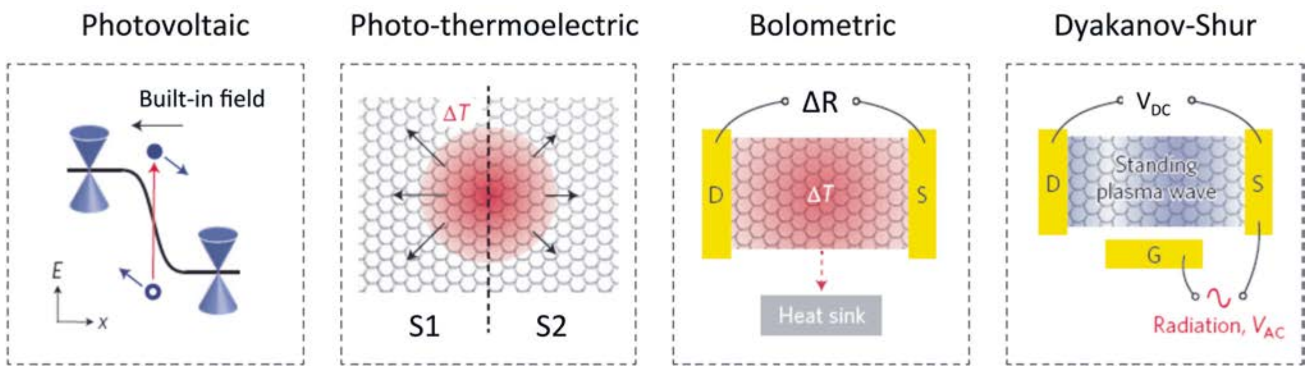
The past decade has witnessed the rise of graphene — a single atomic sheet of graphite — as one of the most studied condensed matter systems. The success of graphene has been followed by a wealth of recent research efforts to study other forms of atomically thin two-dimensional (2D) materials, such as hexagonal boron nitride (hBN) and black phosphorus (BP). This surge of interest in 2D materials is attributed to their exceptional electronic, optical, and magnetic properties and also to their unique amenability to layer-by-layer assembly. That is, multiple different 2D materials can be combined layer by layer into various van der Waals (vdW) heterostructures.

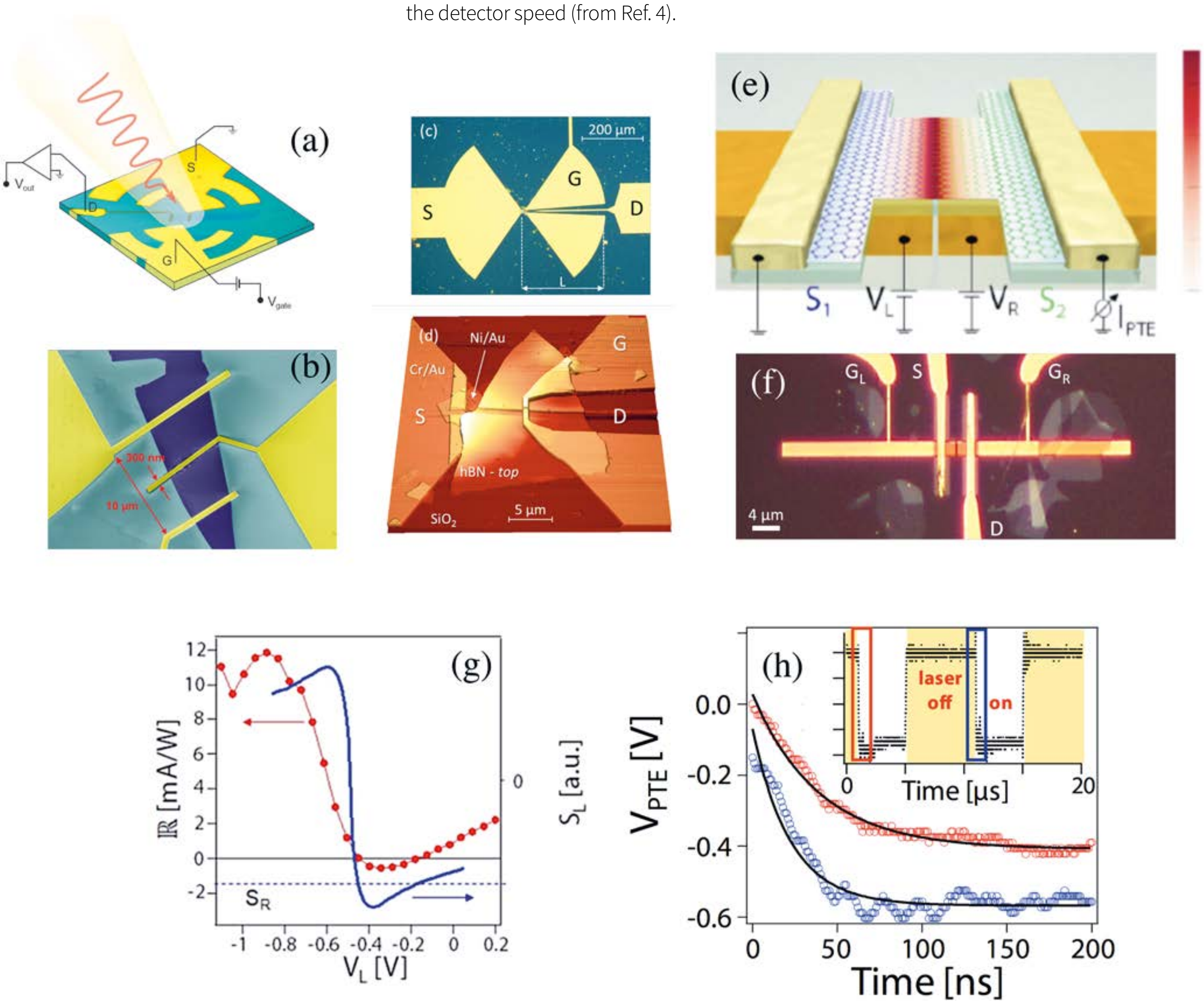
These engineered quantum structures are of both basic and applied interest. They indeed display an extraordinary technological potential for engineering nano-electronic and nano-photonic devices and components; they also provide an intriguing platform for fundamental investigations at the nanoscale, through the exploitation of their confined electronic systems. Intriguingly, the possibility of hybridizing collective electronic motion with light in so-called surface polaritons has also made these materials a versatile platform for extreme light confinement and tailored nanophotonics. Finally, being fully compatible with a wide range of substrates including flexible and transparent ones, if placed on chip with flat integrated optical circuits, they can maximize interaction with light, therefore optimally utilizing their versatile properties for a wealth of applications in transformational optics and high-resolution tomography.

The family of 2D materials is now gaining a renewed interest in more unexplored frequency domains, like the THz) frequency range (0.1-10 THz, 3000–30 μm). ●●●



△ Figure 1.
Schematic representation of the 4 photocurrent generation mechanisms discussed in the main text (from Ref. 1).

▽ Figure 2.
(a) Schematic representation of the graphene FET overdamped plasma wave detector layout with a patterned log-periodic nano-antenna and (b) false-color SEM micrograph of the graphene flake embedded in the FET channel (from Ref. 2). (c) Optical microscopy image of an hBN/BP/hBN FET with a split bow-tie antenna and d) AFM tomographic image of the top-gate field effect transistor (from Ref. 3). (e) Schematic representation (right; not to scale) of the antenna-integrated pn-junction device and (f) related optical microscope image of the fabricated device; (g) Photoresponse as a function of voltages applied to the two antenna branches/gates at 2.52 THz; The blue line represents the calculated Seebeck coefficient; (h) evolution of the thermoelectric voltage as a function of the time from which we extracted the detector speed (from Ref. 4).



Dynamical phenomena (scattering, recombination, and tunneling) in 2D materials indeed typically occur on a time scale of picosecond, *i.e.* at THz frequencies. Graphene and related materials can therefore offer an intriguing perspective for engineering novel THz electronic or photonic devices. Here, I will review some examples of 2D material based THz frequency nano-devices.

A) GRAPHENE AND BLACK-PHOSPHORUS PHOTODETECTORS

Photodetection of light relies on the conversion of photons into a stable electrical signal. In a nanomaterial, and at THz frequencies, such a process can be accomplished by several different physical mechanisms like photo-thermoelectric, photovoltaic, galvanic, bolometric, plasma-wave rectification or can occur through a combination of different effects [1].

In the last few years, 2D materials demonstrated to be an ideal building block for devising THz photo-detectors. As a prototypical example, graphene exhibits ultrafast carrier dynamics, wavelength-independent absorption, tunable optical properties *via* electrostatic doping, and high-mobility, which enables ultrafast conversion of photons or plasmons to electrical currents or voltages. As a major distinctive characteristic, graphene is gapless, allowing charge carrier generation by light absorption over a very wide energy spectrum, while always conducting a significant amount of electricity, meaning that its inherent "leakage" can partially affect the device efficiency.

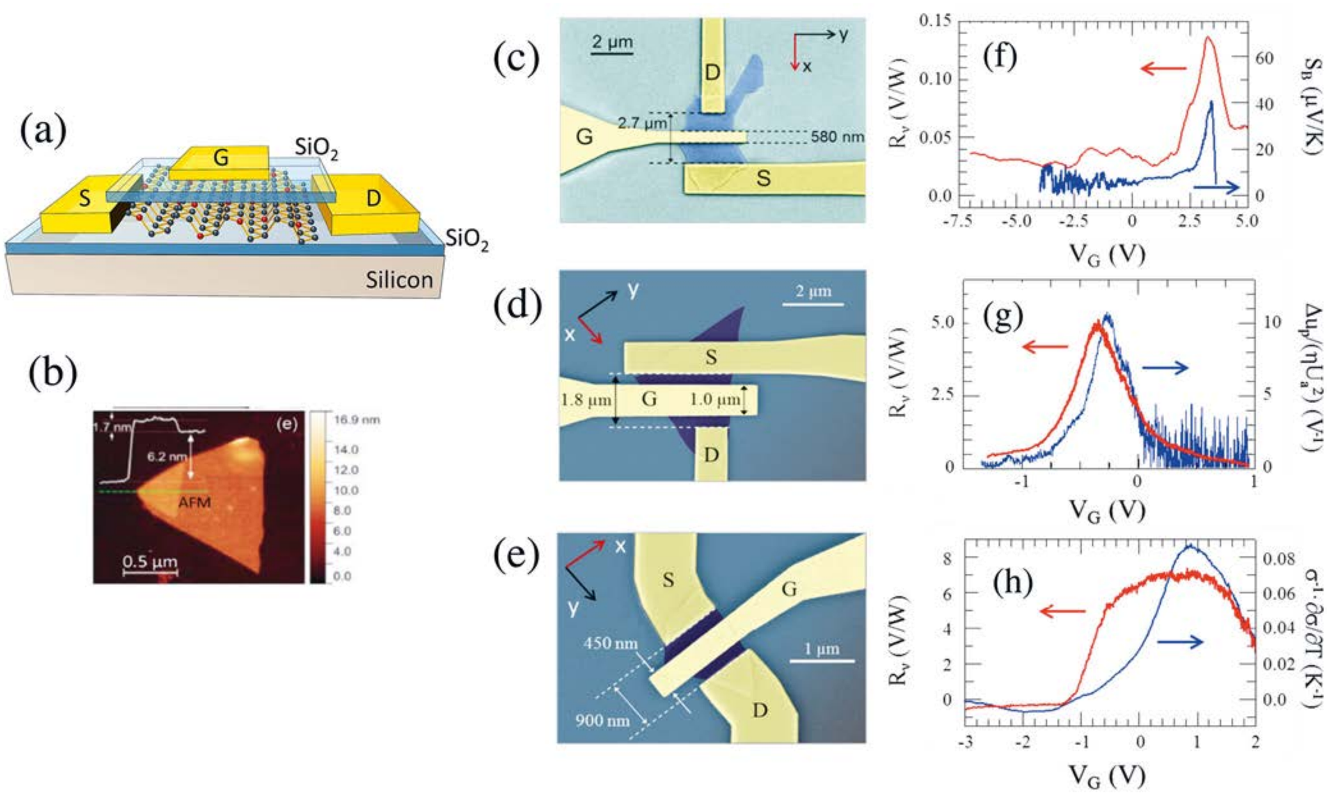
Conversely, BP behaves like a semiconductor, meaning that it only conducts electricity whenever the electrons absorb enough energy through heat, light, and other means. Depending on its specific layer thickness and related specific band structure, and due to its inherently high anisotropy, it can allow engineering the detection dynamics from scratch, allowing highly efficient light detection.

Usually, field effect transistors (FETs) are the most commonly employed architecture for devising THz frequency photodetectors. FETs indeed provide some clear advantages at those frequencies, namely the inherent scalability and the combination of a fast response and high frequency operation (up to 22 THz), very differently from Schottky diodes, whose performances are strongly affected by parasitic capacitances and usually show a dramatic cutoff above 1 THz.

The rich physics involved in 2D materials can be exploited in a FET to engineer the detection dynamics from scratch, playing with the geometrical symmetry. A bolometer can be engineered by exploiting the variation of the channel conductance induced by the homogeneous heating of the channel, either by applying a source-to-drain bias, or, by symmetrically feeding the THz radiation *via* an on-chip integrated symmetric resonant antenna. Conversely, photo-thermoelectric and plasma-wave rectification both require a certain degree of asymmetry in the detector structure. In the first case, this is achieved by inducing a temperature gradient along the FET channel, for example by creating a pn-junction along the FET channel; in the second case, plasma-waves can be rectified inside the transistor when the THz field is coupled asymmetrically, for example between source and gate electrodes.

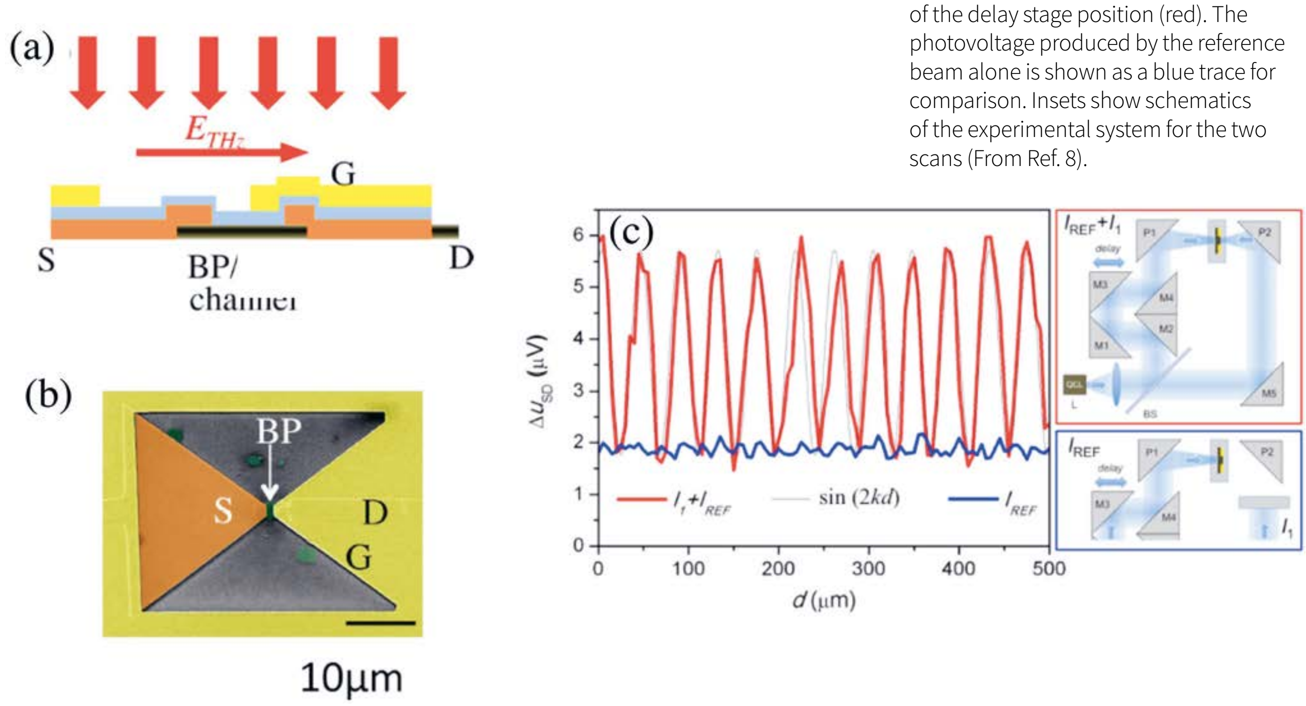
Following the first demonstrations of THz graphene photodetectors operating in the overdamped plasma waves resistive self-mixing regime [2], several architectures have been proposed and implemented [1], including graphene bolometers, ballistic rectifiers [3], and fast photo-thermoelectric sensors, involving a combination of high-mobility hBN-encapsulated graphene and small-area graphene pn-junctions [4].

State of the art performances include room-temperature (RT) operation over the 1.8–4 THz range ●●●



△ **Figure 3.** (a) Schematic representation of the black phosphorus FET detector; (b) AFM image of the intra-channel thin flake of BP (From Ref. 5) (c-e) False-color SEM micrographs of a set of BP FETs with the BP flake oriented along the armchair direction (c), the direction at 45° in between (d), or along the zig-zag direction (e); (f) gate voltage dependence of the responsivity (left vertical axis) of the thermoelectric detector of panel (c) and gate voltage dependence of the extrapolated Seeback coefficient (right vertical axis) (From Ref. 6); (g) gate voltage dependence of the responsivity (left vertical axis) of the over-damped plasma wave detector of panel (d) and gate voltage dependence of the predicted theoretical photovoltage (right vertical axis) (From Ref. 6); (f) gate voltage dependence of the responsivity (left vertical axis) of the bolometer of panel (e) and gate voltage dependence of the extrapolated bolometric coefficient (right vertical axis) (From Ref. 6).

▽ **Figure 4.** THz near-field probe with an embedded nano-detector. (a) Electric field E (red arrow) of the THz wave induces oscillating field between the source (S) and gate (G) electrodes (From Ref. 8). (b) Scanning electron microscopy (SEM) image of a near-field probe with a 20 µm aperture and an embedded thin (14 µm) flake of black phosphorus (BP) (From Ref. 8). (c) Coherent detection using a near-field probe with an embedded NW detector; photovoltage plot as a function of the delay stage position (red). The photovoltage produced by the reference beam alone is shown as a blue trace for comparison. Insets show schematics of the experimental system for the two scans (From Ref. 8).



Dynamical phenomena (scattering, recombination, and tunneling) in 2D materials indeed typically occur on a time scale of picosecond, *i.e.* at THz frequencies.

with NEPs = 80 pW/Hz$^{1/2}$, a dynamic range extending over four decades [4] and 890 ps response time, significantly above any other RT receiver commercially available and demonstrated so far.

As an alternative option, thin flakes of exfoliated BP can be employed in an antenna-coupled THz nanodetector to selectively activate a specific detection process [2,5,6]. The inherent electrical and thermal in-plane anisotropy of BP can be indeed exploited to selectively control the detection dynamics in the BP channel, with state-of-the-art performances. RT operation with ~ 20000 signal-to-noise ratio [2], NEPs ≤10^{-9} W/Hz$^{1/2}$), responsivities > 10 V/W [6], and response times of a few µs [7].

B) NEAR FIELD OPTICAL PROBES

Near-field imaging with sub-10-nm resolution is usually achieved by scattering near field optical spectroscopy (*s-SNOM*), exploiting an atomic force microscope (AFM) tip which converts the incident light into strongly concentrated fields at the tip apex (nanofocus) to locally excite molecular vibrations, plasmons or phonons in the sample. The spatial resolution is thus determined by the tip apex size, but limited by the weak scattering efficiency of the tip.

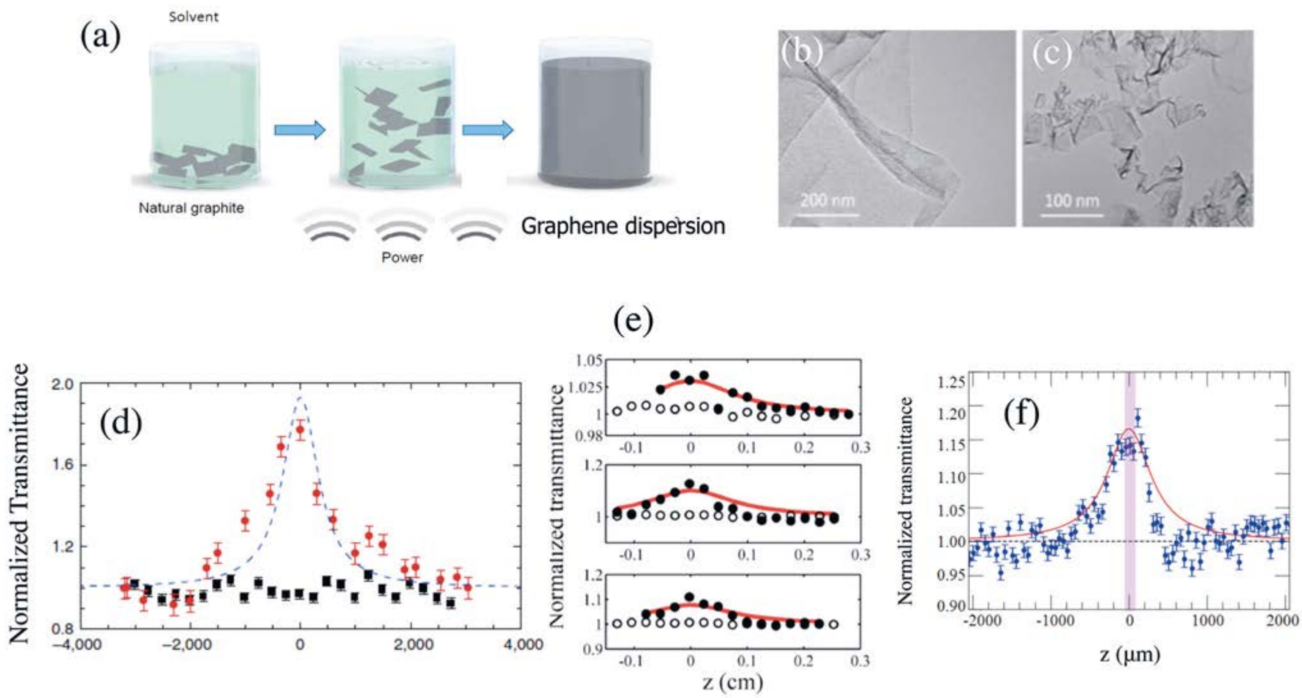
In the THz range, the scattering efficiency of AFM tips is prohibitively low, demanding the use of powerful gas lasers combined with cooled bolometers, or THz time-domain spectroscopy (THz-TDS) systems, which can detect very weak scattered fields, but with limited spectral resolution and slow image acquisition.

At the other end of the spectrum of length scales targeted by THz microscopy, are applications requiring mapping THz absorption properties and THz field distributions in large area samples. The s-SNOM approach is not appropriate for these applications, due to AFM instabilities arising during scans of rough or soft surfaces at the scan-speeds required for large-area imaging. As such, THz microscopy approaches that can address these applications are based on near-field probes with integrated sub-wavelength size THz detectors (a-SNOM). In this latter case, the resolution is limited by the strong reduction of light transmission (*T*) through an aperture (dimension a), according to the Bethe and Bouwkamp law, that follow the power law: $T{\sim}a^6$. Usually, although the field conveyed at the aperture includes both the transmitted and the reflected beam components, only transmitted signals are collected, meaning that the evanescent fields remain practically undetected.

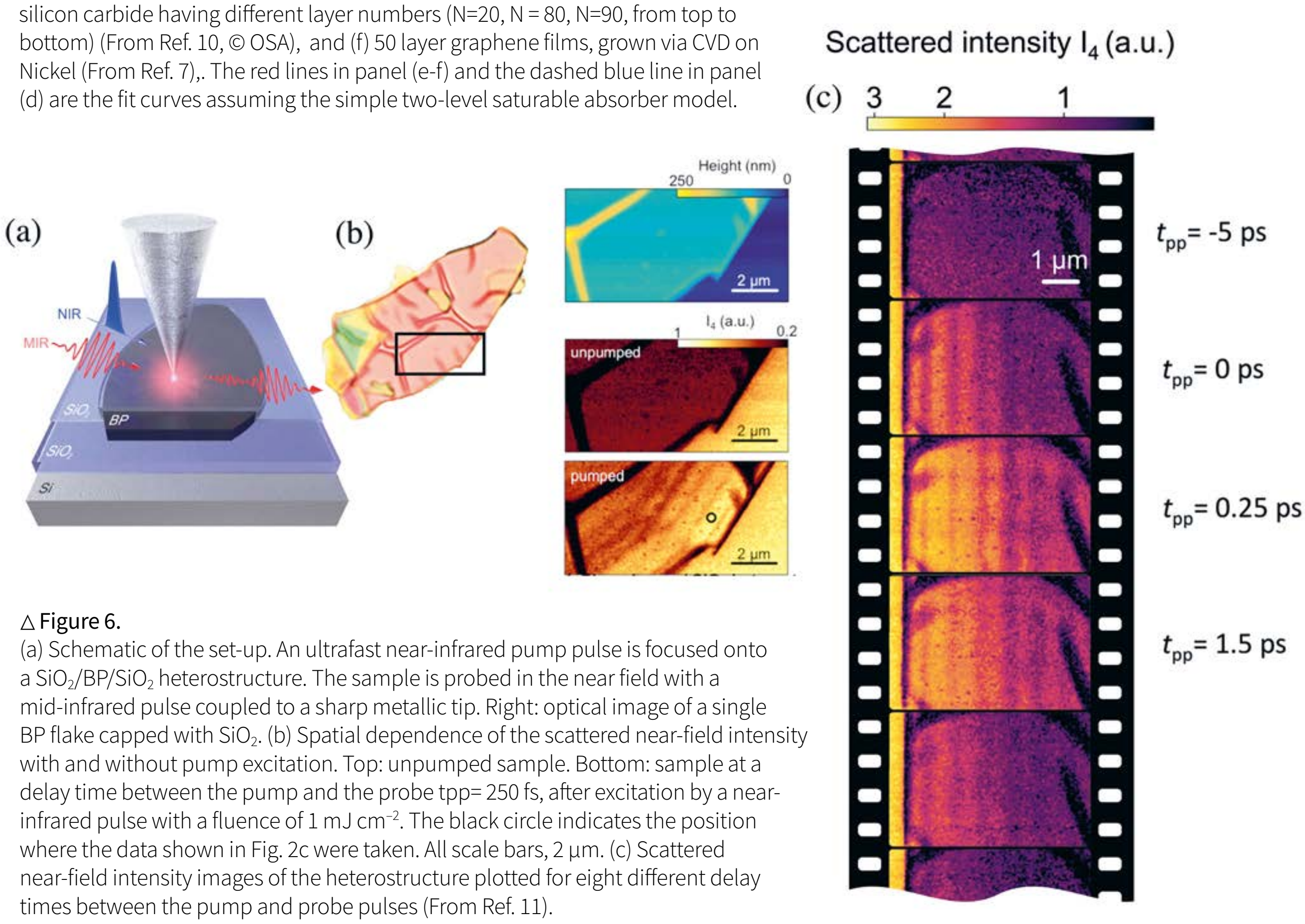
Recently, a novel near-field THz probe concept, in which the evanescent THz field is converted into a detectable electrical signal at the nanoscale has been proposed [8]. To do that, thin crystalline flakes of BP have been integrated into the evanescent field region of a trapezoidal shaped sub-wavelength aperture, simultaneously acting as a probe and as an evanescent field -sensitive photodetector [8]. This allowed realizing, for the first time, coherent THz detection (amplitude and phase) within the a-SNOM probe [8], eliminating the need for a THz TDS system or an external FTIR spectrometer.

C) SATURABLE ABSORBERS

Semiconductor saturable-absorbers are poorly suitable for applications at THz frequencies since the photon energy is smaller than the •••



△ Figure 5.
(a) Schematics of liquid phase graphene exfoliation; (b-c) Transmission electron microscopy images of (b) single-layer graphene flakes from ethanol based and (c) few-layer graphene flakes from water based inks (From Ref. 9). (d-f) z-scan normalized transmittance traces of (d) the water-based graphene saturable absorber (From Ref. 9), of (e) multi-layer graphene grown on the carbon-face of silicon carbide having different layer numbers (N=20, N = 80, N=90, from top to bottom) (From Ref. 10, © OSA), and (f) 50 layer graphene films, grown via CVD on Nickel (From Ref. 7),. The red lines in panel (e-f) and the dashed blue line in panel (d) are the fit curves assuming the simple two-level saturable absorber model.



△ Figure 6.
(a) Schematic of the set-up. An ultrafast near-infrared pump pulse is focused onto a SiO_2/BP/SiO_2 heterostructure. The sample is probed in the near field with a mid-infrared pulse coupled to a sharp metallic tip. Right: optical image of a single BP flake capped with SiO_2. (b) Spatial dependence of the scattered near-field intensity with and without pump excitation. Top: unpumped sample. Bottom: sample at a delay time between the pump and the probe tpp= 250 fs, after excitation by a near-infrared pulse with a fluence of 1 mJ cm^{-2}. The black circle indicates the position where the data shown in Fig. 2c were taken. All scale bars, 2 µm. (c) Scattered near-field intensity images of the heterostructure plotted for eight different delay times between the pump and probe pulses (From Ref. 11).

ADVERTORIAL

GLOPHOTONICS

PIONEERING INDUSTRIAL HOLLOW-CORE PHOTONIC CRYSTAL FIBERS

GLOphotonics (or GLO for short) is a French start-up based in Limoges. It was founded by Fetah Benabid in Bath, UK, in 2008, then transferred to, and re-incubated in Limoges, France, in 2011. GLO is a pioneering market-player in the fabrication and commercialisation of its proprietary hollow-core photonic-crystal-fiber (HCPCF) and photonic microcell™ (PMC).

HCPCF is an optical fiber that stands out from conventional optical fibers by its light guidance, which allows guiding light in a hollow channel. We distinguish two types of guidance mechanisms in HCPCF. The first is called "Photonic Band Gap" and the second is called "Inhibited Coupling". A PMC is a photonic device, which consists of a length of HCPCF filled with a given gas and sealed in a hermetic and controllable fashion. HCPCF and PMC have outstanding key enabling features for a large number of applications, such as optical frequency conversion, ultra-high power pulsed laser beam delivery, laser pulse compression, sensing and precision-timing.

Based on HCPCF and PMC technology, GLO provides the market with a diverse portfolio of components, sub-systems, and technology solutions. In laser beam delivery, GLO offers a large range of products spanning from a tailored HCPCF to highly sophisticated ultra-short laser beam delivery products that include gas handling, thermal management, laser beam pointing stabilization and integration into systems.

FastLas is a unique product family to compress sub-picosecond laser pulses by a factor as high as 30, and achieves pulses as short as ~10 fs. Fastlas technology stands out with its large dynamic in laser pulse energy and wavelength.

Comblas is a light source product family that comprises sources emitting broadband combs spanning from UV (240 nm) to IR. Comblas is an ideal alternative to supercontinuum sources when high spectral power density is required, or to develop light source at exotic wavelength ranges.

In sensing and precision-timing, GLO develops specific PMC as highly efficient and compact spectroscopy cells.

GLO takes pride in counting a large and diverse customers base, from individual scientists to tier 1 industrial companies, and in addressing their requirements with the same level of commitment, and in providing them with unique and high added-value solutions.

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semiconductor band gap and the free carrier absorption losses very high.

Graphene is a potential candidate for crafting saturable absorbers at THz frequencies, thanks to its fast carrier dynamics (< 100 fs), large absorption of incident light (2.3% per layer), the possibility to saturate this absorption in a broad spectral range with relatively low incident power, and its tunable modulation depth. Its optical conductivity being mainly determined by intraband transitions (with a further interband relaxation dynamic, due to hot phonons cooling), graphene optical absorption can be easily modulated by electrical/optical control of its Fermi level. Furthermore, large-area, low-cost, single or multi-layer graphene can be easily grown and integrated in THz laser systems.

THz saturable absorption has been recently demonstrated in graphene [9,7]. By transfer coating and ink-jet printing 50 layers (randomly distributed) of graphene films prepared by liquid phase exfoliation of graphite and through a combination of open-aperture z-scan experiments and Fourier transform infrared (FTIR) spectroscopy, 80% transparency modulation at 3.4 THz has been reported [9]. Despite this technology is very appealing for intracavity embedding, since the graphene is printable and flexible, the thickness uniformity along a large surface is usually poor, meaning that achieving large transparency modulation over large areas (> 0.5 cm) could be demanding.

Alternative reports on THz graphene saturable absorbers include multi-layer graphene grown on the carbon-face of silicon carbide, allowing a maximum absorption modulation of ~10%, inherently limited by disorder [10], or multilayer graphene films, grown *via* CVD on Nickel, in which a 10% transparency modulation, dominated by intraband phenomena has been shown [7].

D) SWITCHES FOR ELECTRONIC WAVES

When light is focused onto a nanometer-sharp metallic tip, miniature waves propagate on the surface of the underneath material in a circular fashion, starting from the tip apex. Such miniature waves can have the potential to be used in future compact electronic devices for lightning-fast information transport. However, to do that, these waves have to be ideally switched on and off at ultrafast timescales.

Recently, SiO_2/black phosphorus/SiO_2 heterostructures have been innovatively employed to this purpose [11]. Upon irradiation of a sequence of thin flakes of SiO_2/black phosphorus/SiO_2 by intense light pulses, freely moving electrons are generated inside the material. Without these electrons, no surface waves are present and the structure is switched "off". However, as soon as the first laser pulse generates the free electrons, a subsequent pulse can start the propagation of surface plasmons from the tip. The expansion of the plasmon waves can be traced in slow motion snapshots, unveiling *fs* switching times [11].

CONCLUSIONS

In conclusion, the superior mechanical pliability and the exceptional optical and transport properties of 2D materials and vdW heterostructures enclose an enormous potential for developing a novel generation of devices, optical components and systems in the THz frequency range (1–10 THz). Exceptional implications can be envisaged in frontier research fields as signal processing and computer technologies, ultrafast optics, plasmonics, and quantum metrology. Large area material production combined with large mobility, are the critical ingredients for a stable and reproducible production of the above technologies, needed for a progressively broader impact on market and research.

ACKNOWLEDGEMENTS

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ALL-DIELECTRIC PHOTOCONDUCTIVE METASURFACES FOR TERAHERTZ APPLICATIONS

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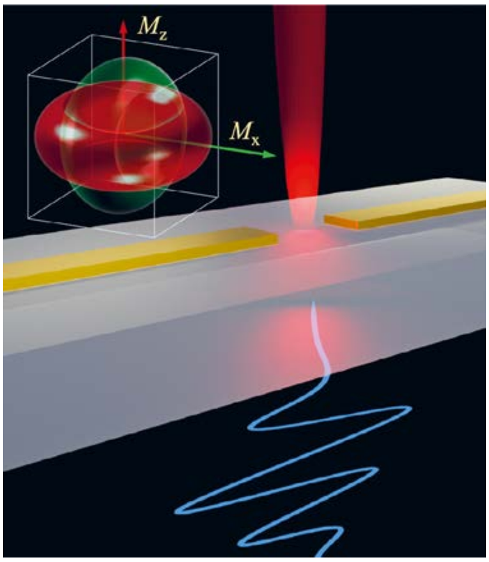

We review applications of all-dielectric metasurfaces for one of the cornerstone technologies in THz research – ultrafast photoconductive (PC) switches – which are widely used as sources and detectors of broadband THz pulses. Nanostructuring the PC switch channel as a perfectly-absorbing and optically thin PC metasurface allows us to engineer the optical as well as the electronic properties of the channel and improve the efficiency of THz detectors. This approach also opens new routes for employing novel PC materials and enabling new device architectures including THz detector arrays.

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Collections of dielectric subwavelength-size particles can lead to new macroscopic electromagnetic behaviour. Although this fact has been known for many decades, only recently two-dimensional arrays of such objects (*all-dielectric metasurfaces*) have started to emerge as a new paradigm for flat optical components, sensors, modulators and switches [1,2]. The incredible potential of metasurfaces comes from the ability to control amplitude, phase and vector orientation of the electromagnetic field through the size, shape and density of the comprising particles [2]. Here, we review recent developments of all-dielectric metasurfaces for terahertz sources and detectors. Integration of such metasurfaces into the active area of ultrafast photoconductive (PC) switches can lead to over an order of magnitude improvement in the performance of THz photodetectors, and may enable the use of new PC materials and development of detector arrays.

During the early days of THz research, ultrafast PC switches, also known as Auston switches [3], dramatically accelerated the development of the field. With the help of ultrafast lasers, the PC switch enabled electrical conductivity switching on a sub-picosecond time scale. Since then, the Auston switch has been serving as an essential technology for THz applications, enabling generation and detection of THz pulses, and THz spectroscopy and imaging. Despite this critical role, the ultrafast PC switch remains highly inefficient, and only a handful of PC materials have been found suitable for the switch due to a demanding combination of required material properties [4].

Several studies recently showed that the switch efficiency can be improved by using plasmonic structures [5-11] and, more recently, all-dielectric metasurfaces [12,13]. By employing the effects of enhanced light absorption and light concentration, it has become possible to achieve better ● ● ●

performance and enable new device architectures. The PC metasurfaces can revolutionize the PC switch technology and lead to more efficient THz radiation detectors and sources.

ULTRAFAST PHOTOCONDUCTIVE SWITCH

We start with the operation principle of the PC switch for detection of THz pulses [3,4]. In the original design (Fig. 1), the PC switch contains a bulk PC region, which can be turned ON optically, and two electrodes, which collect the induced photocurrent. The electrodes also function as an antenna for capturing or emitting THz waves. In the OFF state, the resistance of the PC region is very high and no current flows through the channel; when the switch is illuminated with a near-infrared (NIR) pulse from an ultrafast laser the resistance drops by several orders of magnitude initiating charge transport in the channel. In the presence of a THz wave, the antenna picks up its electric field and induces a voltage bias across the channel. A photocurrent flows in the direction of the THz field until the optical excitation stops. The switch operates as a gated detector of the THz electric field, with NIR light acting as the gate. It allows sampling the electric field of the THz pulse in the time domain, like an ultrafast sampling oscilloscope.

Although the operation principle is simple, it can be implemented only with PC materials, which enable three key physical processes: conversion of a short burst of incident photons into mobile charge carriers; conduction of the photocarriers in response to an external THz field, and fast elimination of the carriers from the channel after the optical excitation ends. These processes dictate three essential requirements for the switch: efficient photo generation of charge carriers, high contrast between the ON and OFF states, and extremely short (sub-picosecond) carrier lifetime.

Fulfilling all three requirements is a challenge. Due to the limited drift velocity in the PC materials, the photoexcited carriers are able to travel only a short distance (<100 nm) before they must recombine and switch the channel OFF. As a result, only photocarriers generated within a distance of 50–100 nm from the electrodes contribute to the photocurrent. However, the probability for an incident photon to be absorbed within that distance is very small (*e.g.* the top 100 nm thick layer of GaAs absorbs about 7% of incident photons at 800 nm). The sub-picosecond carrier lifetime therefore inherently limits the conversion efficiency.

Enhancing optical absorption while reducing the size of the PC channel therefore is one of the main strategies. One solution that has been explored extensively so far has been to concentrate the optical fields near the electrodes using metallic structures supporting plasmonic resonances, *e.g.* electrodes with nanoscale interdigitated fingers [5,6] and field concentrating elements [7,8]. Several examples are illustrated in Figure 2. Excitation of plasmonic resonances leads to generation of the photocarriers mainly •••

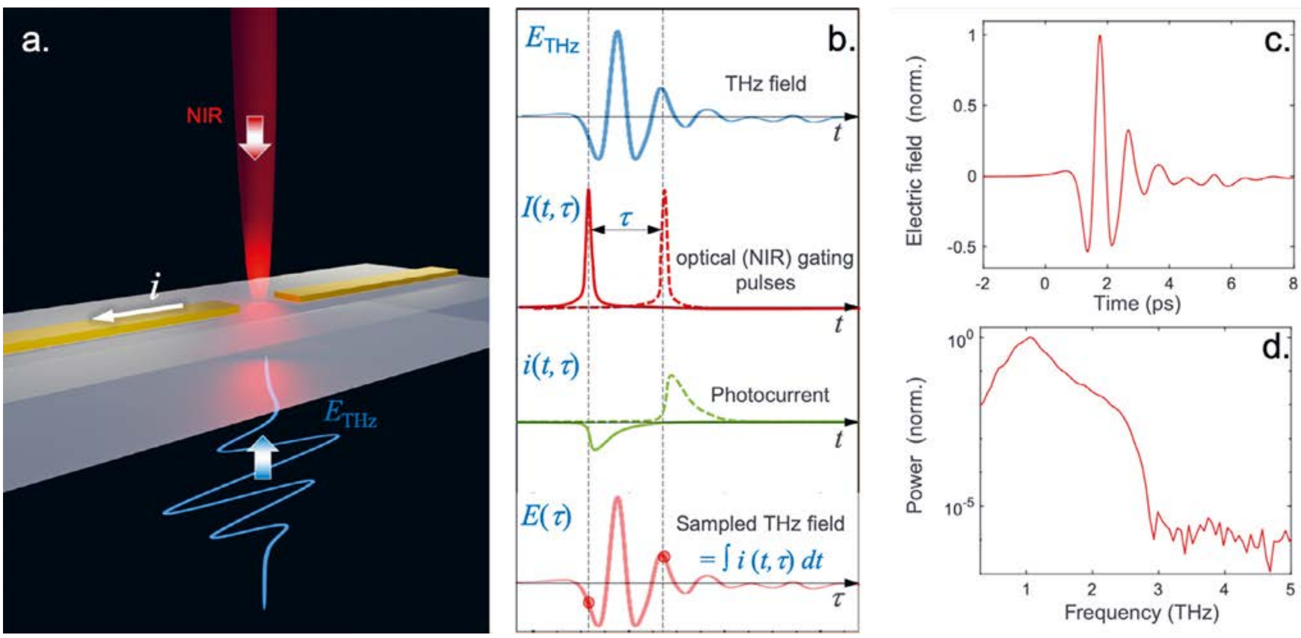


Figure 1.
Operation principle of the photoconductive (PC) switch for THz detection. a. PC switch illustration. b. Process of PC sampling: the switch is illuminated by a THz pulse (top) and a NIR gating pulse (upper middle) with a variable delay between the two pulses. The NIR pulse generates charge carriers and the THz field drives them toward the electrodes. A THz pulse waveform is reconstructed in the time domain using the time-averaged photocurrent $i(t,\tau)$ recorded for different time delays τ (bottom). c. Electric field waveform and d. the Fourier power spectrum of a THz pulse detected using a switch with a PC metasurface channel *(from Ref. 13)*.

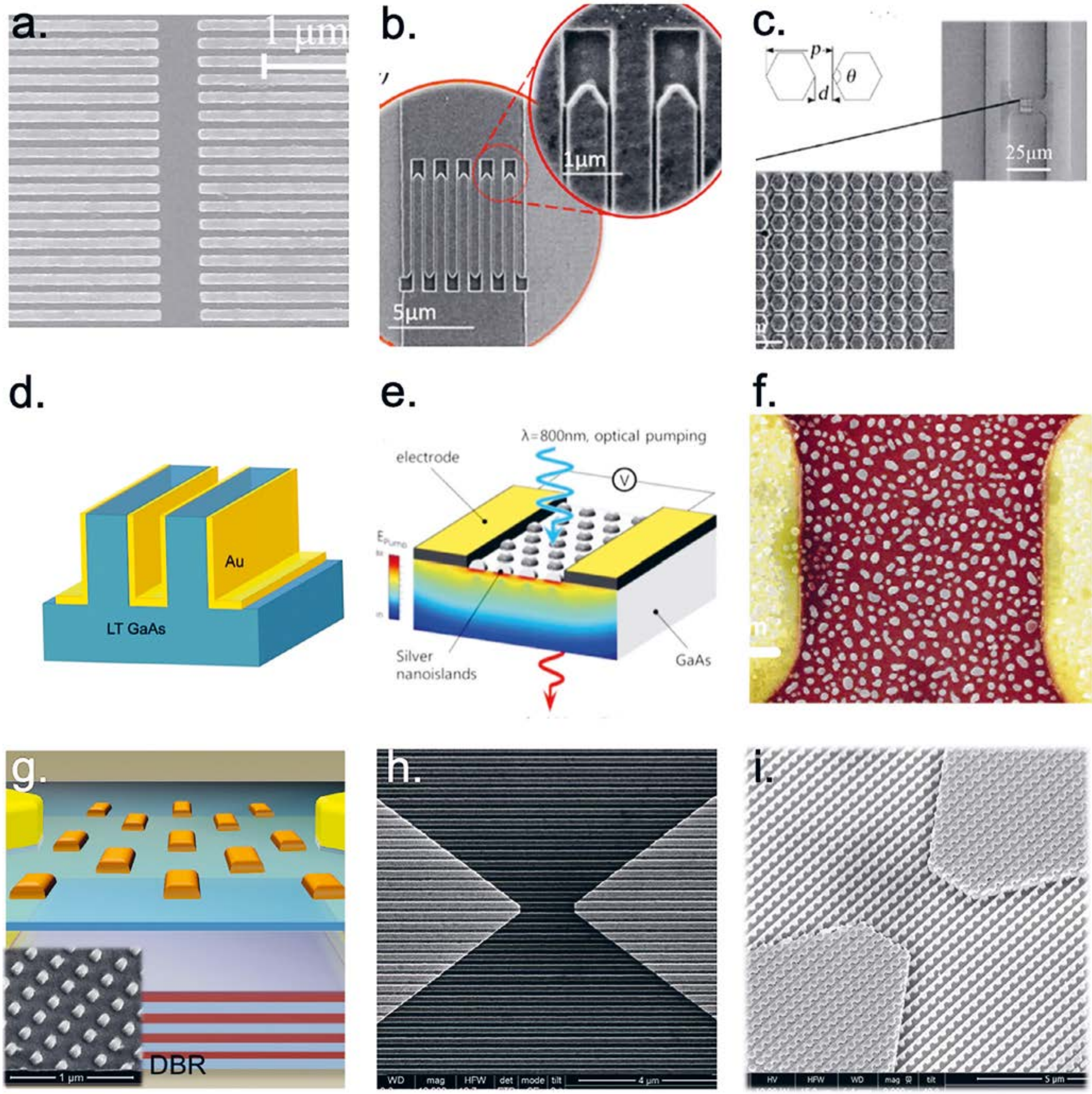


Figure 2.
Examples of nanostructured PC regions in THz switches.
a. Plasmonic nanoantenna array (*reprinted with permission from [5], licensed under CC BY 4.0*); b. Interdigitated electrodes with nanoscale gaps (*reprinted with permission from [6], Copyright 2012 American Chemical Society (ACS)*); c. Plasmonic field concentrators (*reprinted with permission from [7], Copyright 2014 The Optical Society*); d. Three-dimensional plasmonic electrodes [8]; e. Periodic arrays (*reprinted with permission from [9], Copyright 2012 The Optical Society*) and f. Random distribution of plasmonic nanoparticles (*reprinted with permission from [10], licensed under CC BY 4.0*); and g. Hybrid PC optical cavity (*reprinted with permission from [11], Copyright 2015 ACS*). All-dielectric PC metasurfaces: h. Nanobeams with a DBR underneath (*reprinted with permission from [12], licensed under CC BY 4.0*) and i. Perfectly-absorbing network of cubic resonators (*reprinted with permission from [13], Copyright 2019 ACS*).

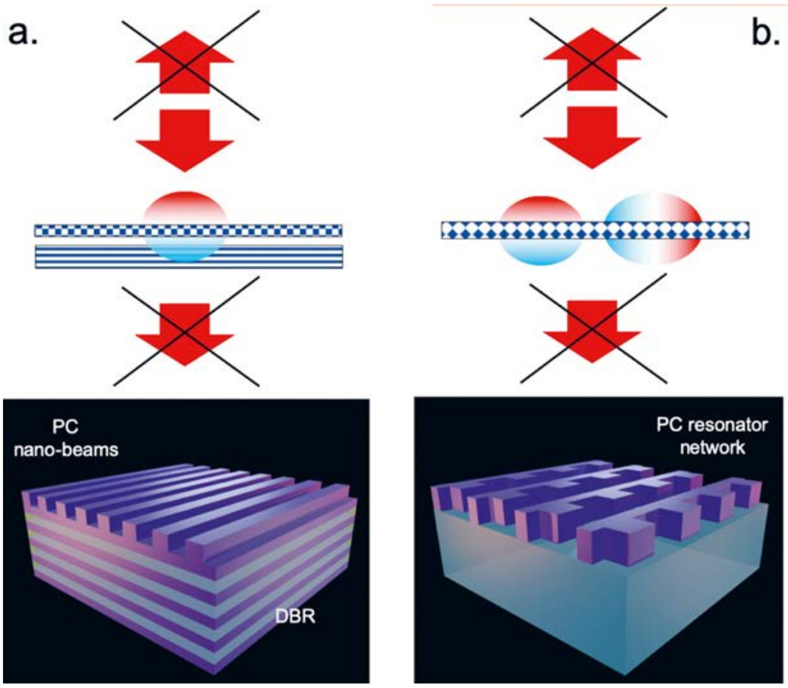


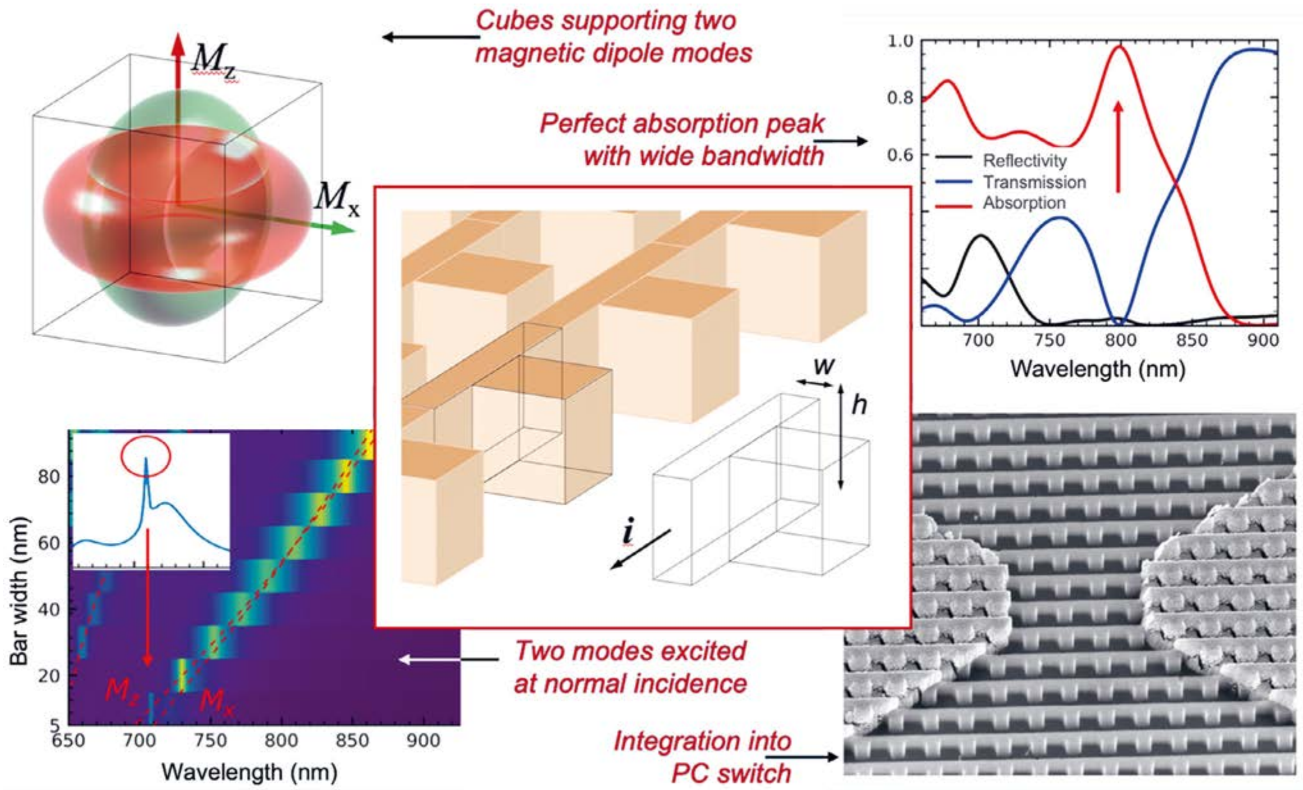
Figure 3.
Perfect absorption schemes in all-dielectric PC metasurfaces. a. Resonant nanobeams with a distributed reflector; and b. Network of cubic resonators with broken symmetry.

within a short distance from the electrodes (~50 nm). Unfortunately, these types of electrodes tend to reduce the OFF-state resistance.

Another plasmonic strategy is to engineer the channel as an optically thin metasurface where the majority of incident photons are absorbed [9-10]. We developed such a metasurface earlier using periodic arrays of nanoantennae over the channel with a distributed Bragg reflector (DBR) below it [11]. The antennae and the DBR form an optical cavity with an ultrathin PC channel, which can be as thin as 50 nm. The antennae are electrically isolated, and the channel OFF-state resistance remains high.

Despite enhancing the overall absorption in the channel, plasmonic elements have another major limitation: they tend to introduce ohmic losses which limit the efficiency and make

Figure 4.
Perfectly-absorbing network of PC resonators. The metasurface consists of an array of cubes connected by side bars into a network (center). Each cube supports magnetic dipole modes (top left) and the bar allows excitation of the dark mode M_z. Perfect absorption occurs if the modes are degenerate (top right); the modes are tuned by adjusting the cube or the bar geometry (bottom left, from Ref. 13). The metasurface serves as the PC channel (bottom right).



> The combination of a higher photocurrent and a higher dark resistance is ideal for a THz detector, as it leads to the highest signal to noise ratio (SNR) at a relatively small level of required incident gating power.

devices more susceptible to thermal damage. All-dielectric metasurfaces provide an alternative route to enhanced photon absorption. In the next section we present two schemes, where the PC channel is structured as a *perfectly absorbing all-dielectric metasurface*.

PERFECT ABSORPTION IN ALL-DIELECTRIC PHOTOCONDUCTIVE METASURFACES

A. NANOSTRUCTURE SUPPORTING AN OPTICAL RESONANCE WITH A REFLECTOR UNDERNEATH THE SURFACE

Enhanced absorption in the first approach is achieved through manipulation of the amplitude and phase of reflected waves for the nanostructured top surface and the distributed Bragg reflector (DBR) below it. For the top-surface structure, we designed the PC channel as an array of resonant nanoscale beams (*nanobeams*), similar to a high-contrast grating. For the DBR, we introduced a standard quarter-wave stack of dielectric layers [Fig. 3(a)]. This structure supports a resonance with spatial field distribution similar to a magnetic dipole mode [12].

An intuitive understanding of this scheme can be gained by considering reflection from the nanostructured surface and the DBR. The nanobeams provide a narrow-band reflection peak corresponding to the resonance, whereas the DBR provides uniform reflectivity within a wider stopband. By controlling the size of the nanobeams, their density and position with respect to the reflector, we minimize reflection through destructive interference of the wave reflected by the DBR and by the nanobeams. This condition leads also to a rise in absorption [12].

B. NANOSTRUCTURE SUPPORTING TWO DEGENERATE AND CRITICALLY COUPLED MIE RESONANCES OF ODD AND EVEN SYMMETRY

In the second approach we employed the perfect absorption scheme that relies on excitation of two degenerate Mie modes of opposite symmetry - odd and even - with respect to the metasurface plane [Fig. 3(b), 13]. Such a structure exhibits perfect absorption at the Mie resonance wavelength if both modes are critically coupled [14-15]. To realize this concept, we designed a cubic resonator supporting magnetic dipole (MD) modes. We chose the MD modes due to the strongest confinement of the field in the dielectric. The cubic symmetry supports three degenerate MD modes: two of the modes have their dipole moments, M_x and M_y, in the *xy*-plane; the corresponding in-plane electric field distributions are odd with respect to the metasurface plane. The dipole moment of the third mode M_z is orthogonal to the plane, and the corresponding in-plane electric field distribution is even with respect to the plane. Perfect absorption can occur when two mode pairs, M_x with M_z, or M_y with M_z, are excited simultaneously. M_z is required in both cases, however it possesses rotational symmetry in the surface plane and therefore cannot be excited by a linearly polarized plane wave at normal incidence. To enable excitation of this dark mode we break the cubic symmetry of the resonators by introducing a bar aligned along one side of the cubes (Fig. 4). With direct excitation of M_z under normal incidence, the condition of perfect absorption is reached by adjusting the size of the bar and the array periodicity [13].

PERFORMANCE OF ALL-DIELECTRIC PHOTOCONDUCTIVE METASURFACES

Structuring the PC region as a perfectly-absorbing metasurface enables efficient photoexcitation of the channel. Our experimental studies of both designs implemented in low temperature (LT) grown GaAs showed strong absorption enhancement at 800 nm. Furthermore, the wavelength range where the absorption is enhanced is sufficiently wide for short pulse excitation (Fig. 4). For both designs, we observed that the photocurrent response increased by an order of magnitude when compared with unstructured PC channels of similar dimensions [12,13].

The switching contrast also increased due to the small physical cross-section of the channels. In the resonator network case, the cross-section of each side bar was only 0.01 µm^2 (Fig. 4). As a result, the dark resistance of the resonator network was as high as 50 GΩ, about 1-2 orders of magnitude higher in comparison to detectors based on unstructured LT GaAs layers [13]. The higher resistance leads to a higher ON/OFF switching contrast and better performance of THz detectors.

The combination of a higher photocurrent and a higher dark resistance is ideal for a THz detector, as it leads to the highest signal to noise ratio (SNR) at a relatively small level of required incident gating power. For the PC metasurface designed as the resonator network, we observed the best SNR for a gating power of only 100 µW [13], which is more than one order of magnitude lower than the optimal operation power required for conventional THz detectors.

CONCLUSIONS

Photoconductive all-dielectric metasurfaces provide a promising new approach for developing efficient THz radiation detectors and THz radiation sources. They can enable close to perfect optical absorption of photons in the photoconductive channel and higher ON/OFF switching contrast, and thus lead to operation at significantly lower switching power levels with excellent noise performance. This approach can revolutionize the photoconductive switch technology by opening doors to new photoconductive materials and routes to novel applications which were deemed impractical previously, such as THz detector arrays, whereas the new architecture of the channel opens exciting opportunities for research on photoexcited carrier dynamics and for innovations in metasurface engineering.

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TERAHERTZ SENSING IN BIOLOGY AND MEDICINE

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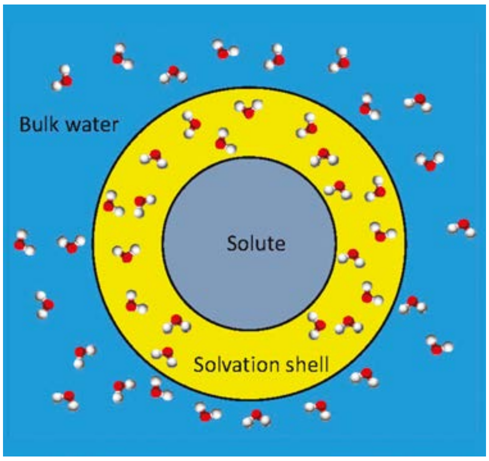

Terahertz radiation offers new contrasts with biological systems, without markers or staining, at the molecular, cellular or tissue level. Thanks to technological advances, it is increasingly emerging as a solution of choice for directly probing the interaction with molecules and biological solutions. Applications range from dynamics of biological molecules to imaging of cancerous tissues, including ion, protein and membrane sensors.

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Many imaging techniques are currently available to observe biological systems in 2D or 3D (microscopy, OCT, X-ray, NMR, PET, ...), each having advantages and drawbacks. The terahertz wave domain (0.1 to 10 THz) is one of the least studied regions of the electromagnetic spectrum, and this is even more notable in the field of sensing and imaging. Until now it has been challenging to generate and detect terahertz radiation. However, these difficulties are gradually being overcome by new commercial terahertz sources and detectors, increasing the development of applications in life sciences. The terahertz range offers new imaging contrasts thanks to a strong coupling with molecular vibrational modes. Water plays a paradoxical central role. On the one hand, its strong absorption significantly limits the penetration depth through biological samples. But on the other hand, the modification of its dielectric properties is a marker for sensing and imaging. After discussing the origin of this contrast, we will present the major techniques used to investigate biological systems. Then, we will detail applications from the sensing of fundamental biological molecules to medical imaging.

THz INTERACTION WITH BIOLOGICAL MOLECULES

Pure water composes about 62% of a human body, followed by proteins/peptides (17%), lipids (14%) and ions (6%). Pure water is a polar liquid and thus strongly absorbs and disperses terahertz radiation. The dielectric constant of bulk water is well fitted by an overdamped Debye-type relaxation model which reflects the coupling with the hydrogen bounding (HB) network in liquid water and several spectrally broad vibration modes (HB binding, stretching, hindered rotation, ...) [1]. The absorption spectrum of water is very broad, with higher absorption at higher frequencies. However, water is never found pure in biology, but associated with solutes such as proteins, peptides and ions. A simple model can explain the modification of the dielectric constant of water by the solutes. Solute molecules, in particular large biomolecules such as proteins, have a dielectric constant different from bulk water. But they also alter the properties of a layer of water molecules close to the solute: the solvation shell. Therefore, the alteration of the terahertz dielectric properties of the solution originates from both the substitution of • • •

bulk water by solute molecules, and from the relative importance of the solvation shell [2]. Small molecules such as ions mostly contribute to the solvation shell, whereas proteins bring their specific vibration modes. Therefore, the nature and concentration of solutes in liquid water is the main contrast factor for biological systems For instance, lipids absorb less than water, which can be used for cancer imaging purpose [3, 4]. In solution, biomolecules (proteins, DNA, ...) exhibit large vibrational modes due to inhomogeneous broadening. Therefore, many investigations are performed in dry or cryogenic states for more accurate spectral analysis, at the expense of preserving the same properties as in-vivo.

SENSING BIOLOGICAL SYSTEMS

TERAHERTZ SPECTROSCOPY

The expansion of terahertz spectroscopy originally started in the 1990's with the development of the terahertz Time Domain Spectroscopy (THz-TDS), either with photoconductive antennas or optical rectification, and based on femtosecond pulsed lasers. THz-TDS probes matter with short pulses of terahertz radiation. Accessible frequencies range from 0.03 to 30 THz. At room temperature, it provides a high precision and consistent measurement of the absorption and refractive index of the material, in transmission or reflection geometries. Fiber based compact systems are now commercially available. A terahertz pulse is recorded in the time-domain, and the complex Fourier transform of the terahertz signal provides the complex dielectric constant of the sample. In biology, the reflection geometry is often preferred due to strong water absorption. Classical Fourier transform infrared spectrometer (FTIR), with their Michelson-like scheme, are still widely used nowadays, in particular above 3 THz. However, they are of less interest for biology because water absorption is very high in their area of interest. High resolution spectroscopy can be achieved by photomixing. Two continuous lasers are mixed together and focused on a photomixer chip which generates tunable frequencies with spectral resolution down to 1 MHz. A wide variety of other terahertz sources can also be used [5]: electronic systems such as klystron, gyrotrons, free electro lasers, BWO, synchrotrons. Terahertz laser sources also include quantum cascade lasers (QCL), semiconductor such as CMOS or gas lasers.

TERAHERTZ MICROSCOPY

To image small samples, the terahertz systems must compete with the diffraction limit in the far field. The far-field resolution Δl is given by Rayleigh criterion $\Delta l = 1.22\,\frac{\lambda f}{D}$ where λ is the wavelength, f the focal length and D the aperture diameter of the lens, making very difficult to obtain a resolution better than the wavelength (*i.e.* 300 μm at 1 THz). This is enough to image large samples such as skin or biopsy samples, but not to resolve individual cells with a typical size of the tens of micrometers. Near-field techniques can break the diffraction limit by coupling the light to a subwavelength object and can reach resolutions as small as $\lambda/100$ [6]. Near-field techniques imply an important loss of energy, thus they require very high signal-to-noise-ratio measurements and a trade-off between signal and resolution. Examples are: near-field imaging with micro-probes or apertures [7], subwavelength electro-optic crystals and photoconductive antennas, terahertz nanoscopy coupled with Scanning Near-Field Microscopy (SNOM) [8], or evanescent waves in Attenuated Total Reflection [9]. Another aspect of microscopy is to reach remote samples, for instance the interior of an organ or a cavity of the body. The terahertz radiation has to be delivered directly into the organ by the help of endoscopes using hollow core fibers, metallic waveguides, or by generating and detecting the terahertz probe directly into the organ using optical fibers.

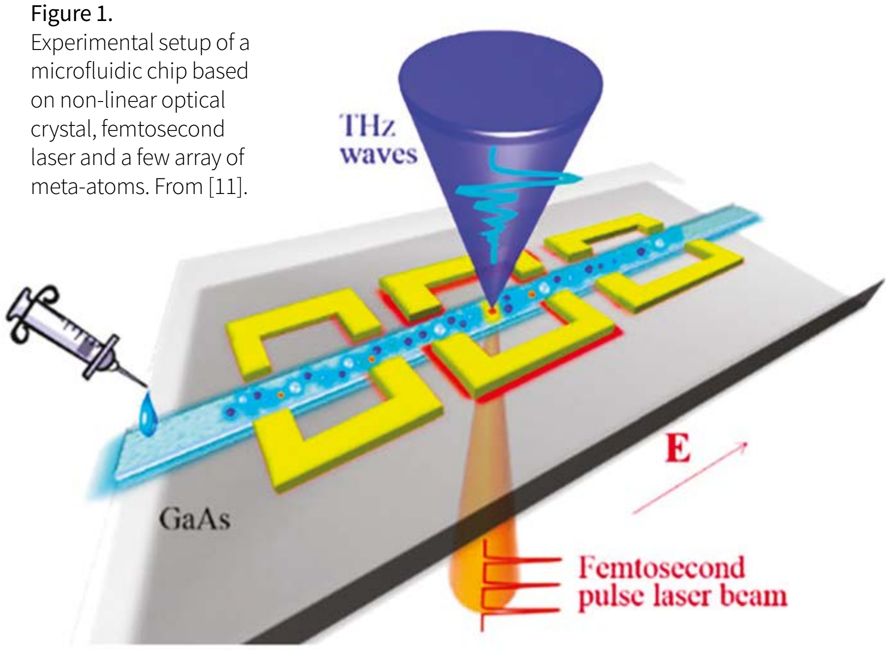

Figure 1.
Experimental setup of a microfluidic chip based on non-linear optical crystal, femtosecond laser and a few array of meta-atoms. From [11].

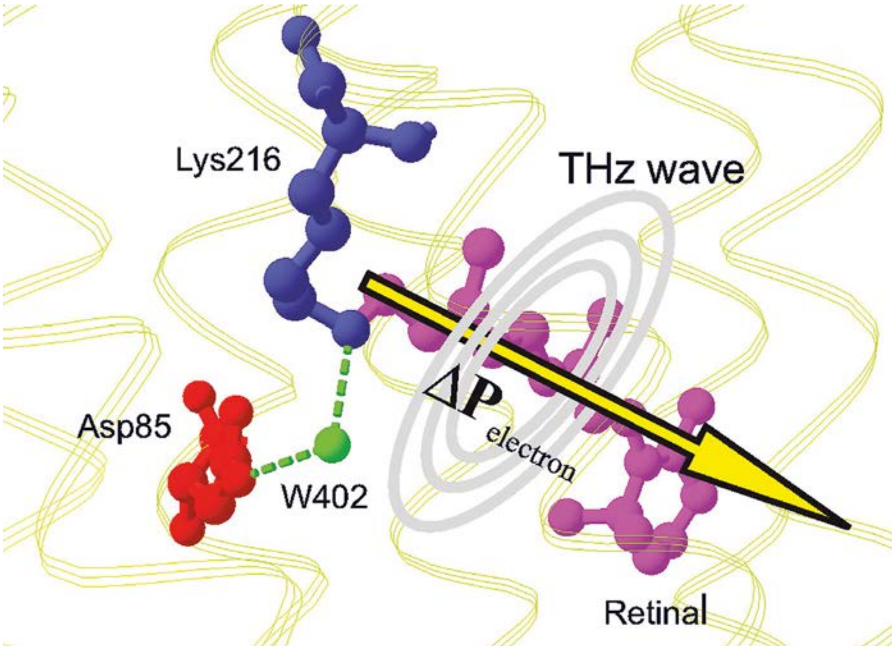

Figure 2.
Deconvoluted 3D image of the axon obtained with near-field technique with aperture, using finite element method (FEM) simulations. From [13]. Copyright (2008) National Academy of Sciences, U.S.A.

BIOSENSORS

Terahertz biosensors are sensors probing molecules of biological interests (proteins, enzymes, antigen, ions, ...) using terahertz radiation. They measure the change of the terahertz permittivity due to biomolecules. Terahertz biosensors focus on two main objectives: improving sensitivity (*i.e.* reaching lower concentration level of biomolecules), and reducing the volume of samples since biomolecules are often found in small quantities. Spectral shift can be used to differentiate molecules, such as hybridized and denatured DNA [10]. Metamaterials can increase the sensitivity of detection by several orders of magnitude, such as split-ring resonators, meta-atoms [11], plasmonic effect in nanoparticles, photonic bandgap sensors, plasmonic antennas. A second aspect is the reduction of the probed volumes. Microfluidic devices (in silicon, PDMS, ...) are of particular interest to transport small quantities of aqueous samples, down to the femto-mole (10^{-15}) level of ions. Combined with metamaterials, microfluidics with enhanced sensitivity capability was used for testing liver cancer biomarkers. Furthermore, microfluidic chips have the potential for parallel sorting and sensing (fig. 1).

APPLICATIONS IN BIOLOGY AND MEDICINE

FUNDAMENTAL PHENOMENA IN BIOLOGICAL SYSTEMS

Fundamental applications in biology involve the probing at the vibrational level of biomolecules, such as proteins, DNA or peptides. This information is related to their dynamics and thus functions *in-vivo*. Retinal molecules are the chromophores in the photoactive proteins rhodopsin and bacteriorhodopsin. Photoinduced isomerization of the chromophore molecule is the primary step in their photocycles. The spectroscopy of 3 isomers of retinal, the key molecule of the vision, was performed by THz-TDS, and related to vibrational modes characteristics [12]. The primary charge translocation phenomena that take place in the proton pump were investigated in bacteriorhodopsin [13]. The authors observed light-induced coherent terahertz radiation from bacteriorhodopsin with femtosecond time resolution, related to an excited-state intramolecular electron transfer within the retinal chromophore. In spectroscopic studies of biomolecules, water strongly modifies the vibrational response of the molecules. Resonances are intensely broadened and mostly disappear, due to the coupling with water molecules. Experiments can be performed on dehydrated or cryogenic samples to study the vibrational modes, but in non-biological conditions. On the other hand, studies in solution are more involved on the solvation of biomolecules. In solid state samples, spectroscopy of amino-acids was reported at room and cryogenic temperature and compared to DFT vibration modes calculation [14]. This allows a better understanding of empirical force fields in biological molecules, which are essential for the modelling of complex molecules such as proteins or DNA. Direct spectroscopy measurements were also performed on proteins such as lysozyme in solid state. In solution, the hydration number is the number of water molecules interacting with a solute molecule. A solvation shell is found around the solute, with hydration numbers different from bulk water. The spectral and dynamical properties of the solute and hydration shell (hydration number, solvation shell thickness, ...) can be inferred from terahertz measurements. Combined by molecular dynamics simulation, the hydration number and hydration shell thickness are important parameters related to the dynamics and thus biochemical properties of biomolecules in solution, such as sugars and peptides, carbohydrates, proteins, ions, RNA [2, 15] (Fig. 2).

Fundamental applications in biology involve the probing at the vibrational level of biomolecules, such as proteins, DNA or peptides.

TERAHERTZ IMAGING

Profiting from the contrast given by the water content of tissues or by solutes, terahertz imaging investigated a wide range of biological systems [1]. Cancer has been studied by many groups. The goal is to detect cancerous tissues containing more water and absorbing more terahertz radiations, due to abnormal angiogenesis compared to healthy ones. Many studies used reflection techniques to reduce absorption in in-vivo experiments, while others employed thin or partially dehydrated biopsies [16]. Skin carcinoma received many attention [4,17], as well as breast cancer [3,18]. Other types of cancers studied are glioma, or ovarian. More specific systems were also studied. Neuron was imaged with near-field ionic contrast [7]. Corneal tissue hydration was also investigated. Most terahertz imaging measurements imply to deal with a lot of information, in particular when time-domain or spectroscopic signals are involved.

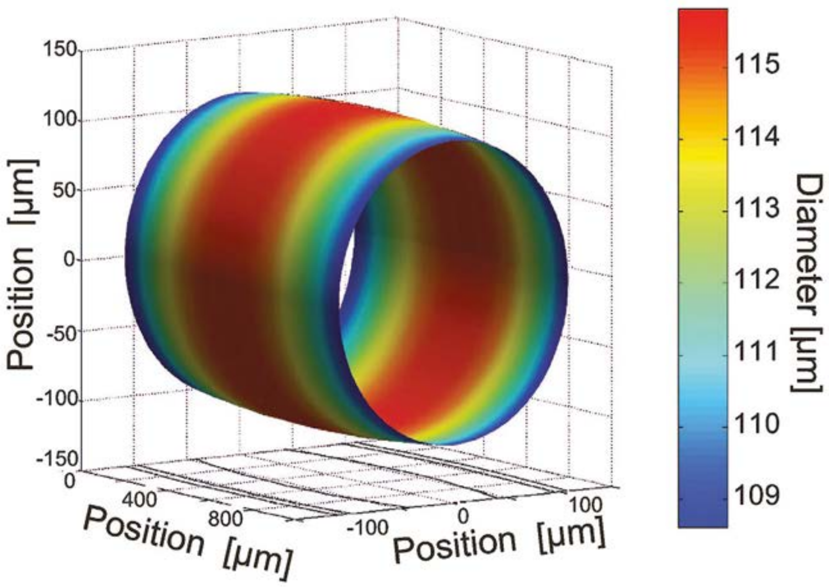

Figure 3.
Deconvoluted 3D image of the axon obtained with near-field technique with aperture, using finite element method (FEM) simulations. From [7]. Copyright (2006) National Academy of Sciences, U.S.A.

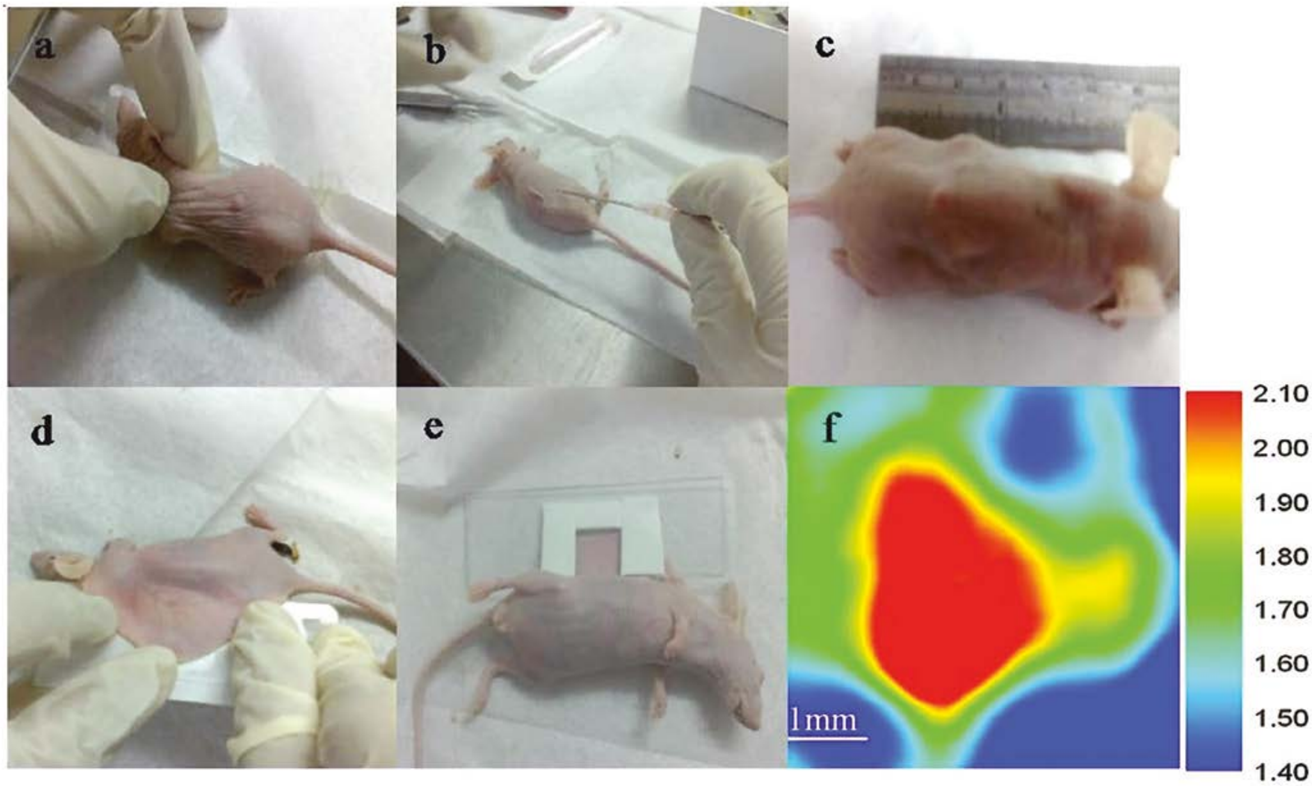

Figure 4.
Imaging of a human breast tumor implanted in a mouse. (a) a visible tumor. (e) Stretched tumor between two cover glasses. (f) In-vivo terahertz imaging. From [18], © OSA.

The choice of the relevant parameters is often very important for an accurate analysis. Mathematical statistical methods such as principal component analysis (PCA) can minimize the correlated variables into useful uncorrelated variables (Figs. 3,4).

BIOLOGICAL SENSORS

A last field of applications is related to biosensors seeking to detect low amount of biomolecules with high precision, and to correlate the measurements with biological and medical relevant indicators. Microfluidic circuits compatible with •••

terahertz radiation have also been developed to merge small volumes and sorting capability. Sensors can be based on spectral analyses, by a change of permittivity or a shift of resonance in human cancer cells or blood cells. Other demonstrations involved near-field time-dependent measurement of ionic flow during auricular muscle electrical activity [19] or plasmonic antennas on bacterial layers allowing the selective recognition of the Gram type of the bacteria. Sensitivity enhancement by plasmonic techniques is also very promising. Integrated planar terahertz probing demonstrated an enhancement of the detection threshold allowing the differentiation of denatured and hybridized DNA in solution [10]. THz scattering-type scanning nearfield optical microscopy (THz s-SNOM) demonstrated sub-attomole sensitivity on crystalline lactose and offers the detection of fingerprints of biomolecules at very low volumes. Very low volume detection was also achieved with split-ring resonators (SRR) [11], as low as 30 fmol of ions in 300 pmol of water. SRR were also integrated with microfluidics circuit for live cancer biomarkers. High-Q factor meta-sensors based on toroidal surface plasmon resonance enhanced by gold nanoparticles also targeted biomarker proteins.

CONCLUSION

Water plays a central role in life, as well as in the probing of biological systems by terahertz radiation. Thanks to the development of better terahertz sources and detectors, the analysis of the dielectric constant of solutions brings new solutions for imaging and sensing biomolecules and tissues, in addition to existing and more conventional techniques.

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SPATIAL LIGHT MODULATORS

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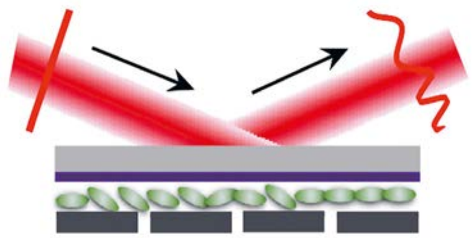

Spatial Light Modulators (SLMs) are quasi-planar devices, allowing for the modulation of the amplitude, phase and polarization, or a combination of these parameters of an incident light beam according to the two spatial dimensions of the modulator. SLMs are employed in many different fields and are the subject of continuous technological development.

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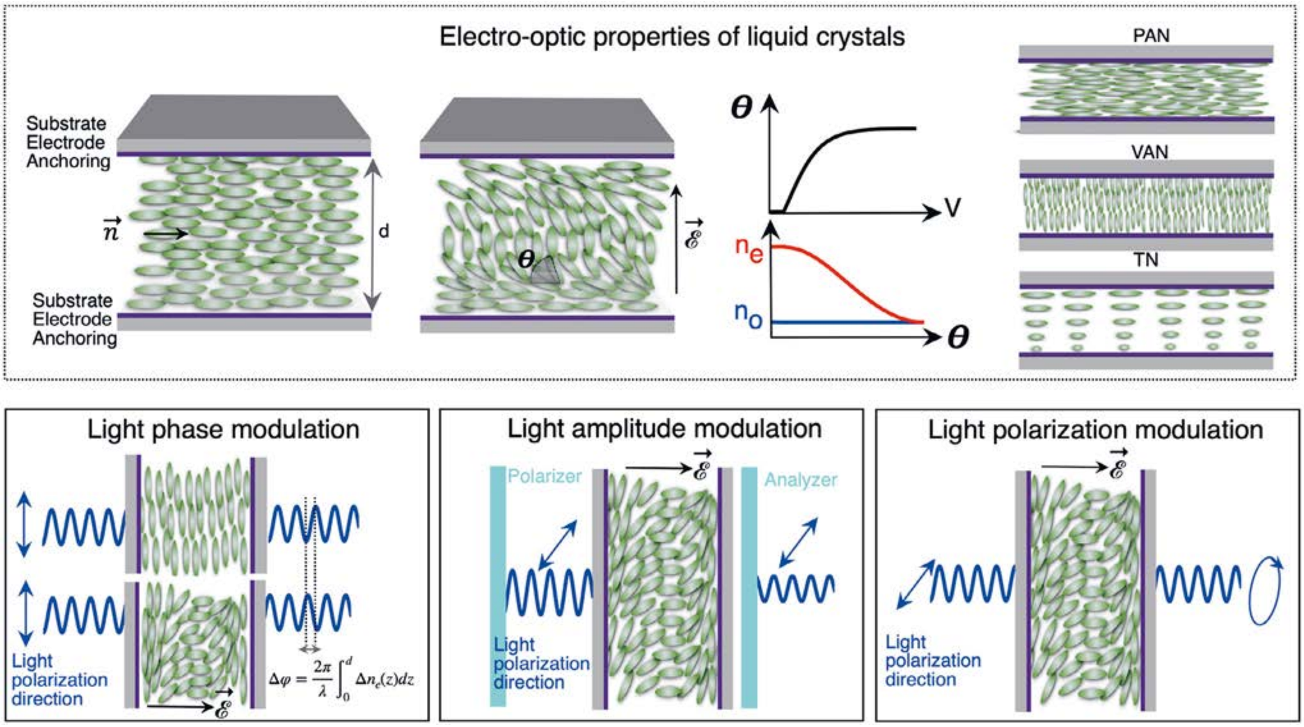
Spatial light modulation is a well-established optical technology with a wide range of applications. Spatial light modulators (SLMs) are two-dimensional objects, enabling to modulate, at any point of the SLM surface, through a local change of the optical path, the intensity, phase or polarization of an incident light beam. They are usually organized into categories according to (i) their use in reflection or transmission, (ii) the modulated optical parameter(s): amplitude, phase, polarization, and (iii) the type of the driving signal: electrical or optical.

Although spatial light modulation has been made possible through a plethora of technologies, among them mechanically or thermally deformable mirrors, digital micro-mirror device (DMD), magneto-optic devices or acoustic-optic Bragg cells,



the denomination most often refers to non-mechanical components which exploit the electro-optical anisotropy of liquid crystals (LCs). Thereafter, we will focus onto the physical and technical characteristics of the LC-based SLMs (LC-SLMs) [1].

Figure 1: Electro-optical properties of nematic liquid crystal layers enable to locally change the phase of the propagating readout light. The application of the electric field induces an average molecular rotation, which in return changes the refractive index, according to the input light polarization. Typical planar anchoring conditions can be vertical (VAN) or horizontal (PAN) or both, *e.g.* twisted (TN). Such a simple device allows for the modulation of the phase, amplitude or polarization of light according to the design details and the presence or absence of additional polarizing elements.

PRINCIPLE AND APPLICATIONS

Principle. Liquid crystals are organic materials whose physico-chemical properties are intermediate between those of solids and liquids. The elongated LC molecules therefore have both a structural order and anisotropy specific to crystals such as optical, dielectric or even elastic anisotropy. The optical anisotropy is generally higher than in crystals: an optical birefringence ranging between 0.1 and 0.2 for example is common in LCs. The existence of a liquid order also guarantees the fluid nature of the different LC mesophases and, to some extent, the tunability of their properties. These characteristics, combined with a wide spectral transparency, have made LCs materials widely used in optics.

In the nematic mesophase, molecules do not have a positional order but are oriented in a preferential direction, defined by a vector $\vec{n}$, the so-called director axis. They feature properties of an anisotropic uniaxial medium with an optical axis oriented along $\vec{n}$. This direction can be experimentally specified by defining specific boundary conditions at the surface of the sample. Typical anchoring conditions can be planar (PAN), homeotropic (VAN) or twisted (TN). Furthermore, the orientation of the director axis can be controlled by applying external electric and / or magnetic fields. As a matter of fact, the application of an electric field results in the creation of elastic forces leading to the reorientation of the molecules that tend to line up in the direction where the strain energy is minimal. For LCs with a positive dielectric anisotropy, the minimum energy is reached when the molecules are aligned in the direction of the electric field. The strength of the electric field modulates the average molecular orientation. Therefore, the optical refractive index of the medium is electrically-controlled and the phase of a propagating light is modified accordingly.

Spatial control of the applied electric field, on one or two dimensions, offers the ability to spatially modulate the phase of an incident optical wave. The latter is referred in the following as the "readout beam", while the recording signal contains the information to be "printed" on the phase of the readout light. The readout beam has to be polarized. In addition, its polarization is a mean to control the parameter modulated by the LC component, whether it is the phase, amplitude or polarization [2]. Indeed, projection of an initially linearly polarized light at 45° with respect to the LC extraordinary axis provides a phase-mismatch between the two crossed-polarized components. This variable phase shift allows the modulation of the light amplitude if the component is placed between polarizer and analyzer, and the modification of the linear polarization state to elliptical otherwise. Subsequently, phase-only, amplitude-only, polarization, or the combination of phase-amplitude modulation can be readily realized with a LC-SLM, as illustrated in Figure 1.

Applications. For decades, the large market of image projection and displays has fed the development of LC-SLMs that address otherwise uncountable applications in a wide field of scientific investigations. Nowadays, SLMs are used in fields as varied as imaging, digital holography, optical switching, microstructure fabrication, optical vortex generation. In the context of adaptive optics, SLMs are employed to correct the wavefront of lasers and optimize the point spread function for biomedical applications and microscopy. In addition, SLMs enable ultrashort optical pulse shaping through a process known as Fourier-domain pulse shaping. Recently, such devices have also been used in the field of telecommunications in order to achieve modal multiplexing in multimode optical fibers. Some illustrations are available in Figure 2.

SLM MAJOR FAMILIES AND PERFORMANCES

Most of commercial SLMs are electrically-addressed, for instance through standard digital video interface with each grey level being related to a given voltage. They can operate either in reflection or in transmission.

Transmissive SLMs. Transmissive SLMs include a nematic LC layer confined between two transparent conductive windows. At least one electrode is segmented, in order to provide individual electrical control over a certain amount of pixels. A particular type of transmissive SLM is the well-known LCD (Liquid Crystal Display), for amplitude light modulation. LCD relies on TN-type LC-SLM, placed between parallel or crossed polarizers.

Reflective SLMs. Reflective SLMs are particularly sought as they enable to fold the associated optical system, while light propagates twice in the modulating layer, which, in turn, increases the dynamic range. In this family, the most popular technology is LCoS (Fig. 3): Liquid Crystal on Silicium, mainly used for phase-only or amplitude-only light modulation. Most of current commercial electrically-addressed LC-SLMs are based on this technology.

Therefore, the nature and concentration of solutes in liquid water is the main contrast factor for biological systems.

LCoS are microdisplays, composed of a layer of nematic liquid crystals enclosed between a transparent electrode and a matrix of CMOS (complementary metal oxide semiconductor) integrated circuitry on a silicon backplane. The latter operate in reflection through a reflective treatment deposited on the CMOS matrix. Anchoring layers on one side of the electrode and on the reflective layer allow the molecules to be oriented in a direction parallel to the surface. An electric field maintained between the transparent electrode and the semiconductor controls the local average molecular orientation of the liquid crystal and modulates its refractive index.

Performances criteria. The different components of the LC-SLM multi-layer structure can be individually optimized according to the targeted application. Performances of

LC-SLMs are then characterized as *a priori*ty by their active area, transmittance / reflectance, spectral acceptance, spatial resolution, response time and modulation dynamics.

Modulation range and response time. The modulation range is the maximum retardation that can be applied to a given wavelength while the dynamic response time is defined as the switching time from 10% to 90% and from 90% to 10% (rise and fall time). Theses two features are primarily determined by the LC layer material and thickness. Independently from the technology, the thickness of the LC layer is generally limited to 20 µm in most SLMs, and results from a balance between the desired modulation range (e.g. maximum phase modulation), maximum control voltage, molecular disorder issues, and dynamic response time. For radiation in the visible spectral range, the phase modulation evolves between 0 and 2π or 0 and 4π. The dynamic response time, meanwhile, ranges typically between 1–100 ms for 10–90% rise and fall times.

Active area. LC-SLMs for scientific applications present an active area usually around 1–2 cm^2, with some specific extension in the array configuration, up to 7 cm × 1 cm.

Spatial resolution. The spatial resolution is related to two parameters: the pixel density and the cross-talk between adjacent pixels. The pixel pitch depends on the category of SLMs. Higher pixel densities are achieved with LCoS, typically 1920 × 1080 pixels, but also up to 4160 × 2464. Transmissive SLMs are restricted to a larger pixel size (a few tens of µm for transmissive SLMs, as opposed to a few µm for LCoS). When specified beyond the simple number of pixels, the spatial resolution of an LC-SLM is around 40 lines per /mm, that is between 20–30 µm.

Filling factor. The electrically controlled LC-SLM makes it possible to control the properties of the readout light over a limited number of zones predefined by the manufacturer, this number being approximately equal to the number of electrode segments. In addition, at the junction between two adjacent segments, there are gaps where the SLM is inactive and / or has discontinuities in the modulated optical property. Inactive gaps are responsible for light scattering. This feature is translated as the so-called filling factor, usually slightly above 90% for commercial systems.

Reflectivity (transmittance). The reflectivity (transmittance) is not 100% as some of the light may be diffracted into higher orders due to the grating like structure of the pixel matrix while some part of light is also scattered and absorbed at the interpixel gaps. In addition, the overall reflectivity (transmittance) is limited by losses at the multiple interfaces of the multi-layer structure, the electrode transparency, the reflectivity of the metallic or dielectric coating in LCoS. Typical values spread between 70% and 90%.

Spectral acceptance. Commercial SLMs make it possible to address different spectral ranges, with bandwidth around 200 nm, centered in the visible, near-infrared or close to telecommunication bandwidths. A remaining drawback of the electrically-addressed LC-SLM technology is the presence of a top electrode. Most of the time, Indium Tin Oxyde (ITO, typically transparent over 0.3–1 µm, with partial transmission up to 1.5 µm) is employed, which tends to reduce the spectral acceptance, by comparison with the LC mixture itself. Moreover, as the phase modulation range scales with the optical frequency, extending the spectral range towards the infrared tends to require thicker LC layers, which, in turn, constraints the electrical addressing scheme. These two features limit the practical use of LC-SLMs in the visible and near infrared spectral range.

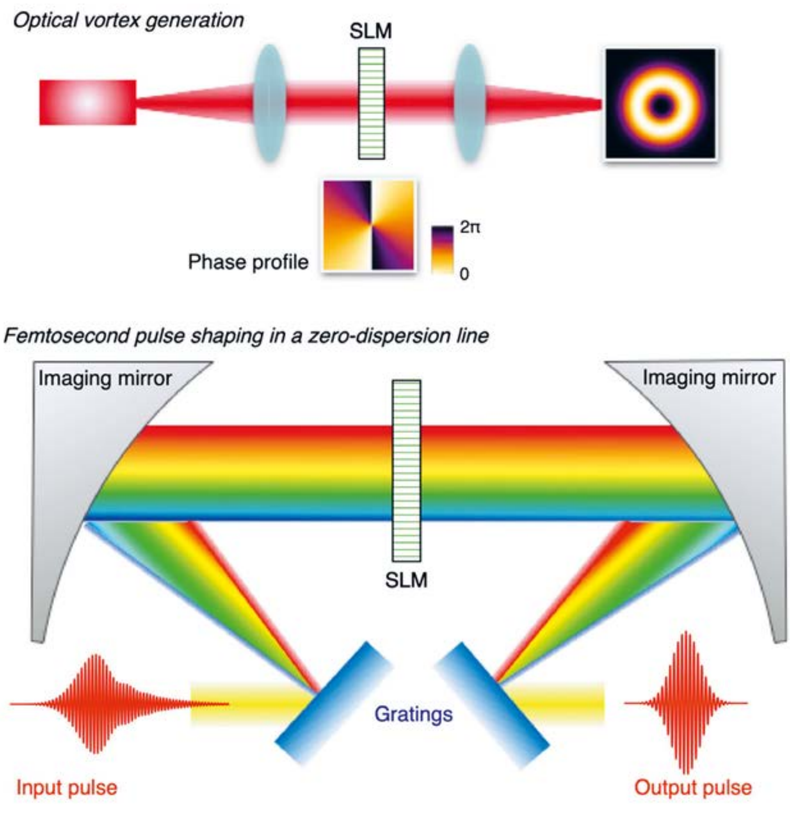


Figure 2: Illustration of some applications of SLMs. Top: a spiral phase pattern leads to optical vortex beams [3]. Bottom: a SLM inserted in a zero-dispersion line enables the temporal shaping of a femtosecond pulse [4].

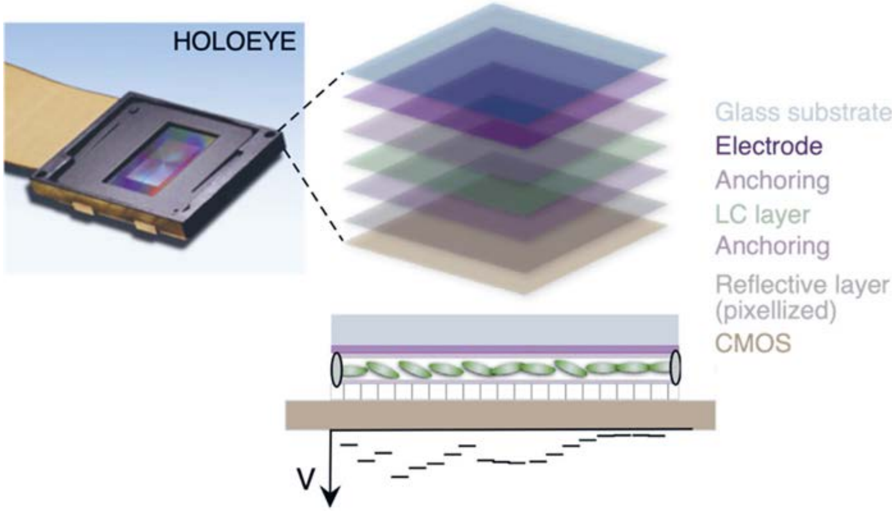


Figure 3: Structure and cross-section of an LCoS SLM and photograph of an industrial product from Holoeye.

Flicker. The flickering phase corresponds to the phase fluctuation due to electric polarization of the LC molecules and can be reduced to 0.01π by carefully designing control electronics.

Damage threshold. LC-SLM can tailor the properties of high power laser beams. Some damages might alter the SLM behavior, either due to laser ablation of one of the LC confining substrates, or to heating of the LC layer. According to the available data, the damage threshold is limited by electrodes and/or metallic coating in LCoS and is around 5W/cm^2 for continuous light radiation, and decreases to 0.1 J/cm^2 for pulsed femtosecond lasers.

LIMITATIONS AND RECENT ADVANCES

Although LC-SLMs are very performant and popular optical systems, some limitations can be deduced from the performances detailed above. Among them, the pixelisation and limited spectral acceptance in the mid-infrared spectral range are the most challenging issues. Nevertheless, research and development of innovative LC-SLMs is still very active. In particular, other solutions for controlling the birefringence are being investigated.

Replacing the electrical addressing by an optical addressing solves the pixelisation issue and ensures arbitrary and continuous phase modulation.

In so-called light valve modulators, or OASLM, a biased photo-conductive substrate replaces the segmented electrode and the voltage across the LC layer is locally controlled by an ancillary absorbed control beam, often referred as the "recording" beam, as opposed to the "readout" beam. This electrode is, however, mandatory, as an oscillating electric field has to be maintained across the LC layer to control the average orientation of the molecular director. Moreover, conventional optical valves require an isolation layer to prevent cross-talk between the recording and readout beams.

Finally, novel technological developments in this field are steadily proposed. Thermal or thermo-optical control of the LC layer or photo-polymerization of the anchoring layer might be promising methods to provide continuous phase modulation while eliminating the need for an electrode. Dielectric metasurfaces might also be part of the next-generation of SLMs.

CONCLUSION

Spatial light modulators, thanks to their dynamic attractive optical capacities and to their technological maturity, are widespread in several scientific and industrial domains. The most common components exploit the electro-optical anisotropy of liquid crystals and are commercialized following LCD or LCoS technologies. Several performance criteria, such as panel resolution, active optical area, refreshing rate and spectral acceptance must be considered in order to define the most appropriate SLM for a targeted application. It should be noted that several developments towards innovating technologies could further boost the practical applications in the coming years.

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