ON THE PREHISTORY OF OPTICAL METASURFACES

Philippe LALANNE[1], Pierre CHAVEL[2]
[1] Lab. Photonique, Numérique et Nanosciences (LP2N), IOGS, Univ. Bordeaux, CNRS, 33400 Talence Cedex, France
[2] Lab. Hubert Curien, Université de Lyon, Univ. Jean Monnet de Saint Etienne, IOGS, CNRS UMR 5516, 42000 Saint Etienne, France
*** philippe.lalanne@institutoptique.fr, pierre.chavel@institutoptique.fr**

Before the word « metasurface » first appeared, optical elements that were thinner than a wavelength and deflected light in a direction incompatible with Snell's law already existed. Based on three examples, we review the underlying concepts and their evolution in the past few decades.

https://doi.org/10.1051/photon/202311941

Before the word "metasurface" first appeared, optical elements that were thinner than a wavelength and deflected light in a direction incompatible with Snell's law already existed. Based on three examples, we review the underlying concepts and their evolution in the past few decades.

The word "metasurfaces" first appeared around 2010, in connection with metamaterials, which implement some original property of matter through technology. Specifically, an optical "metasurface" implements such an original property, sometimes not found in nature, in a small thickness, possibly much smaller than the wavelength. While various optical properties may be controlled by an optical metasurface, of particular interest are metasurfaces that deflect or reflect light in a direction incompatible with Snell's laws for reflection and refraction (in this short article, we do not emphasize polarization effects). For that reason, Reference [1] generalizes the Snell's laws to account for abnormal ray deflection. Indeed, diffraction gratings, that have been known for more than two centuries, can be deeply subwavelength in thickness and follow the generalized Snell's law: their diffracted orders follow the grating equation, not Snell's equations. Some holograms qualify just as well, and other examples, at radiofrequencies, can be traced to the early times of Maxwell equations. Here, looking back to the 1950's, we review three milestone concepts and experiments on computer-generated optical diffractive elements that deserve to be called metasurfaces in the sense just defined.

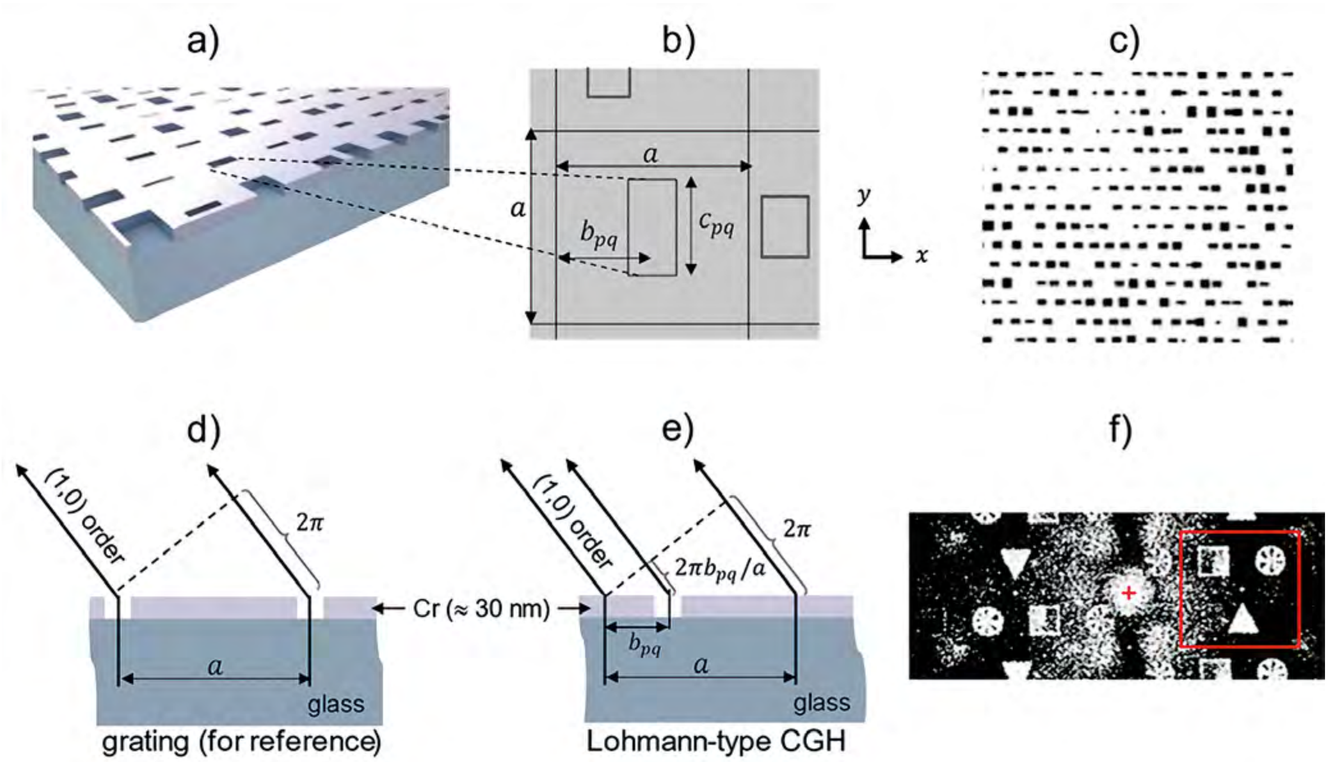
THE LOHMANN "DÉTOUR PHASE": A WAVEFRONT SHAPING HEURISTIC

Around the same time as, based on Gabor's work, Leith and Upatnieks first used a laser to record and reconstruct holograms, computers were reaching a state where they could calculate diffraction integrals and control a printer to produce an approximation of a simple diffraction pattern. That was a way to "synthetize" a wave front. Such « computer generated holograms » (CGH) were initially printed on paper by electromechanical pen plotters and then photo reduced on a photographic plate. Shortly thereafter, it became possible to fabricate them by etching a chromium coating of a thickness in the tens of nanometers range. Therefore, those components can be qualified as "metasurfaces". A.W. Lohmann [2] based his seminal CGH coding method on an analogy with the operation of a grating.

The basic principle of grating diffraction is that for an illuminating plane wave, two rays separated by one grating pitch emerge in order 1 with a relative path difference of exactly one wavelength. Consider a grating composed of equidistant slits on an opaque background, separated by the pitch distance a in the x-direction: observed from order 1, those slits carry phases of 0, 2π, ...$2m\pi$ (m integer), proportional to the abscissa x of their centres. Now, as a thought experiment, shift slit 0 by αa across x. Its phase in the direction of order 1 is then $2\pi\alpha$.

The Lohmann "détour-phase" method applies that idea to arbitrary wavefronts, such as the computed Fraunhofer diffraction pattern of some object Obj, periodically sampled in 2D. Let $t_{pq} = |t_{pq}| \exp i\phi_{pq}$ be the sampled complex amplitude at sample location p, q. The goal is to visualize Obj at infinity (Fraunhofer diffraction) around the direction of order 1 across x (order 0 across y). Phase ϕ_{pq} is obtained by etching an aperture at a position shifted by $\frac{a\phi_{pq}}{2\pi}$ with respect to sampling point p, q. The modulus is obtained by just scaling the aperture area proportionally to $|t_{pq}|$. The method is exact in the direction of order 1 and is a fair approximation in its neighbourhood. Therefore, the Lohmann détour-phase method is based on the "generalized Snell's law" because it relies on the

Figure 1. a) Sketch of a Lohmann-type hologram implemented on a chromium mask. b) Every cell (p, q) independently controls the complex-valued amplitude $t_{pq} = |t_{pq}| \exp i\phi_{pq}$ of the wave transmitted in the (1,0) order of the 2D square lattice. c) Photograph of a 1976 Lohmann CGH drawn printed on paper. The latter was reduced approximately 100 times and projected onto a silver halide photographic plate. d) For reference, the underlying grating structure. e) The phase is controlled by a shift, $b_{pq} = \frac{a\phi_{pq}}{2\pi}$, of the aperture across x. The amplitude transmitted by the aperture is proportional to the area of the rectangular aperture $|t_{pq}| \propto c_{pq}$. f) Central part of the CGH reconstruction in Fraunhofer diffraction plane using a HeNe laser (orders in the direction are mostly truncated). The red '+' mark shows the (0,0) order and the useful order (1,0) is highlighted by a red square.



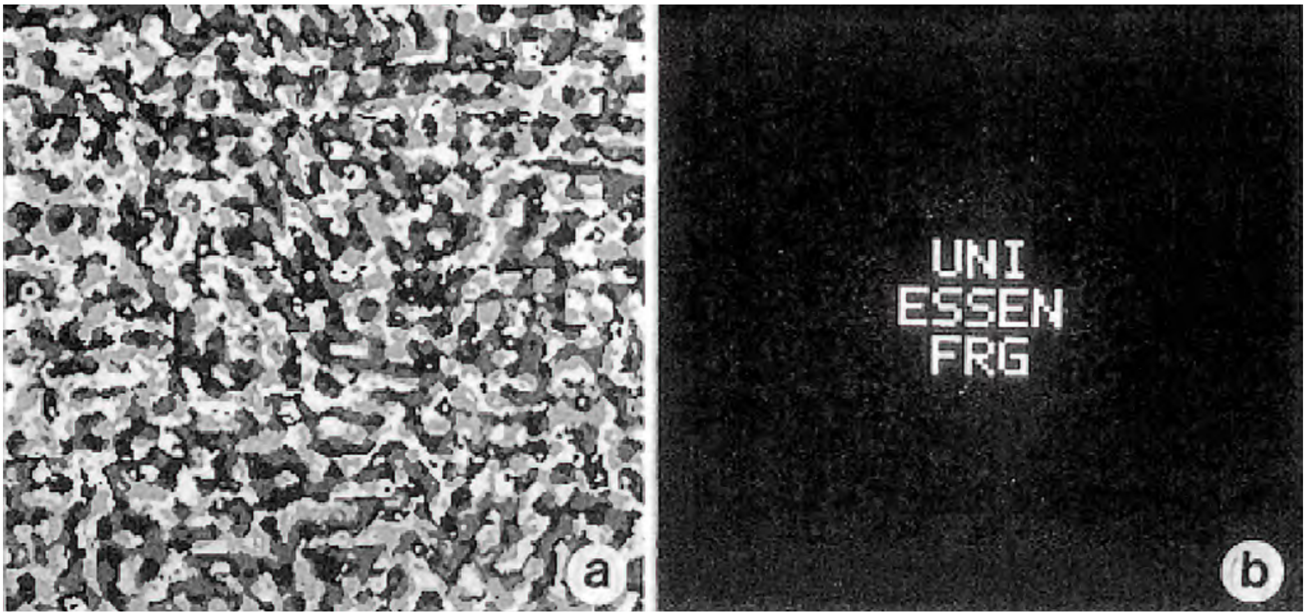


Figure 2. Example of unintuitive optimization of CGHs in the 1980's. a) Iteratively optimized 4-phase-level pattern. b) Calculated intensity of the diffracted light in a Fourier plane. Reprinted with permission from [3] © The Optical Society

deflection of light in order 1 of a grating to encode an arbitrary phase (Figure 1).

Many metasurfaces nowadays are designed with a computer and therefore qualify as "computer generated holograms". Similarly, Lohmann CGHs with a thin chromium coating qualify as "metasurfaces". In fact, as opposed to current metasurfaces, they used large cell sizes due to obvious limitations in lithography resolution at the time. Another difference is that they faithfully implemented the desired wavefront with an independent control of phase and modulus amplitude. But just like look-up type metasurfaces, they were based on one-to-one relation between the diffractive pattern and the desired local complex amplitude, and they suffered rather low diffraction efficiencies (a few percents) that are comparable to those reported in [1] with 'V' patterns of a similar thickness.

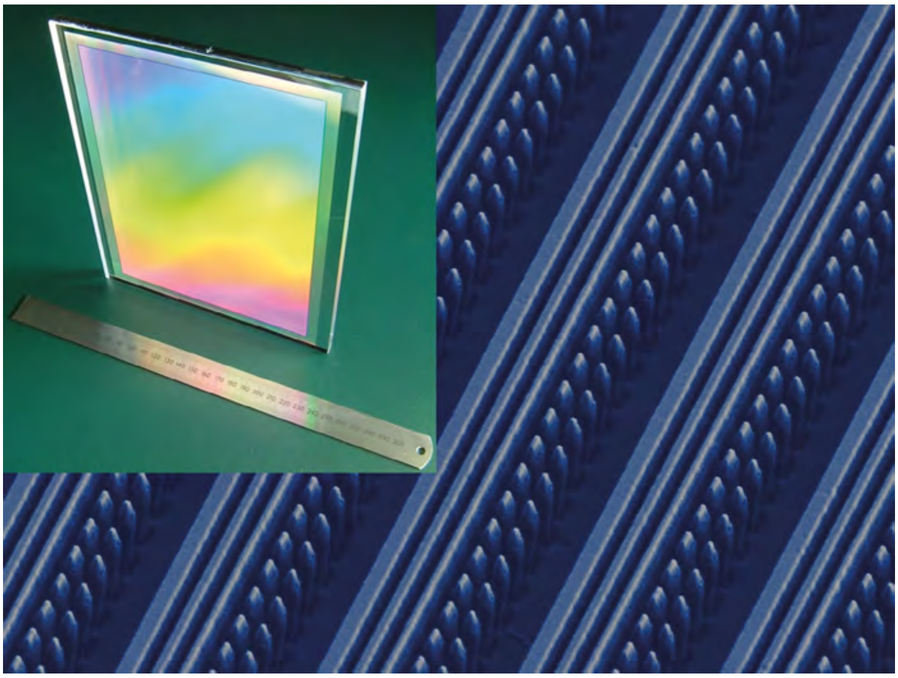


Figure 3. Scanning electron micrography of 20.5×15.5 cm² grating used in a spectrophotometer sent to space in 2013. The initial design was composed of pillars only for polarization insensitivity issue. Optimization has led to a combination owing to the difficulty of manufacturing high-aspect ratio pillars with large surface coverages. Courtesy Uwe Zeitner.
See [6] or http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=44093.

UNINTUITIVE DESIGN THROUGH ITERATIVE ENCODING OPTIMIZATION

Around the last quarter of the last century, efforts to improve the efficiency of such CGHs were therefore developed. To that end, the phase coding by an inclined carrier was abandoned, and therefore holographic concepts as well. In parallel, the wavefront sampling grew smaller as technology improved. Thus, it became possible to waste less energy into parasitic diffraction orders (in Fig. 1f, only a few are shown). To do this, one option is to fabricate continuous microstructures whose thickness is modulated between 0 and $\lambda/(n-1)$ associated to a phase delay between 0 and 2π.

This continuous approach is relevant for transmittances requiring only phase modulation, *e.g.*, lenses. When the desired transmittance further requires a modulation of the modulus of the transmitted wave, maintaining high efficiency becomes problematic and there is no general solution. However, when only the illumination matters in the observation plane as it is the case for display holograms, an elegant solution, very popular in the 80s, consists in exploiting the degrees of freedom left by the phase of the diffracted wave, and finding a transmittance $\exp i\varphi(x, y)$ of a pure phase component which produces the target intensity distribution $I_s(x', y')$ in a prescribed angular window W, while wasting as little light as possible outside that window for the benefit of diffraction efficiency.

This synthesis of phase profiles by inverse diffraction is a complex optimization problem that can be solved by iterative methods. The latter may be based on the minimization of a cost function, $E_\varphi = \iint_W \left(\eta I_s(x', y') - G_\varphi(x', y')\right)^2 dx'dy'$, where η determines the diffraction efficiency and G_φ is the intensity observed in the signal window for a given phase function $\varphi(x, y)$ at the exit of the metasurface. Generally, the cost function minimization is performed for discrete phase values. For a diffraction efficiency close to unity, the signal window differs from the target intensity distribution and the cost function takes on a large value. By lowering the targeted efficiency, *e.g.*, to 80%, very acceptable fidelity may often be achieved using 4 or 8 phase levels diffractive components (Figure 2).

The algorithms used to minimize the cost function rely on iterative direct and inverse fast-Fourier transforms in the case of a small angle window of interest, where Fourier optics is the appropriate framework. They are reminiscent of the adjoint gradient methods developed in the 1950s for logistic optimization, and further used since the 1980s for machine learning, and nowadays also for inverse design in various photonics problems. As shown in Figure 2, the resulting patterns are rather unintuitive. The technology was passed to industries around the turn of the millennium and is used nowadays for manufacturing various diffractive optical elements ("array generators" to illuminate a prescribed set of points, diffusers with specified scattering diagrams ...).

As the lithographic technology moved to smaller and smaller resolutions, electromagnetic models progressively took over from Fourier optics for modelling, implying heavier calculations but leading to wide angular windows W. In that case, the sampling period becomes smaller than the wavelength and the modulation is devoted to shaping the only existing nonevanescent order, the (0,0) order, as will be discussed in the last section.

NANOSTRUCTURED METASURFACES

Nothing was subwavelength in the visible domain before the 90's and design relied on scalar optics. In the 90's, photonic research was starting to enjoy the benefits of nanotechnologies and rapidly, metasurfaces

In parallel, the first metasurfaces composed of minutely arranged arrays of nanostructures, *e.g.*, holes, pillars, or combination of both in the most advanced design accounting for dispersion, were implemented for beam shaping or beam steering.

much similar to those encountered nowadays were implemented. In a first phase, designs inspired by effective medium theory were used for fabricating other functions than wavefront shaping including moth-eye antireflection coatings or optical analogues of the wire-grid polarizers used at radiofrequencies by Hertz in the late nineteenth century or broadband wave plates [4]. It was also during this period that the first resonant filters, now known as nonlocal metasurfaces, were successfully fabricated by etching gratings in waveguides [5].

In parallel, the first metasurfaces composed of minutely arranged arrays of nanostructures, *e.g.*, holes, pillars, or combination of both in the most advanced design accounting for dispersion, were implemented for beam shaping or beam steering. It was then realized that efficiencies much larger than those achieved with classical sawtooth surface-relief profiles could be achieved for gratings with large deviation angles or lenses with high numerical apertures, by abandoning effective medium considerations and by controlling the phase instead through high-index single-mode nano waveguides operating nearly independently [4].

As a conclusion and summarizing the progress made in the 1990s in the field, Figure 3 shows a remarkable "metagrating" [6] designed and manufactured at Jena and sent in space on 19. Dec. 2013 in the Gaia-satellite of the ESA. The grating has been optimized for operation at 850 nm. The design was able to overcome the challenges of fabricating dense pillar arrays over large surfaces and relies on a combination of tiny pillars and large ridges. Its behavior is nearly insensitive to the polarization. Over the 205×155 mm^2 area surface, the efficiency measured for unpolarized light varies between 80% and 84% and the wavefront accuracy in the first order is 8.4 nm rms. Such gratings are indeed much more costly than sawtooth profile gratings that can be fabricated at low price over large area by embossing plastic films for instance, but they are more efficient and are able to meet the stringent requirements of space applications.

ACKNOWLEDGEMENTS

The authors thank Adrian Agreda for preparing Fig. 1a.

REFERENCES

[1] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, *Science* **334**, 333–337 (2011).

[2] B. R. Brown and A. W. Lohmann, *Appl. Opt.* **6**, 1739 (1966).

[3] F. Wyrowski, *J. Opt. Soc. Am. A* **7**, 961-969 (1990).

[4] H. Benisty, J.J. Greffet, and P. Lalanne, *"Introduction to nanophotonics"*, Oxford University Press, Oxford, (2022), ISBN 978-0-19-878613-9, Sections 18.4 and 18.5.

[5] S. Peng and G. M. Morris, *Opt. Lett.* **21**, 549-551 (1996).

[6] U. D. Zeitner, M. Oliva, F. Fuchs, D. Michaelis, T. Benkenstein, T. Harzendorf and E.-B Kley, *Appl. Phys. A* **109**, 789-796 (2012).