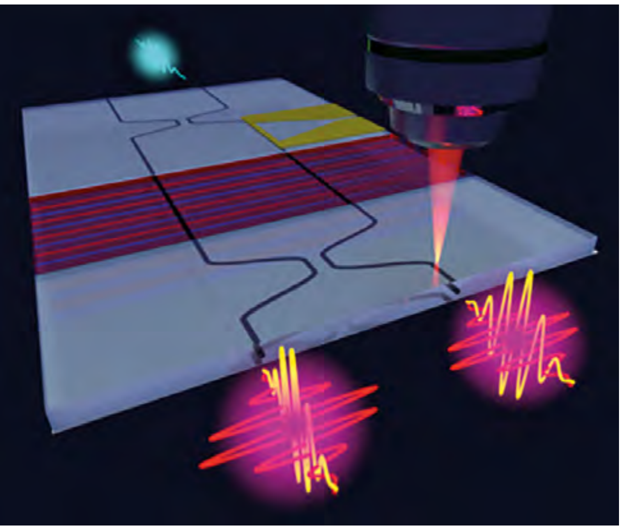
PHOTONIC INTEGRATED CIRCUITS THROUGH FEMTOSECOND LASER WAVEGUIDE WRITING IN GLASS

Francesco CECCARELLI[1,2], Roberto OSELLAME[1,2,*]
[1] Istituto di Fotonica e Nanotecnologie – Consiglio Nazionale delle Ricerche (IFN-CNR), Piazza Leonardo da Vinci 32, 20133 Milan, Italy.
[2] Ephos Inc., 333 Bush Street, San Francisco, CA 94104, USA.
*** roberto.osellame@cnr.it**



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Integrated photonics is increasingly pivotal across various fields due to its inherent stability, scalability, and compactness. In the landscape of integrated photonic platforms, femtosecond laser writing is a novel microfabrication technique that is swiftly emerging as a strong contender to established photolithography-based methods. This paper presents a primer on the femtosecond laser writing process and explores its capabilities for creating versatile and reprogrammable processors. Furthermore, we examine the application of this technology to the realization of integrated devices designed to leverage the distinctive features of this technology for critical areas such as quantum information processing and astrophotonics.

INTEGRATED PHOTONICS

Photonics serves as a cornerstone technology, pervasive in modern life, particularly in data communication for its high bandwidth, low energy consumption, and perfect electromagnetic compatibility. It plays an important role also in sensing for remote and extreme condition monitoring. In addition, photonics is also becoming an enabling tool in three-dimensional vision and imaging, as well as in classical and quantum computing. However, conventional discrete optical components are impractical for creating compact and complex devices (Figure 1a). For this task, integrated photonics is the technology of choice, with the fabrication of all necessary components on a monolithic substrate, allowing light to travel through optical waveguides and information to be processed by means of interferometric devices (Figure 1b).

The production of integrated photonic circuits is a mature and expansive field, often utilizing CMOS-compatible processes to benefit from the existing micro and nanoelectronics facilities, enabling cost-effective mass production in materials like silicon or silicon nitride. However, the reliance on these established processes has slowed the broader adoption of integrated photonics. • • •

Large foundries are not incentivized to develop processes for small product batches, hindering the penetration of integrated photonics into new or niche fields. Moreover, standard photolithography-based fabrication is efficient for mass replication but costly and slow for new development, limiting the technology's application in areas where it could offer significant benefits.

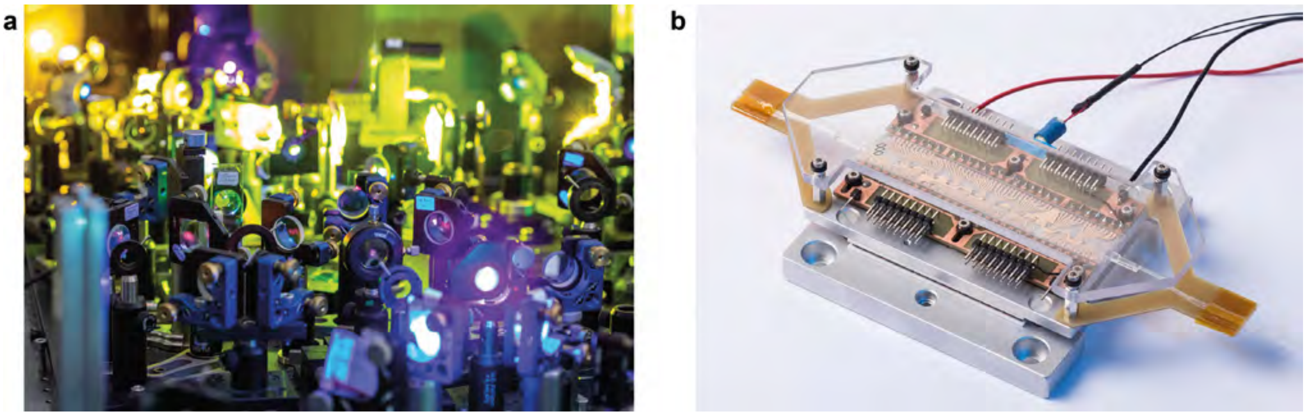
The need for a microfabrication technology that allows for the rapid and economical prototyping of integrated photonic circuits in small to medium volumes is clear. Such a technology exists in the form of direct waveguide writing with ultrashort laser pulses, also known as femtosecond laser writing (FLW). Discovered in 1996 [1], this approach has matured over more than two decades into a dependable industrial tool, now adopted by a growing number of companies. The subsequent sections will provide an overview of this technology, highlighting its several advantages over traditional methods, with a special focus on programmable integrated devices and applications such as quantum information processing [2] and astrophotonics [3].

FEMTOSECOND LASER WRITING IN GLASS

Transparent materials are those that allow light to pass through without absorbing it. Simply put, in a transparent material the energy of the single incoming photons is not enough to overcome the energy gap between the valence and conduction bands and, as a result, photons are allowed to pass right through the material without being absorbed. However, when we focus intense, ultrashort laser pulses inside the same material, the concentration of photons in the focal volume at a given instant of time is high enough to induce multiphoton ionization and other nonlinear processes that cause a localized absorption of a fraction of the impinging photons. On the contrary, outside the focal volume the light spreads out and the probability of triggering such phenomena drops rapidly. As a result, this technique allows for precise and confined modification of the material properties at the microscopic scale. An example of this modification is the local increase of the refractive index in glasses such as borosilicate and fused silica, allowing for waveguide writing by simply translating the substrate with respect to the laser beam. Figure 2a depicts a graphical representation of the FLW process.

FLW is a serial fabrication technique and might not be ideal for mass production compared to photolithography. However, its speed and simplicity make it an attractive option for at least medium-scale production in rapidly evolving areas such as the quantum technology one. The change in the refractive index that can be achieved is modest, so devices are not as miniaturized as they could be with other platforms like silicon or silicon nitride. Yet, FLW stands out by allowing for three-dimensional circuit layouts (Figure 2b-c), compatibility with various materials beyond glass (facilitating the hybrid integration of composite devices) and low-loss connections to standard optical fibers. FLW is only one of the several micromachining processes made possible by the nonlinear interaction of ultrashort laser pulses with transparent materials. Another example is femtosecond laser ablation, which allows for the precise removal of material aimed at creating three-dimensional microstructures as the microtrenches depicted in Figure 2a. Combining FLW and laser ablation, one can enhance the performance of integrated photonic devices, as in the case of programmable photonic integrated circuits [5], which integrate waveguides, electrically programmable interferometers and hollow structures realized to achieve very low levels of

Figure 1. Comparison between bulk and integrated photonics. a) Experimental setup based on discrete optical components such as lenses and mirrors. Courtesy of Mr. Maurizio Contran (Politecnico di Milano) and Dr. Cristian Manzoni (IFN-CNR). b) Integrated photonic circuit encompassing a mesh of 28 programmable interferometers over a set of 8 optical modes. Courtesy of Ephos Inc.



power dissipation during their operation. Like field-programmable gate arrays (FPGAs) in electronics, these devices are programmable for different uses and are key components in more complex photonic systems for a plethora of applications.

UNIVERSAL PHOTONIC PROCESSORS

Integrated photonic circuits become programmable by exploiting various physical phenomena, with thermo-optic phase shifters being the preferred technique for FLW circuits [8]. These devices integrate an electrical circuit atop the photonic structure, where resistive microheaters are placed on the waveguides to be tuned. Heating the waveguides through the microheaters changes the material's refractive index, causing the desired phase shift in the light path. For FLW devices, design must consider shallow waveguides (less than 30 µm deep) for effective thermal interaction and, as already mentioned, thermal insulation to focus heat and minimize power dissipation, with microtrenches and three-dimensional microbridges realized by femtosecond laser ablation being the most common choices in these devices.

A notable class of programmable photonic integrated circuits is represented by the universal photonic processors. These devices are designed to implement an arbitrary optical operation, usually represented as a unitary transfer matrix between the input and output photonic modes, reprogrammable by the user even at runtime. The simplest universal processor encompasses only 2 modes and can be implemented in an integrated fashion by resorting to a Mach-Zehnder interferometer (MZI), made programmable by two thermo-optic phase shifters, one external and one inside the MZI (Figure 3a, top-left inset) . This 2-mode universal processor can act as the basic building block for a rectangular interferometric network, such as the one reported in the rendering of Figure 3a, for multimode operation. FLW universal processors have now reached 6 modes [6], offering a rapid and cost-effective alternative to standard fabrication processes. Figure 3a (bottom-right inset) shows a microscope picture of an MZI column of the processor showing the trenches (dark lines) and the microheaters (thin gold lines in between). Moreover, these devices offer low insertion losses (< 3 dB) over the whole visible range up to the telecom band. and a very high fidelity (> 99.7% on average) between the implemented and the desired optical transformations. Finally, these circuits have the unique property of implementing the same transformation for any polarization state ● ● ●

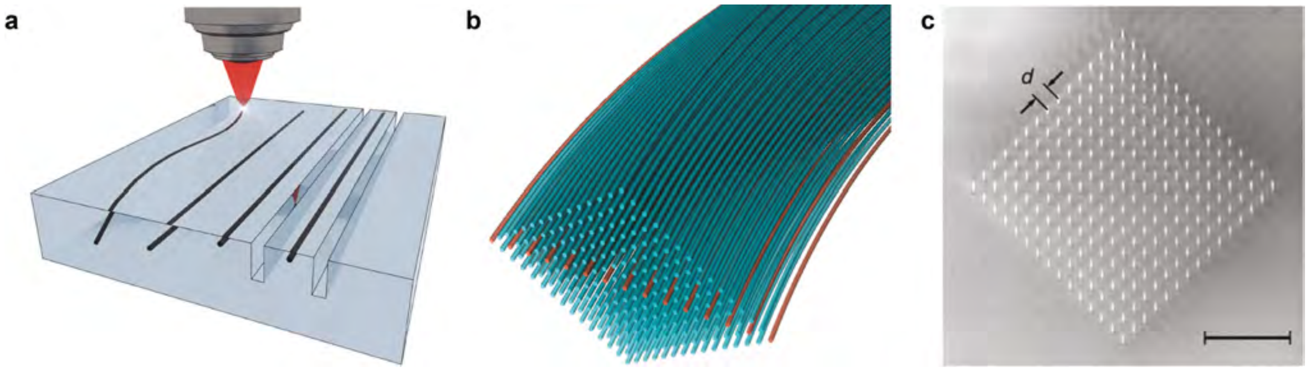


Figure 2. The capabilities of FLW for the realization of integrated photonic devices. a) The illustration shows two key fabrication processes enabled by using femtosecond lasers: the ability to inscribe waveguides in three dimensions and the ablation of material for realizing microstructures such as microtrenches. Reproduced under terms of the CC-BY license from [2]. b) A graphical representation of a three-dimensional waveguide matrix inscribed by using the FLW technology. Adapted from [4]. c) A microscope view of the cross-section of the same waveguide matrix, where the scale bar is 100 µm and the waveguides pitch is d = 19 µm. Reproduced from [4].

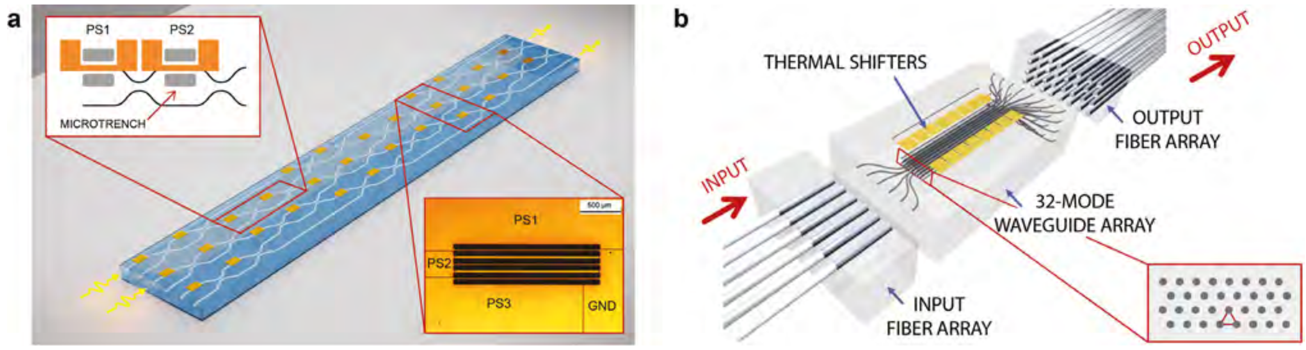
of the input light. This is very useful for processing signals that do not have a fixed polarization.

In terms of scalability, a major goal is to increase the number of optical modes without extending circuit length and thus without increasing losses. Since number of modes and length increase together in MZI-based processors, efforts include compactifying MZI cells and exploiting completely new photonic processor layouts, aiming at improving the scaling law between circuit length and number of modes. Regarding this second approach, Hoch *et al.* [7] recently proposed a novel FLW fabrication strategy based on a three-dimensional continuously-coupled waveguide matrix, including reconfiguration through thermo-optic phase shifters (Figure 3b). This approach promises to break the tradeoff between number of modes and length by moving from a linear scaling law to a square root dependence. A 32-mode processor with 16 heaters was developed and characterized to demonstrate the potential of this design. However, the development of a control algorithm for universal unitary transformations remains a key challenge, with machine learning emerging as a promising solution for these advanced devices.

APPLICATIONS

FLW photonic integrated circuits have a wide range of uses. They are key components in compact systems that merge integrated photonics with

Figure 3. Universal photonic processors and their realization using the FLW technology. a) A 6-mode universal photonic processor based on a planar mesh of MZI cells. Top-left inset shows the schematic layout of an individual MZI of the device with two thermo-optic phase shifters (PS1 and PS2) isolated by microtrenches. Bottom-right inset is a microscope picture of an MZI column of three thermo-optic phase shifters, where it is possible to see the microtrench structures (larger black rectangles), the metal film (orange) and the ablations in the film. PS1, PS2 and PS3 are three contact pads used to independently control the thermo-optic phase shifters, while GND is their common ground. Adapted under terms of the CC-BY license from [6]. e) A 32-mode programmable photonic processor built upon a three-dimensional continuously-coupled FLW waveguide matrix with thermo-optic phase shifters placed atop the device. Fiber arrays are used for light injection and collection in the circuit. Within the highlighted red rectangle, the waveguides are organized into a triangular lattice. Adapted under terms of the CC-BY license from [7].



microfluidics [8], important for analyzing biological samples, and they also play a critical role in realizing low-loss optical interconnects within telecommunications systems [9], linking dense waveguide circuits with fibers that have multiple cores or modes. This discussion will focus on two emerging areas where FLW's distinctive qualities have gained a role of paramount importance: quantum technologies and astrophotonics.

Quantum technologies aim at revolutionizing how we process and communicate data. Amongst the various quantum applications, building a scalable quantum computing system is considered the ultimate goal. This is driven by the potential to solve complex problems, like simulating specific chemical reactions for pharmaceutical development, that current computers cannot handle. Although we have seen significant progress, realizing this breakthrough still seems a distant dream, likely more than a decade away. Therefore, the field has shifted focus to more immediate milestones: proving that quantum devices can outperform classical computers in certain tasks. One such task involves sampling from the distribution probability of numerous identical bosons passing through a multimode linear interferometer, a challenge known as boson sampling. This task, in the specific case of an interferometer lacking any pattern or symmetry, is thought to be beyond the capabilities of classical computers. Photonic particles (Figure 4a) have emerged as the leading option for boson sampling demonstrations due to their relative ease of use in contrast to other quantum computing approaches. In this experiment, FLW has been pivotal, allowing the first practical demonstrations of boson sampling [10]. Today, different studies have demonstrated a quantum advantage, some of them employing photonic boson sampling methods [11, 12]. Although integrated photonic processors are a natural choice for the implementation of an N-mode interferometer, an integrated version of a boson sampling experiment that can achieve the quantum advantage regime has not been realized yet. This is because a large-scale experiment's success requires not just several modes, but also minimal photon losses to maintain a reasonable measurement time. However, as previously noted, expanding the modes while maintaining low losses in an integrated processor is challenging. A significant advancement was made with the FLW three-dimensional photonic processor described in [7], which could achieve 32 modes with only 3.5 dB of photon loss and broad reconfigurability thanks to the 16 thermo-optic phase shifters. With this processor, boson sampling experiments with 3 and 4 photons were successfully validated, proving the potential of FLW devices for large-scale quantum information processing systems.

FLW is also playing a significant role in the field of astrophotonics. This emerging application aims at enhancing the observation of celestial bodies by integrating photonic circuits with telescopes. The use of single mode waveguides for light collection provides spatial filtering which, along with controlled waveguide-to-waveguide interactions, yields interference effects with larger visibility and better scalability than traditional bulk interferometers, thus improving angular resolution for imaging astronomical objects. FLW's glass technology offers several advantages in this regard: it provides single mode waveguides optimized across visible and near-infrared spectra, exhibits low birefringence making devices polarization-transparent, and supports three-dimensional fabrication for stable pupil remapping and efficient beam combining. An example of this is represented by the aperture masking interferometry (Figure 4b), where light on a telescope's pupil plane is sampled and its interference pattern analyzed to reconstruct images. This technique, which offers improved resolution and atmospheric aberration resistance, uses integrated optical waveguides for signal sampling and remapping. The proposed device, *i.e.* a discrete beam combiner (DBC), has been successfully realized and tested thanks to the FLW technology at the William Herschel Telescope [13], demonstrating polarization

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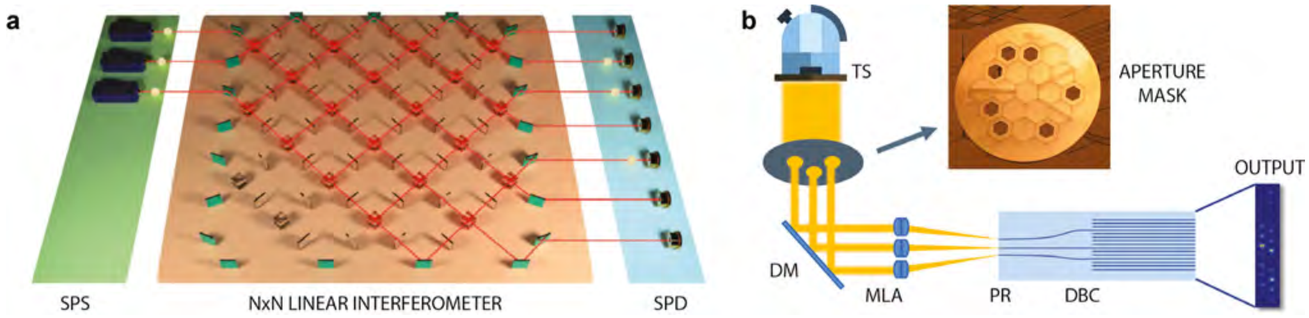

Figure 4. Applications of FLW photonic integrated circuits. a) Artwork of a photonic boson sampling experiment, which includes single-photon sources (SPSs), an N-mode photonic interferometer, and single-photon detectors (SPDs). Reproduced under terms of the CC-BY license from [10]. b) Graphic representation of the aperture masking interferometry system used at the William Herschel Telescope in 2019 for astral observations. This system comprises a telescope (TS), a deformable mirror (DM), a microlens array (MLA), a pupil remapper (PR), and a discrete beam combiner (DBC). To simplify the representation, only three input beams are shown and the circuit's fan-out area is not depicted. Full description of the experiment is reported in [13].

insensitivity and effective light analysis without the need for polarization filtering. Furthermore, DBCs are applied to the coherent combination of light coming from multiple telescopes to enhance angular resolution, simulating a larger synthetic aperture. This technique typically relies on complex interferometers that are difficult to scale. However, a laboratory-tested DBC manufactured by FLW has already shown the potential to combine signals from six telescopes simultaneously in the J band [14], indicating a likely path toward high-resolution astronomical observations.

CONCLUSION AND PERSPECTIVE

Over the past four decades, advancements in photonic technologies, such as lasers and optical fibers, have spurred a revolution across various sectors, including medicine, material processing in industry, and telecommunications. The next step is to integrate all the photonic components into a cohesive platform, which could vastly enhance the capabilities of many innovative applications. Presently, the integrated photonic technology equivalent to the CMOS one in electronics has not been clearly identified yet. Different platforms are emerging to fulfill specific functions within the field, leading also to a growing interest in hybrid integrated platforms. These platforms are particularly appealing for applications that demand the ultimate optimization of the entire photonic system — from the photon source, through the optical circuit, to the detector.

Our projection is that FLW will be critical in this landscape due to its efficient interfacing between photonic components with minimal photon loss and its versatility and adaptability to the rapidly evolving requirements of the applications. FLW photonic integrated circuits are now a commercial reality, bolstering fields like quantum information processing and astrophotonics. This article has highlighted FLW devices that have already been successfully utilized in these areas. Nonetheless, we anticipate that FLW devices have a much broader application potential and, consequently, we foresee that, in the coming years, FLW technology will establish itself as a leading platform in the integrated photonic field. ●

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