Ultrafast-laser-inscribed 3D integrated photonics: challenges and emerging applications

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Abstract: Since the discovery that tightly focused femtosecond laser pulses can induce a highly localised and permanent refractive index modification in a large number of transparent dielectrics, the technique of ultrafast laser inscription has received great attention from a wide range of applications. In particular, the capability to create three-dimensional optical waveguide circuits has opened up new opportunities for integrated photonics that would not have been possible with traditional planar fabrication techniques because it enables full access to the many degrees of freedom in a photon. This paper reviews the basic techniques and technological challenges of 3D integrated photonics fabricated using ultrafast laser inscription as well as reviews the most recent progress in the fields of astrophotonics, optical communication, quantum photonics, emulation of quantum systems, optofluidics and sensing.

1 Introduction

Integrated computer chips are ubiquitous, enabling all our consumer electronics and more. It is less well known that integrated photonic chips also represent a vital part of modern society. Indeed, the Internet is enabled by photonic chips such as arrayed waveguide gratings, optical splitters and Mach–Zehnder modulators that route, split and multiplex optical signals as well as perform the conversion from electrical to optical signals in order to interface with computers. However, whereas the root materials and manufacturing technology for computer chips is mature and well established, the materials and manufacturing methods used to create photonic chips are relatively immature, and the common approach is to adapt the planar (2D) lithography methods originally developed for silicon microelectronics. Unfortunately, this is akin to pushing a square peg into a round hole because photons, the elementary particle of light, have many degrees of freedom, in contrast to electrons which have few. For example, a stream of electrons can be characterised in terms of current and voltage. A stream of photons, on the other hand, can exhibit different traits based on velocity and brightness, the optical equivalent to current and voltage as well as wavelength, polarisation, spatial mode and orbital angular momentum. These additional features reflect the three dimensionality of light, features that cannot be fully exploited with planar circuitry. International concerns regarding the so-called ‘data crunch’, the point where we will run out of data bandwidth [1], is one of many drivers stimulating interest in 3D photonic solutions.

The field of ultrafast-laser-inscribed microphotoniccs originated with the pioneering work of Davis et al. [2] and Glezer et al. [3]. Those seminal studies were quick to recognise the opportunities of this direct-write technique for 3D photonics. In brief, refractive index changes ranging from $10^{-4}$ to $10^{-2}$ and varying in size from a few micrometres to tens of micrometres, can be induced inside different types of glasses when irradiated with the tightly focused output of a femtosecond laser. The magnitude and dimensions of the laser-induced index change are comparable to those of conventional optical fibres. In contrast to optical fibres, this method allows optical waveguides to be written in 3D.

This field has grown significantly in the past 10 years with more than 50 research groups and several commercial enterprises that are currently active in this pursuit. This community has improved the performance characteristics of this fabrication platform to the point that modest propagation losses, typically ~0.1 dB/cm, wavelength versatility [visible to mid-infrared (IR)] and complex architectures are now possible. This capability has triggered a diverse range of applications in classical and non-classical optics, waveguide and fibre lasers, telecommunications, astronomy, bio-photonics and sensing; appli-
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Figure 1: Longitudinal (A) and transverse (B) ultrafast laser inscription. The arrow indicates the sample's translation direction.

Figure 2: Waveguide geometries in glass and crystals. (A) Waveguide with a positive index contrast based on a smooth Type I modification. (B) Depressed cladding waveguide created from partially overlapping Type I modifications surrounding an unmodified core. (C) Stress-induced waveguide in crystals based on two parallel Type II tracks. The guided mode is located in between the two damage lines. The anisotropic stress-field, indicated by the red-dashed lines, typically only guides a single polarization. (D) Depressed cladding geometry based on Type II modifications in crystals.

This paper reviews the fabrication technology and challenges associated with ultrafast laser inscription, in particular the fabrication of 3D lightwave circuits. Recent progress and emerging applications of 3D-integrated photonics, with a particular focus on astrophotonics and optical communication, are discussed. Furthermore, the latest developments in quantum photonics, modelling of quantum systems using waveguide arrays, and optofluidics as well as sensing are presented. The first section gives a general overview and background of ultrafast laser inscription, whilst the second section highlights and discusses the particular challenges faced when fabricating 3D lightwave circuits. The third section introduces the aforementioned applications that benefit from the 3D fabrication capability inherent to ultrafast laser inscription, followed by a conclusion.

2 Background

Ultrafast laser inscription relies on a tightly focused femtosecond laser beam. The sample is placed on computer-controlled motion control equipment to translate it in three dimensions with respect to the focal spot. The sample can either be translated parallel to the laser beam direction, the so-called longitudinal writing, or perpendicular to the laser beam, that is, transverse writing as illustrated in Figure 1. The latter is more commonly used because the maximum device length is not restricted by the working distance of the focusing objective. However, achieving circular waveguides in the transverse writing geometry is more challenging as it is discussed in Section 3.

The high peak intensity at the location of the focal spot during ultrafast laser inscription causes nonlinear optical breakdown of the material. This results in energy deposition, triggering a highly localised structural modification of the substrate. In general, three different types of structural modification can be identified depending on the peak intensity of the femtosecond laser pulse [12]. For low intensities, a smooth refractive index change, referred to as Type I modification is generated [13]. The sign of refractive index change can be either positive or negative. At intermediate intensities, a non-isotropic index change has been observed, resulting in birefringence. The birefringence is caused by self-aligned nanogratings that are perpendicular to the electric field vector of the inscription laser [14]. This type of index change has been observed in fused silica [15, 16], multicomponent silicate [17] and fluoroaluminate glass [18] as well as in a few crystals such as TeO$_2$ [19] and sapphire [20]. These in volume nanogratings should not be confused with laser-induced surface nanostructures. At high peak intensities, optical damage and

Unauthenticated
voids caused by micro-explosions are created [21]. These modifications are referred to as Type II.

Nonlinear optical breakdown can be triggered inside virtually any transparent dielectric, making ultrafast laser inscription exceptionally versatile in terms of material choice. Waveguides have been demonstrated in a multitude of vitreous media, covering the silica, phosphate, heavy metal oxide, chalcogenide and halide glass families [2, 22–26]. These waveguides are mainly based on a single track of smooth, positive refractive index change induced at low peak intensities as shown in Figure 2A. To inscribe high-quality waveguides, the refractive index change does not necessarily need to be positive in sign. Waveguides can also be created using modifications of negative index change by forming a depressed cladding around an unmodified core [27], as illustrated in Figure 2B. Waveguides can also be inscribed in crystalline and ceramic media [28], where typically only optical damage, that is, Type II modifications, can be induced. Thus waveguiding is achieved by creating a stress-field between two damage lines resulting in a waveguide in between [29] (see Figure 2C) or by fabricating a depressed cladding from Type II damages [30], as shown in Figure 2D. Type I modifications have only been observed in a handful of crystals, such as lithium fluoride [31], lithium niobate [32], strontium barium niobate [33], lithium tantalite [34], yttrium aluminium garnet [35], yttrium calcium oxoborate (YCOB) [36] and bismuth germanate crystals [37, 38]. For completeness, it should be noted that ultrafast laser inscription also enables the fabrication of waveguides in polymers [39, 40].

In glasses, the structural modification of the glass network depends on the irradiation condition and the glass itself. In general, two distinctly different modification regimes can be identified, the athermal and thermal regime, as presented in Figure 3. Fabrication in the athermal regime uses a low-repetition-rate pulse train, typically a few kilohertz, and high pulse energies of hundreds of nanojoules up to a few microjoules. Furthermore, low numerical aperture (NA) focusing (NA < 0.6) is used, thus maximizing the vertical real-estate available because of the longer physical working distance of such microscope objectives. In the athermal regime, there is sufficient time between two consecutive pulses, that is, longer than the thermal diffusion time of ~1 μs in glass, for the generated heat to diffuse out of the focal volume before the next pulse arrives [41, 42]. This results in a repetitive, pulse-by-pulse modification of the material. A characteristic of this regime is that the shape of the modified area reflects the intensity distribution of the laser beam. Furthermore, in order to create a continuous smooth waveguide, sufficient spatial overlap between pulses is required, limiting the translation speed to tens of micrometres per second. Hence the fabrication of relatively complex devices can take from a few hours to days, thereby making the process sensitive to environmental influences. In contrast, in the thermal fabrication regime, a high-repetition-rate femtosecond pulse train is used with hundreds of kilohertz to several megahertz repetition rate and a few tens of nanojoules to a few hundred nanojoules pulse energy. The relatively low pulse energy available from high-repetition-rate laser systems requires focusing by high-NA objectives (typically, NA > 1.0) and thereby limiting the vertical real-estate to a few hundred micrometres. In contrast to athermal fabrication, the short period between pulses means that there is insufficient time for the heat to diffuse out of the focal volume before the next pulse arrives. Thus an accumulation of heat occurs causing local melting of the material [42–44]. As the sample is translated, the melt is quenched on a millisecond timescale (depending on the translation speed). Owing to the isotropic heat diffusion, the modifications are of circular cross-section and generally much larger than the size of the focal spot. In the thermal, that is, cumulative heating regime, the samples are translated at speeds of millimetres per second, enabling device fabrication within minutes.

In glasses, the origin of refractive index strongly depends on the inscription parameters and the material itself. For instance, the athermal regime leads to a densification and creation of colour centres in fused silica, resulting in an increased refractive index of the irradiated volume [23]. In contrast, in the multicomponent silicate glass BK7, the increase in refractive index after exposure to low-repetition-rate pulses was attributed to an increase in the polarisability of the glass network. For phosphate glass, an increase in Q1 tetrahedra and the resultant increased polarisability were attributed to the increase in refractive index at low repetition rates [46]. When irradiating phosphate glass with high-repetition-rate pulses, expansion and contraction of the glass network was observed, leading to regions of positive as well as negative index change [47]. This is a result of the migration of elements within the laser-irradiated volume [48], as illustrated in Figure 4. Similarly, when irradiating BK7 in the cumulative heating regime, a densification of the glass network results in an increase in refractive index [45]. Ion migration under high-repetition-rate irradiation is due to temperature gradients within the irradiated volume [49]. The migration of elements can be controlled by tailoring the temperature distribution by simultaneous irradiation with multiple focal spots [50] or astigmatic beam shaping [51]. Improved understanding of the underlying struc-
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Figure 3: (A) Athermal fabrication using a low numerical aperture (NA), long working distance microscope objective. The pulse period which is significantly longer than the thermal diffusion time, results in a repetitive, pulse-by-pulse modification of the material, because there is sufficient time between pulses for the heat to diffuse out before the next pulse arrives. (B) Thermal fabrication regime using a high-NA oil immersion objective with a short working distance. The high laser repetition rate results in cumulative heating, causing melting of the material.

Figure 4: Ion migration due to temperature gradients arising from high-repetition-rate laser (250 kHz) irradiation in 50 CaO - 50 SiO₂ (mol%) glass. The left-hand column shows optical microscope (OM) images of the structures. The corresponding spatially resolved relative concentrations of Ca, Si and O are shown on the right-hand side. (A) Single spot irradiation. (B) Two-spot irradiation with 42.7 µm separation. (C) Two-spot irradiation with 31.9 µm separation. With permission from [49]. Copyright 2011 The Optical Society.

A. Athermal fabrication regime (1 kHz)

B. Thermal fabrication regime (5 MHz)

Figure 4: Ion migration due to temperature gradients arising from high-repetition-rate laser (250 kHz) irradiation in 50 CaO - 50 SiO₂ (mol%) glass. The left-hand column shows optical microscope (OM) images of the structures. The corresponding spatially resolved relative concentrations of Ca, Si and O are shown on the right-hand side. (A) Single spot irradiation. (B) Two-spot irradiation with 42.7 µm separation. (C) Two-spot irradiation with 31.9 µm separation. With permission from [49]. Copyright 2011 The Optical Society.
panel displays, iron impurities cause 0.27 dB/cm absorption losses at 1550 nm, thereby limiting the waveguide transmission [59].

With high-index-contrast waveguides, tighter bends are possible, shrinking the overall size of the photonic chip. The typical femtosecond-laser-induced refractive index changes are in the range of \(10^{-4}\) to \(10^{-2}\) depending on the material and exposure conditions [60–64]. This index contrast is comparable to standard optical fibres, enabling efficient coupling between optical fibres and laser-inscribed waveguides. Overwriting the waveguides several times can lead to an increase in index contrast [2, 65, 66] and thereby reduced bend losses. An alternative approach for reducing bend losses of waveguides inscribed in the cumulative heating regime is to thermally anneal the structures [67]. Unlike removing transient defects for reduction of propagation losses, this step exploits differential thermal stabilities of the different regions within the usually complex structures induced by high-repetition-rate femtosecond pulses in multicomponent silicates. The thermal annealing post-processing step enables the inscription of large high-index-contrast modifications that are initially multi-mode at the design wavelength. Thermal annealing reduces the physical size of the index modification, resulting in a single-mode waveguide with only minor decrease in index contrast. However, the index contrast after annealing is still significantly larger than that of a low-pulse-energy-inscribed single-mode waveguide.

### 3 Fabrication challenges

Ultrafast laser inscription uses tightly focused, high-peak-power femtosecond pulses that have intrinsic fabrication challenges associated with them. The cross-sectional intensity of a tightly focused beam is elliptical, causing non-circular waveguides in the transverse writing geometry, thus lossy coupling to optical fibres. Furthermore, tight focusing into a transparent dielectric suffers from spherical aberrations caused by the refractive index mismatch between the immersion medium (air) and the sample itself. These aberrations are focusing depth dependent and reduce the focal intensity, thus limiting the 3D capability of ultrafast laser inscription. Using high peak power, pulses can trigger Kerr self-focusing if the peak power is beyond a certain value. This distorts the intensity distribution and thus the waveguide shape and can result in a complete spatial collapse of the pulse and the evolution of a filament. Waveguide circularity, spherical aberrations and Kerr self-focusing are discussed in more detail in the following sections.

#### Beam shaping

Circular waveguides and mode-field profiles are essential for low loss coupling between femtosecond laser written waveguides and optical fibres. However, the ratio between the Rayleigh range and waist diameter of a focused Gaussian beam depends on the NA under which the beam is focused and the sample’s refractive index. This is most important for athermal fabrication, whereas isotropic heat diffusion in the thermal regime enables the inscription of circular symmetric structures. In the athermal regime, approximately circular symmetric waveguides can only be inscribed by using high-NA oil immersion microscope objectives (NA > 1.0). These waveguides are micrometre-sized and as such guide visible light in a single mode but do not guide near-IR wavelengths such as the important telecommunication band at 1.5 \(\mu m\). Therefore, sev-
eral methods have been demonstrated to inscribe circular structure when using low-NA objectives. A cylindrical telescope, as shown in Figure 5A, can be inserted before the microscope objective, reducing the beam size in the direction transverse to the waveguide’s axis and thereby increasing the focal spot size in the same direction to obtain a circular waveguide [68, 69]. Alternatively, a slit with the long axis parallel to the waveguide can be used instead of the cylindrical telescope in order to create circular symmetric waveguides [70], as illustrated in Figure 5B and 5C. In either case, if a 90° bent waveguide is required, the cylindrical telescope, slit or the sample itself has to be mechanically rotated in order to preserve the circular waveguide cross section along the bend. Mechanical rotation of optics or the sample can be avoided by imprinting a virtual slit onto a software programmable spatial light modulator (SLM) [71, 72]. The virtual slit also enables dynamic tapering of the waveguides [71]. Also a deformable mirror (DM) can be used instead of an SLM in order to astigmatically shape the laser focal spot [73]. Another popular method to obtain circular mode fields is to use the multiscan technique [58, 74]. Using low-NA focusing and by inscribing multiple elliptical modifications next to one another, a rectangular- or square-shaped waveguide can be created. This method exhibits great flexibility in the waveguide shape at the expense of fabrication speed because of the multiple passes required. Also simultaneous spatial and temporal focusing (SSTF) can be used to create circular symmetric structures [75–77]. SSTF exploits spatio-temporal effects by using a beam that is spectrally dispersed in one direction in front of the focusing objective, as shown in Figure 5D. As the beam is focused, the spectral components only overlap at the focal spot, thus the shortest pulse and hence highest peak intensity is only reached there. Outside the focal plane, the beam is highly chirped, thus reducing the peak intensity. Therefore, the aspect ratio of the laser-induced modifications can be tailored by changing the beam aspect ratio, that is, the amount of spectral dispersion in front of the objective. Unlike astigmatic beam shaping based on a cylindrical telescope or a slit, SSTF enables the inscription of circular modifications parallel and transverse to the spectrally dispersed axis [78]. However, non-reciprocal writing can occur due to the strong pulse front tilt [79].

**Spherical aberrations**

Spherical aberrations are caused by the refractive index mismatch between the sample and immersion medium,
which is air for low-NA objectives or oil immersion in the case of high-NA immersion objectives. Spherical aberrations result in a distortion of the focal spot, that is, an increased focal spot size and an axial elongation, as illustrated in Figure 6A. The amount of aberration depends on the magnitude of refractive index mismatch, the focal depth and focusing NA [80]. The aberrations increase with focusing depth, causing a depth-dependent peak intensity and thus an increased laser pulse energy threshold for material modification [81]. High-NA objectives are strongly affected by spherical aberrations compared to low-NA objectives [82], as shown in Figure 6B. Thus without compensation, the properties of the inscribed waveguides become highly depth dependent, that is, their size, shape and index contrast changes. Insertion of a cylindrical telescope or slit not only supports fabrication of circular waveguides but also reduces the effective focusing NA, thereby reducing the susceptibility to spherical aberrations. This has been exploited to fabricate circular waveguides up to 7 mm deep in fused silica in the athermal regime [83]. Similarly, low-NA focusing can also be exploited in the thermal regime, where high-NA objectives are commonly used to extend the depth over which high-quality waveguides can be inscribed [42]. In general, the waveguide shape in the thermal regime is less sensitive to spherical aberrations as long as enough energy can be deposited in the substrate to cause cumulative heating. For substrates with a refractive index close to \( n_0 = 1.518 \), oil immersion objectives can be used for mitigating the influence of spherical aberrations. However, oil immersion objectives are limited to a physical working distance of a few hundred micrometres. Alternatively, the laser power can be elevated with increasing depth in order to keep the deposited energy roughly constant as a function of depth [84, 85]. Whilst these two approaches can moderate the influence of spherical aberrations, a complete compensation can be achieved by using an SLM or a DM with the conjugate phase pattern of the spherical aberrations imprinted [86–88], as presented in Figure 6C&6D. Moreover, an SLM or a DM can be used to compensate for the aberrations present in the beam delivery optics. This can be accomplished by sensing the plasma emission during the inscription process and using a feedback loop to optimise the plasma brightness whilst applying different Zernike polynomials [87]. A Shack–Hartman wavefront sensor can also be placed before the focusing objective to measure the system aberrations and feed the conjugate back onto the SLM [89]. The magnitude of spherical aberrations an SLM or DM can correct for depends on the pixellation and phase wrapping or mechanical stroke and maximum phase gradient, respectively [90]. Imaging a circular aperture of 500 pixels diameter from an SLM onto the back aperture of a 0.5 NA objective enables diffraction limited focusing across a depth of 10 mm in fused silica at a laser wavelength of 790 nm [91]. However, the maximum correction depth rapidly drops because of phase wrapping. At 0.95 NA and otherwise identical conditions, the maximum depth reduces to 120 μm. SLMs cannot only be used for aberration compensation but can also provide an effective means for parallel processing. Using a computer-generated hologram, multiple foci can be positioned in three dimensions [92, 93]. This enables the single-sweep writing of several waveguides [94–97] or the inscription of multiscan waveguides in a single pass [98].

Kerr self-focusing

Self-focusing occurs because of a non-permanent local refractive index change self-induced by the laser field as a result of the 3\(^{rd}\)-order nonlinearity (Kerr nonlinearity) of the medium. The nonlinear nature of the process makes it difficult to control and thus the waveguide inscription challenging [24, 99]. It can distort the waveguide shape [26] or even entirely inhibit waveguide formation [100, 101]. The Kerr nonlinearity results in an intensity-dependent refractive index change that follows the spatial intensity profile of the laser. A Gaussian intensity profile results in the evolution of a positive or negative lens, depending on the sign of the nonlinear refractive index. In the femtosecond laser direct-write regime, the nonlinear refractive index is usually positive for most materials. With sufficiently high intensities, the light can be confined in a self-trapped state, where diffraction and self-focusing are precisely balanced. This is predicted to occur when the peak power of the incident beam is above the critical power for catastrophic self-focusing [102]. The critical power for self-focusing in fused silica at 800 nm is 2.4 MW. For a sech\(^2\) pulse with 100-fs FWHM (full-width at half maximum) pulse duration, this corresponds to a pulse energy of 270 nJ. Highly nonlinear materials such as chalcogenide glass exhibit significantly lower thresholds. The critical power for self-focusing also depends on the polarisation, circular polarisation has a 50% higher critical power than linear [102]. Furthermore, the critical power increases with increasing beam ellipticity [103]. As a beam self-focuses within a nonlinear medium, the peak intensity increases; hence, free carriers are being created by photoionisation, which counteracts the self-focusing effect [104]. The evolving plasma alters the refractive index and acts as a defocusing lens. This effect can clamp the plasma well below the critical density where catastrophic damage of the material occurs [105],...
therefore enabling the fabrication of waveguides based on filaments without material damage when using the longitudinal writing geometry. However, for self-trapping of the laser beam over a length of several millimetres, the incident peak power needs to be significantly larger than the threshold for critical self-focusing. The length and threshold for a filament depends on the focusing conditions [106]. Loose focusing shows larger thresholds but results in longer filaments [107]. Nevertheless, even for powers below the threshold, the influence of self-focusing is observable. Reductions in focal spot sizes of 6, 10 and 20% for 0.65, 0.45 and 0.25 NA focusing in borosilicate glass have been reported [108]. This leads to nonlinear break-down occurring before the geometric focus. Self-focusing is negligible for 1.0 and 1.4 NA focusing, because the bulk damage threshold is reached well below the critical power for self-focusing [108]. However, the 3D capability is limited by the short working distance of high-NA objectives. In order to mitigate the influence of nonlinear propagation effects, chirping the laser pulses to a few hundred femtoseconds up to a few picoseconds has been shown to be an effective means for the inscription of waveguides in highly nonlinear media such as lithium niobate [109], zinc selenide [100] and chalcogenide glass [101]. Moreover, complex temporal pulse envelopes can be used to spatially optimise the energy deposition, thereby simultaneously compensating for spherical aberrations and nonlinear pulse propagation [110]. Nonlinear propagation effects can be minimised by using diffraction limited focusing, that is, compensation for spherical aberrations using an SLM. This minimises the required peak power in order to reach the threshold intensity for material modification at the focal spot to below the critical power for self-focusing. As a result, the fabrication of structures with a small axial cross section even in a high band-gap and highly nonlinear material such as diamond is possible [111].

4 Applications

4.1 Astrophotonics

The field of astrophotonics aims at applying photonic technologies to astronomical instruments [112]. Compared to bulk optical instruments, photonic instruments are more compact and environmental stable, and they offer the potential for mass production and thereby are more cost efficient. Photonics enable new capabilities such as low loss multi-mode to single-mode conversion using a device called a photonic lantern. Fibre Bragg gratings can be used as narrow-band spectral filters to remove unwanted background. Single-mode waveguides are efficient spatial filters and can be used to sample the telescope’s pupil and remap the light for stellar interferometry. Furthermore, photonics enable high-fidelity on-chip interferometric processing of stellar light.

Early on, the astrophotonics community realised the potential of 3D-integrated photonics enabled by ultrafast laser inscription [113]. This allowed the fabrication of on-chip photonic lanterns, which are inherently 3D devices. Remapping for stellar interferometry requires stringent optical path length matching between waveguides, a task that strongly benefits from the added flexibility of the third dimension. Interferometric processing requires cascades of splitters, thus by having access to an additional spatial dimension, compact beam combiners can be created.

Stellar photons are sparse. Therefore, a key requirement of ultrafast laser written devices for astronomy is low loss. Furthermore, low-waveguide birefringence as well as a broad operational bandwidth is desirable, in particular for interferometry.

Integrated photonic lanterns

The advent of the next generation of astronomical telescopes will enable astronomers to look at fainter objects and peer deeper into space than ever before. These so-called extremely large telescopes (ELTs) are vastly larger than any previous telescope with primary mirrors of the size of a tennis court. However, this means that astronomical instrumentation is facing significant challenges, because the size of the instruments increases proportional to the size of the telescope’s primary mirror. This is in particular true for astronomical spectrographs. The increased size makes these instruments extremely costly to build and results in demanding mechanical and optical requirements in order to achieve the necessary stabilities [114]. A photonic lantern is an adiabatically tapered transition from a multi-mode waveguide to a number of single-mode waveguides [115–117]. The motivation for using this device in astrophotonics is its capability to transform multi-mode light as received from the telescope into multiple single-mode outputs, where a linear arrangement of the inputs can be used to form a virtual input slit of a spectrograph. This enables the use of single-mode, that is, diffraction limited, spectrographs in order to resolve the light emitted from stars for gaining information on their chemical composition, age and radial velocity. Compared to their multi-mode counterparts, single-
mode spectrographs are smaller and thus considerably more cost efficient to build whilst maintaining the same spectral resolving power [114]. Furthermore, because the star light is carried in single-mode optical fibres, other photonic technologies can be applied, such as fibre Bragg gratings for narrow-band spectral filtering of detrimental background light. This has been successfully applied to suppress 148 bright emission lines arising from hydroxyl groups in our Earth’s atmosphere [118]. However, fibre-based photonic lanterns are difficult to scale to higher number of single-mode fibres and are labour intensive to fabricate. The inherent 3D nature of a photonic lantern makes them attractive for the fabrication using ultrafast laser inscription. Thomson et al. was the first to demonstrate a laser-inscribed photonic lantern with 16 ports [6], as shown in Figure 7. Laser inscription requires careful optimisation of the multi-mode section of the lantern in order to achieve low losses [119]. With optimised design of the length as well as the shape of the tapered transition, a multi-mode to slit reformatting integrated photonic lantern can achieve 95% efficiency at a wavelength of 1550 nm excluding the glass absorption losses [120]. Furthermore, the combination of laser written photonic lanterns with Bragg gratings for potential narrow-band filtering in a single, compact, integrated device was first demonstrated by Spaleniak et al. [121]. In principle, the number of single-mode channels that can be fabricated using ultrafast laser inscription is only limited by the available vertical real-estate, because the individual waveguides need to evenly fan out in the transition region. Even though photonic lanterns can directly receive light from an astronomical telescope, it has been shown that by using adaptive optics to dynamically correct for atmospheric turbulences, a significant improvement in coupling efficiency can be achieved [122]. Besides astronomy, photonic lanterns have also found application in optical communication, which will be discussed in detail later in the text.

**Pupil remapping**

So far, the majority of extra-solar planets have been detected using indirect techniques, such as radial velocity and transit detection [123]. However, they require observation of the target over a prolonged period of time, and they cannot resolve planets with arbitrary orbital orientations with respect to the observer. The inherent aberrations caused by the Earth’s atmosphere make terrestrial direct imaging of exoplanets challenging and complex adaptive optics systems are required to dynamically compensate for the aberrations to regain the diffraction limit of the telescope. An alternative technique to imaging at the diffraction limit, regardless of the Earth’s atmosphere, is aperture masking interferometry, where a hole mask is placed in the telescope’s pupil [124]. This creates a complex interferogram in the image plane of the telescope instead of an image of the star. From this interferogram, a powerful observable called closure phase can be retrieved in order to reconstruct the image. Closure phase is insensitive to the atmosphere-induced aberrations, and therefore, diffraction-limited imaging is possible without the need for adaptive optics. However, the aperture mask blocks the majority of the star light, and residual atmospheric aberrations across the holes of the mask cause instabilities in the interferogram. Therefore, it was proposed to use single-mode optical fibres or waveguides arranged in a 2D pattern at the input, similar to the holes in an aperture mask, in order to sample the pupil of the telescope and re-arrange those waveguides/fibres into a linear array [125]. The linear array enables the retrieval of phase information (fringes) as well as spectral information by dispersing the light in the perpendicular direction with respect to the array. This is not possible with an aperture mask. By using single-mode fibres or waveguides, the injected light is spatially filtered because only a plane wavefront can propagate in the waveguides, thus improving the fringe visibility. Additionally, unlike an aperture mask, the entire telescope’s pupil plane can be potentially sampled by the waveguides, resulting in a great improvement in throughput. The challenge of using optical fibres for this purpose is the requirement for precise optical path length matching between the individual fibres. A 3D waveguide architecture benefiting from the inherent stability of the in-bulk embedded waveguides created by ultrafast laser inscription...
is an elegant solution for this challenge. An instrument called DRAGONFLY was first to use the 3D waveguide approach and was also the first demonstration of stellar light captured by an astronomical telescope (3.9 m Anglo Australian Telescope) being injected into an ultrafast-laser-inscribed optical chip [10]. The 3D waveguide chip contained eight waveguides to sample the telescope’s pupil and remap the light via a side step into a linear array at the output, as shown in Figure 8. The side step was necessary in order to suppress background light that was not injected into the waveguides from otherwise interfering at the output and thereby causing a reduction in closure phase stability [126]. In order to design 3D path-length-matched waveguides, a novel algorithm was developed. The algorithm takes the limitation of the fabrication process such as accessible vertical real-estate, bends losses as well as minimum distance between waveguide to mitigate cross-coupling into account and creates an optimised waveguide layout with path length matching to within 100 nm [127]. Whilst the first generation of pupil remapping chips suffered from low throughput caused by bend losses [10], improved fabrication exploiting thermal annealing [67] vastly increased the transmission as well as closure phase stability [126].

**Beam combining**

In long baseline interferometry, using light from multiple telescopes, as well as aperture masking based on pupil remapping where light from multiple sub-apertures of a single telescope is used, the captured star light has to be interferometrically combined in order to retrieve phase information [128]. Performing this task in planar beam combiners, it has been shown that fringe visibility and closure phase can also be retrieved by injecting light into a 2D array of evanescently coupled waveguides [133]. This approach potentially offers scalability to a large number of inputs in a compact chip [134]. However, dispersion of the output in order to recover spectral information is challenging because of the 2D arrangement of waveguides instead of a linear array [135]. Furthermore, the beam combiner is sensitive to non-uniform and polarisation-dependent coupling in the array [135].

**4.2 Optical communication**

The backbone of all global Internet communication is the optical fibre. Currently, 80 exabytes of data are transferred across optical fibres every single day [136]. This corresponds to transferring every 5 minutes the gigabyte equivalent of all movies ever made. Owing to the basic human desire to communicate, the Internet data demand is exponentially increasing. By 2018, the total Internet data demand is projected to triple with respect to 2013. However, there is a fundamental limit to how much data can be carried across currently deployed single-mode optical fibres, the nonlinear Shannon limit [137]. This limit is caused by optical nonlinearities and is intrinsic to the fibre design and material. As a result, new technologies are required to further scale the transmission capacity and avoid the capacity crunch. The most promising technology is space-division multiplexing [1, 138]. The basic idea of space-division multiplexing is to either have multiple single-mode cores within a common optical cladding or to use few-moded optical fibres. In both cases, the transmission capacity scales proportional to the number of single-mode cores or number of modes supported by the few-moded optical fibre, respectively. Furthermore, space-division multiplexing brings significant improvements in cost per bit as well as energy efficiency because of a reduction in the number of individual components in optical communication systems compared to individual single-mode fibres [1, 139].

In both space-division multiplexing concepts, the use of fibres with multiple single-mode cores, that is, multicore fibres (MCFs), or the use of individual modes of few-moded optical fibres, that is, mode-division multiplexing, inherently benefit from 3D-integrated optics. In the case of MCFs, the individual cores need to be re-routed...
into a linear array in order to interface them with lasers, optical modulators or arrayed waveguide gratings. Similarly, mode-division multiplexing of rotationally asymmetric linearly polarised (LP) modes requires 3D waveguides [140]. Also optical angular momentum (OAM) beams can be used for mode-division multiplexing [141]. This approach is in particular attractive for free-space optical communication with a recent demonstration of using a hybrid 3D photonic circuit for multiplexing and demultiplexing of different OAM beams [7].

Multicore fibre fan-out

The 2D cross-sectional arrangement of the cores in an MCF requires 3D-integrated photonics in order to bring the cores into a linear array for interfacing the fibre with typical planar optical communication components. Microoptic [142] and fused fibre fan-in/fan-out [143] devices have been demonstrated. However, they are limited to small numbers of cores as well as in the flexibility of the geometric arrangement of the individual cores. Thomson et al. successfully demonstrated a four-core MCF fan-out device that takes the 50 μm-spaced cores arranged in a square and reformats them into an linear array with 250 μm pitch to match a commercial fibre V-groove arrays [144]. The work was followed up with fan-out device for a 120-core MCF [145]. Even though both suffered from insertion losses between 5 and 7 dB at a wavelength of 1550 nm, subsequent optimisation of the inscription process resulted in the commercial availability of devices with insertion losses on the order of 1 dB [146].

Mode-division multiplexers

The challenge of mode-division multiplexing using few-moded optical fibres is the selective excitation and detection of individual modes. Mode-multiplexing has been demonstrated using phase-plate and liquid crystal SLMs [147, 148]. Being based on bulk optics means that these setups are lossy, take up a large footprint and in the case of SLMs even require electrical power and exhibit strong polarisation sensitivity. Ideally, a mode multiplexer...
should be compact, entirely passive and compatible with few-mode fibres; operate over a broad wavelength band; and exhibit low insertion and mode-dependent losses as well as feature mode selectivity. Low insertion losses increase the transmission span length without the need for optical amplification, low mode-dependent losses maximise the transmission capacity [149] and mode selectivity reduces the electronic single processing complexity [150]. These requirements can be met by photonic lanterns, mode-selective directional couplers [151] and mode-selective tapered velocity couplers [152]. Photonic lanterns can simultaneously multiplex a large number of modes [153]. However, uniform lanterns do not exhibit mode selectivity, that is, light injected into one single-mode port will couple into multiple modes at the few-modeled output. This modal cross-talk has to be unravelled using multiple-input multiple-output (MIMO) signal processing. Nevertheless, a 255 Tbit/s optical link over a seven-core two-mode few-moded MCF has been demonstrated by using a 2D array of ultrafast-laser-inscribed photonic lanterns [154] for mode multiplexing and as MCF fan-out [155], as illustrated in Figure 9. In order to achieve mode selectivity in a photonic lantern, asymmetry has to be introduced. This breaks the degeneracy at the single-mode ports by using single-mode fibres of different propagation constants as demonstrated in a fibre lantern [156, 157] and recently in a laser-etched lantern [158]. Using ultrafast laser inscription, asymmetry can simply be introduced by either writing waveguides of different size or by varying the index contrast via adjusting the laser power. In contrast, mode selectivity in a fibre lantern requires many different single-mode fibres that can be limited by the commercial availability of suitable fibres. In order to minimise mode-dependent losses, the geometric arrangement of the individual waveguides in the tapered transition region has to match the symmetry of the LP modes [153]. Furthermore, the interface between the photonic lantern and the few-moded transition region can cause mode-dependent losses arising from the mode mismatch between the lantern and the fibre. Fibre tapering can be used to reduce the coupling and mode-dependent losses between an ultrafast-laser-etched photonic lantern and a few-moded graded index fibre [159].

A mode-selective directional coupler is an asymmetric directional coupler based on a few-moded waveguide and a single-mode waveguide, where the propagation constant of the single-mode waveguide matches the propagation constant of the particular higher order mode in the few-moded waveguide. Whilst maintaining phase matching and with appropriate choice of the interaction region length, full power transfer between the modes can be achieved. Precise geometric arrangement of the waveguides is essential in order to multiplex and demultiplex both orientation states of rotationally asymmetric LP modes [140]. Ultrafast laser inscription enables the inscription of the auxiliary cores at arbitrary positions tailored for particular higher order modes. Thus, compact mode multiplexers, as shown in Figure 10, with > 10 dB power transfer to the LP_{11} mode, low insertion losses, and operating across the entire telecommunication C-band (1525–1575 nm) can be realised [160], as shown in Figure 10. By varying the length of the interaction region or the waveguide spacing, arbitrary tap-off couplers can be fabricated. Furthermore, a linear cascade of mode-selective directional couplers can be created to multiplex a large number of modes, which in practice is only limited by insertion losses. However, because of the requirement for precise phase matching, the devices are inherently sensitive to day-to-day variations of the inscription parameters.

Mode-selective tapered velocity couplers are similar in their geometry to mode-selective directional couplers. However, the few-moded waveguide is up-tapered in the interaction region and the single-mode waveguide is down-tapered [161]. Because of the opposing taper directions, such a device is difficult to realise in fibre. For multiplexing a particular higher order mode, phase matching somewhere in the middle of the interaction region between the fundamental mode in the single-mode waveguide and the particular higher-order mode of the few-moded waveguide is necessary. If the two waveguide are sufficiently close, strong coupling and nearly 100% power transfer occurs. Unlike directional couplers, phase matching over a prolonged distance is not required, but the adiabatic tapers have to be sufficiently slow for full power transfer between the waveguides. As a result of the tapers, the devices are insensitive to day-to-day changes in in-
scription parameters. Furthermore, they can operate over a broad wavelength band. A 3D laser-inscribed tapered velocity coupler has been shown to operate over a 400-nm-broad wavelength band with 20 dB coupling into the \( \text{LP}_{11} \) mode [11]. Moreover, the device exhibits high mode purity in excess of 20 dB and low cross-talk. Tapering of the waveguides was accomplished by changing the laser power during sample translation. Similar to directional couplers, a linear chain of tapered couplers can be used to increase the number of addressable modes. However, their footprint is in general larger because of the slow taper. In comparison to ultrafast-laser-inscribed photonic lanterns, the output of the mode-selective couplers is a single few-moded waveguide instead of several partially overlapping single-mode waveguides. Therefore, low coupling losses to few-moded fibres can be achieved.

Like the LP modes, OAM can also be used as an orthogonal basis set of modes for mode-division multiplexing in order to scale the transmission capacity of fibre as well as free-space communication links [141]. An OAM beam exhibits a helical phase front, where the OAM order is the number of \( 2\pi \) phase shifts in a circle around the beam axis. OAM beams of different orders are orthogonal and can propagate coaxially, which is exploited to create individual data channels. The order can be positive as well as negative. The helical phase front has a singularity in the centre resulting in an OAM beam’s characteristic doughnut-like intensity shape. OAM beams can be generated, for instance, using spiral phase-plates, q-plates or holograms, and spatially overlapped using a set of beam splitters. Alternatively, multiplexing can be accomplished using an optical geometrical transformation [162]. However, all these concepts rely on bulk optics. An integrated optic OAM multiplexer and demultiplexer based on a hybrid photonic chip was demonstrated by Guan et al. [7]. The device uses a silica planar lightwave circuit with a free propagation region to create a linear phase tilt across a linear array of 16 waveguides, as shown in Figure 11. The 16 waveguides are coupled to a ultrafast-laser-inscribed 3D photonic chip that reforms the waveguides into a circle of 204 \( \mu \text{m} \) diameter with 40 \( \mu \text{m} \) waveguide spacing whilst maintaining identical optical path length within 40 \( \mu \text{m} \). The circular array of waveguides efficiently samples the incoming OAM beam, and sorting of the OAM orders is performed by the free-propagation region. Similarly, the waveguides can act as a synthetic aperture for the generation of OAM beams of different orders.

### 4.3 Other

#### 3D quantum photonics

Integrated optics overcome many of the stability and scalability shortcomings of bulk optical quantum architectures [163, 164]. As it was demonstrated that ultrafast-laser-inscribed couplers can perform on par with lithographic ones for path-encoded [165] and polarization-encoded qubits [166], ultrafast laser inscription has received considerable attention from the quantum community [167]. Moreover, unlike lithography, ultrafast laser inscription is a maskless fabrication process, thereby enabling rapid prototyping of quantum circuitry as well as enabling access to the third dimension. The third dimension has been exploited to observe continuous quantum random walks in an elliptical waveguide array [8], showing the feasibility of emulating quantum systems in such a structure. A 2D “Swiss cross” waveguide geometry with high-visibility two-photon quantum interference has been shown to exhibit a composite behaviour of path entanglement and distinguishability, a direct result of the 2D waveguide array [168]. 3D photonic circuitry has been exploited for the generation and verification of single-photon W-states, a robust quantum superposition state that features a uniform photon distribution across multiple modes [169]. Non-classical three-photon interfer-
ence has been observed in 3D three-waveguide splitters for quantum interferometry and metrology [170, 171]. Indeed, a 3D three-path laser written interferometer has been shown to exhibit enhanced phase sensitivity by using non-classical photons, thus potentially enabling highly sensitive metrology [172].

Physics in 2D waveguide arrays

Arrays of evanescently coupled waveguides have been widely exploited as models for quantum mechanics, enabling the observation of quantum phenomena using classical optics in the linear as well as the nonlinear regime [173, 174]. The light propagation in a waveguide array is analogous to the evolution of particle wavefunctions, thus tuning of diffraction and dispersion of a waveguide array can be used to emulate a particular quantum system. The waveguide arrays enable the straightforward implementation of artificial defects, and external potentials can be introduced by curving the waveguides. Of importance in these 2D waveguides arrays is uniform coupling across an extended depth range as well as precise control over directional evanescent coupling between waveguides [175]. Self-imaging has been demonstrated in segmented 2D square waveguide arrays [176]. Furthermore, spatial solitons and nonlinear localisation has been observed when injecting high peak power pulses into one of the waveguides [174]. This has applications in all-optical switching and routing [177]. The biphoton generation, that is, the generation of entangled photons via spontaneous parametric down conversion, has been modelled in a square waveguide arrayed using classical optics [178]. By removing every second waveguide in every second row of a square array, a photonic Lieb lattice can be created. A Lieb lattice exhibits two linearly dispersing intersecting bands as well as a flat-band intersecting between waveguides [175]. The biphoton generation, that is, the generation of entangled photons via spontaneous parametric down conversion, has been modelled in a square waveguide arrayed using classical optics [178]. By removing every second waveguide in every second row of a square array, a photonic Lieb lattice can be created. A Lieb lattice exhibits two linearly dispersing intersecting bands as well as a flat-band intersecting between waveguides [175].

Optofluidics and sensing

Optofluidics, that is, the integration of waveguides and microfluidics, has been enabled by the fact that a femtosecond laser cannot only be used for the inscription of waveguides but can also to create 3D microfluidic channels and micro-optics via a process called femtosecond laser irradiation followed by chemical etching (FLICE). The fabrication of channels takes advantage from the increased chemical etch rate of photosensitive glass [188] or fused silica [189] after exposure to femtosecond pulses. In the case of a photosensitive glass, such as Schott Foturan, the increased etch rate results from the formation of metasilicate crystallites initiated by the laser irradiation. These crystallites exhibit a preferable solubility in hydrofluoric acid (HF) [188]. In contrast, irradiation of fused silica with a linearly polarized femtosecond laser results in the formation of nanogratings, thus increasing the etch rate of the glass because of diffusion of the etchant into the nanocracks when immersed in HF or potassium hydroxide (KOH) [190].

Crespi et al. integrated a 3D waveguide Mach–Zehnder interferometer into a commercial microfluidic chip as well as an entirely femtosecond-laser-fabricated microfluidic chip [191]. One arm of the interferometer orthogonally crosses the microfluidic channel and the other arm passes over the top of the channel. This enabled the highly sensitive detection of refractive index changes within the analyte. 3D waveguides can also be used for the excitation and collection of fluorescence within microfluidic channels. It has been shown that a 2D waveguide array can enhance the fluorescence collection efficiency [192]. The femtosecond laser fabrication of microfluidic and optofluidic sensors has been reviewed in [193, 194]. Furthermore, it has been the topic of a recent book [195].

Ultrafast laser inscription doesn’t necessarily require a planar substrate. Waveguides and microfluidic components can also be fabricated within the cladding of an optical fibre. Lee et al. demonstrated a three-dimensional bend sensor inscribed into a coreless optical fibre with 125 µm diameter [196]. The sensor consists of a 1 × 3 splitter connecting three groups of three waveguide Bragg gratings each. Each group is located at a different vertex of a right-angled isosceles triangle placed off-centre within the fibre. With two groups aligned orthogonal with respect to each other and one placed in the centre of the fibre, accurate measurement of the fibre bend radius and the sensor’s azimuthal angle was possible after calibration of the tem-
Figure 12: Lab-in-fibre concept, combining 3D waveguides with microfluidics within a 125 µm diameter optical fibre to create compact sensors. The through hole can be used for fluorescence detection and absorption spectroscopy. The fibre Bragg grating enables temperature and strain measurements. The Fabry-Perot interferometers (FPI) facilitate refractive index and pressure sensing, and the total internal reflection (TIR) 45° mirror acts as light tap or cladding mode stripper. With permission from [197]. Copyright 2014 The Royal Society of Chemistry.

Moreover, other building blocks, such as Fabry–Perot interferometers, microfluidic reservoirs and channels, through holes, waveguide X-couplers and 45° turning mirrors can be integrated into optical fibres using ultrafast laser inscription. This enables intricate and highly compact lab-in-fibre sensors with a variety of functionalities, such as fluorescence detection, absorption spectroscopy, temperature and strain measurement as well as refractive index and pressure sensing [197].

5 Conclusion

Ultrafast laser inscription has an unprecedented versatility in the choice of substrate materials for waveguide fabrication, ranging from vitreous to crystalline media up to polymers. A change in substrate doesn’t require a change in the fundamental process but only an adjustment and optimisation of the processing parameters such as laser repetition rate, pulse energy, translation speed and focusing condition. This versatility in combination with the rapid prototyping capability has made ultrafast laser inscription tremendously attractive for a large variety of applications. However, it is the ability to create 3D waveguide circuits that has transformed thinking. As an example, the optical communication community, which has pioneered the development of planar lightwave circuits, is now looking at 3D integrated photonics enabled by ultrafast laser inscription. In order to capitalise on the full 3D real-estate, several fabrication challenges have to be faced, such as the compensation for spherical aberrations during focusing as well as managing nonlinear propagation effects caused by the Kerr nonlinearity of the substrate material. Improvements in the fabrication process have enabled the inscription of novel 3D lightwave circuits, such as efficient multi-mode to single-mode converters for astronomical spectographs as well as telescope pupil remappers and beam combiners for stellar interferometry to detect exoplanets. Moreover, low loss fan-in and fan-out circuits to interface with multicore optical fibres, intricate mode converters and OAM beam generators for space-division multiplexed optical communication have been demonstrated. Two-photon interference and quantum walks have been shown in 3D circuits as well as highly sensitive quantum metrology. Furthermore, 2D waveguide arrays have been used to study complex quantum systems such as graphene, and the versatility of ultrafast waveguide processing has been exploited to integrate microfluidic channels and 3D waveguides not only on chip but also directly into the cladding of an optical fibre.

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References


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[129] Li G., Bai N., Zhao N., Xia C., Space-division multiplexing: the next frontier in optical communication, Adv Opt Photonics 2014; 6:413.


