Photonic device fabrication using ultrafast laser waveguide inscription

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Recent advances in ultrafast laser waveguide inscription significantly increase its potential for fabricating novel 2D and 3D lightwave circuits.

Lightwave circuits (LCs) are the optical equivalent of electronic integrated circuits. However, instead of using thin metallic wires to control the flow of current, LCs use the principle of total internal reflection to guide light along micron-scale dielectric waveguides. Using such waveguides, complex optical circuits can be constructed to perform multiple functions on an input optical signal.

Currently, most LCs are fabricated using approaches that rely on photolithography to define the waveguide regions. Such techniques are expensive for device prototyping and do not lend themselves to 3D device fabrication. Recently, a new fabrication route using ultrafast lasers has attracted significant interest. By focusing femto- and picosecond pulses of sub-bandgap radiation inside a dielectric material, optical energy can be deposited in the focal region by nonlinear absorption. The deposited energy can modify the refractive index of the material at the focus, which can then be used to fabricate optical waveguides. This is done by translating the material in three dimensions through the focus, as shown in Figure 1.

Our efforts in this field are directed at fabricating broadband optical amplifiers and nonlinear optical devices. In our optical amplifier work, we have fabricated waveguides in two types of active glass: Bi-doped silicate\(^1\) and Er-doped oxyfluoride-silicate, both supplied by Animesh Jha’s group at the University of Leeds. To fabricate these waveguides, we have used the recently demonstrated ‘multiscan’ fabrication technique to control the waveguide cross-section and the refractive index contrast independently.\(^2\) The multiscan technique uses many successive scans of the sample through the focus to construct the desired waveguide cross-section from the individual lines of the modified material created by each scan, as illustrated in Figure 2.

Our Bi-doped glass work demonstrated the successful fabrication of low-insertion-loss waveguides and—significantly—ultra-broadband fluorescence emission with an FWHM (full-width half-maximum) of over 500nm centered at 1.3\(\mu\)m under optical pumping.\(^1\) An optical amplifier that shows such a large bandwidth in the 1.3\(\mu\)m region has great potential for telecommunications applications. Experiments are under way to characterize the gain operation of these waveguides.

As a result of our Er-doped glass work, we demonstrated, for the first time, internal gain from an Er-doped oxyfluoride-silicate glass waveguide.\(^2\) Figure 3(a) shows a micrograph image of the

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multiscan fabricated waveguide facet after polishing. Figure 3 also compares the near-field images of the 1550nm mode obtained from the fabricated waveguide (b) and from a Corning SMF-28 fiber (c). The waveguide cross-section is close to symmetric, exhibiting a 1550nm mode comparable to that of the SMF-28 fiber. Figure 4 shows a photograph of the bidirectionally pumped Er-doped waveguide. The homogeneity of the green upconversion confirms the low-loss nature of this waveguide. We are confident that further device optimization will yield substantial net gains comparable with those reported using phosphate glass hosts.

Through our optical modulator and wavelength converter work, we have also demonstrated a waveguide fabricated in crystalline LiNbO$_3$ using ultrafast laser waveguide inscription that supports a well-confined mode at 1550nm.$^3$ We believe that this result could pave the way to fabricating novel nonlinear devices and modulators for telecommunications applications.

![Multiscan Fabrication Technique](image)

**Figure 2.** Construction of the desired waveguide cross-section using the multiscan fabrication technique.

![Transmission Mode Images](image)

(a) Transmission-mode optical microscope image of the multiscan fabricated Er-doped waveguide end facet. (b) Near-field image of the 1550nm mode from the Er-doped waveguide and (c) from a Corning SMF-28 fiber.

**Figure 3.**

The potential of ultrafast laser waveguide inscription to fabricate already existing as well as entirely new 2D/3D photonic devices is clearly very high. It is our belief that this technique has only just begun to be seriously explored and that the next few years will represent an extremely fruitful and exciting period of investigation.

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