FIBER TECHNOLOGY

Mobile Waveguides: **Freestanding Waveguides Steered by Light**

Spatial light modulators enable us to create reconfigurable light distributions for the targeted delivery of optical energy and momentum. However, distribution possibilities are constrained by Maxwell's equations. Waveguides are needed for integrated optics and light delivery applications with challenging light paths and confinement—but most waveguide solutions tend to have static architectures.

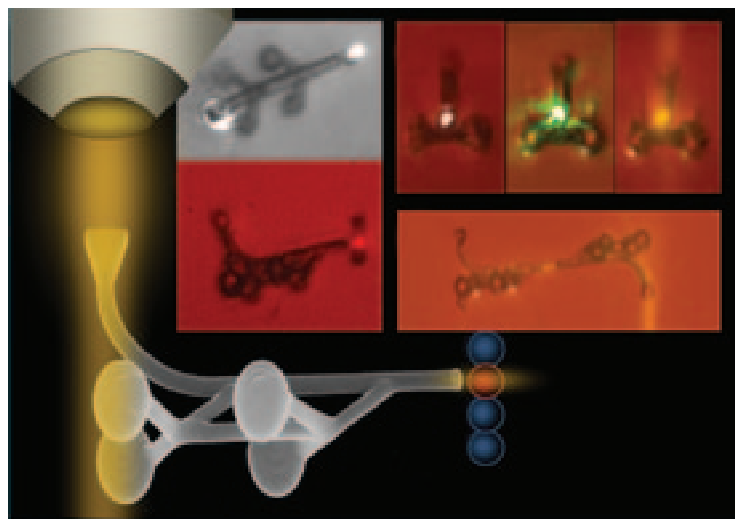
We have demonstrated reconfigurable micro-environments by optically manipulating microfabricated building blocks.[1] We advanced the idea of reconfigurable microstructures using optically steerable freestanding waveguides that can break away from static waveguide limitations.[2]

Microfabrication by two-photon polymerization offers 3-D resolutions for customized monolithic microstructures equipped with optical trapping handles for mechanical control.[3] We extended this capability by including functional structures in the fabricated structures.

We tested the idea of optically steerable freestanding waveguides using our BioPhotonics Workstation (BWS).[4] BWS uses real-time reconfigurable counter-propagating beam traps controlled by direct spatial mapping from an addressable light-shaping module. Axial manipulation is achieved by balancing the intensity ratios of the counter-propagating beams. A side-view microscope offers vision feedback for active trap stabilization.[5] By controlling multiple traps in 3-D, we have simultaneously and independently manipulated complex microstructures with six degrees of freedom.

Experiments show that we can couple in a low-NA beam through a high-NA bent waveguide that is steered by optical traps to position and orient its exit tip. Simulations show a much narrower exit beam, which can be tailored by the waveguide's tapering profile. We can position trapped micro-optics at the tip to modify the exit beam. The bidirectional waveguide can redirect light back to the limited NA of an observing microscope.

Combining microfabrication with optical trapping and micromanipulation allows us to exploit waveguides in versatile and dynamically reconfigurable architectures. This technique can help realize waveguide-based light delivery and/or light sensing in application geometries that would otherwise be challenging for static waveguides. OPN



Versatile light delivery through a freestanding waveguide manipulated by optical traps. The narrow beam exiting the tip selectively excites fluorescence on a microsphere within a vertical stack. (Left inset) Top- and side-view snapshots from actual experiment. (Right inset) Composite side-view microscope snapshots of tip emissions for different input wavelengths; right-most image shows fluorescence from surrounding medium. The schematic overlays graphics onto an actual SEM image of a two-photon polymerized structure.[2]

Visit **www.opnmagazine-digital.com** to view the video that accompanies this article.

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FIBER TECHNOLOGY

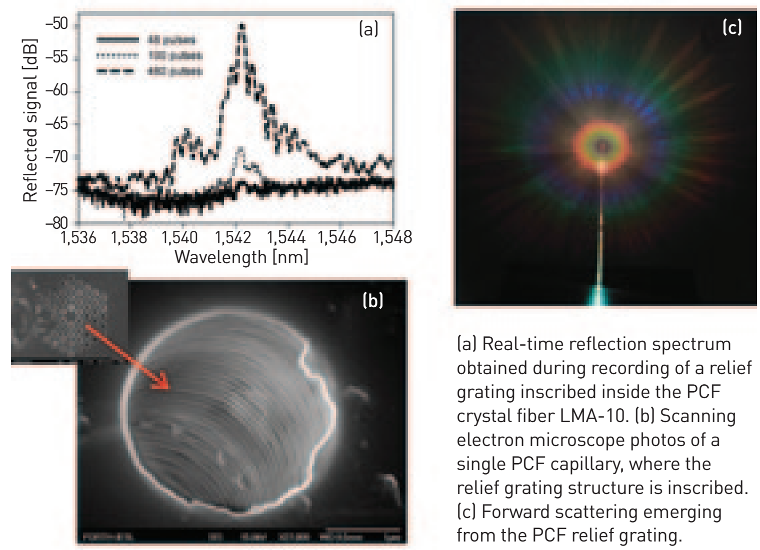
Relief Photonic Crystal **Fiber Bragg Grating Reflectors**

Microstructured optical fibers (MOFs) and photonic crystal fibers (PCFs) offer advanced photonic and microfluidic functionalities in a single, integrated platform. This unique combination constitutes the main axis for the emerging "lab-in-fiber" protocol. The microcapillaries of MOFs and PCFs can be used as a lab bench for attaching molecules, infiltrating nanomaterials or performing photochemical processes, being useful in sensors and actuators development.[1]

Bragg reflectors are indispensible photonic elements for lab-in-fiber technology; their inscription in MOFs and PCFs is a technically challenging task. We have demonstrated the inscription of relief Bragg grating reflectors of submicron period inside the capillaries of a commercial PCF using a variation of the photothermal, laser-induced backside wet etching technique and 248-nm excimer laser radiation.[2,3]

In this scheme, the PCF is infiltrated using toluene vapors or a toluene layer adsorbed onto the capillaries' walls. Next, the Bragg grating is side-inscribed using a standard phase mask technique. Toluene absorbs strongly at 248 nm, leading to super-heated liquid formation at the bright fringes of interference and the subsequent melting and removal of a thin silica glass layer by the induced shockwave. By controlling the exposure conditions and the absorption of the toluene medium (by increasing the temperature), we etched a relief grating pattern on the PCF capillaries without damaging them, thereby sustaining the guiding properties of the fiber. This process is faster than inscriptions of photosensitive gratings, forming relief groove structures tens of nanometers deep, while usually reaching saturation in a few hundred pulses.

The relief in-fiber reflectors backscatter at the Bragg wavelength, while they front-scatter light at shorter wavelengths, increasing the beam coupling possibilities available through the PCF cladding. The fabricated relief PCF Bragg gratings are annealed, retaining most of their strength at temperatures greater than the strain relaxation point of silica (950 °C) for tens of hours, whereas completely demarking at 1,200 °C. The last exemplifies their potential usefulness for the development of optical fiber sensors for harsh environments.



(a) Real-time reflection spectrum obtained during recording of a relief grating inscribed inside the PCF crystal fiber LMA-10. (b) Scanning electron microscope photos of a single PCF capillary, where the relief grating structure is inscribed. (c) Forward scattering emerging from the PCF relief grating.

We recently obtained promising preliminary results on the etching of relief Bragg grating reflectors in hollow core PCFs, targeting gas sensing and pulse shaping applications. Solid-core PCF relief Bragg gratings are currently infiltrated using glass melts for studying the optical properties of the molten glass but also for testing the thermal durability of those reflectors. Similar Bragg reflectors and long-period gratings have been etched into MOFs of different geometries.

This technique could open new horizons in the development of compact and multifunctional sensing and actuating devices, simultaneously exhibiting advanced interrogation capabilities due to high refractive index contrast and extreme temperature durability. OPN

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FIBER TECHNOLOGY

Sapphire-Derived **All-Glass Optical Fibers**

If we could eliminate the phenomenon of stimulated Brillouin scattering (SBS), we could create pulsed laser sources for spectroscopic and coherent lidar applications, as well as multi-kW narrow-linewidth fiber laser sources for coherently phased laser arrays.

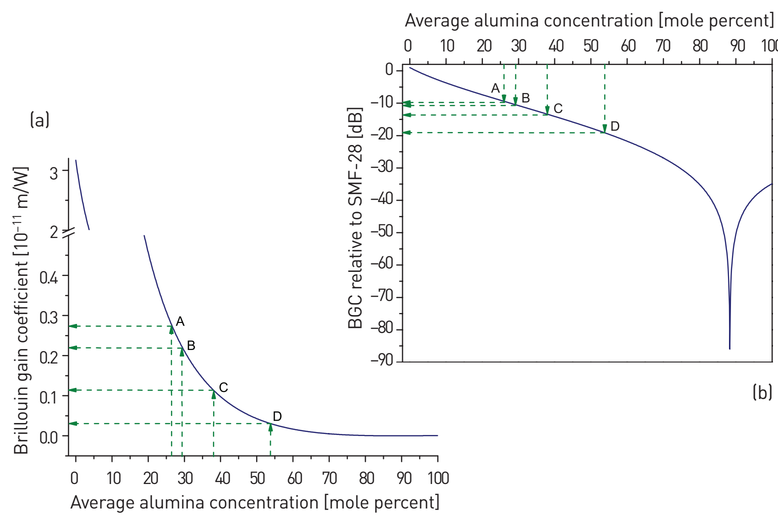
With that in mind, we used a novel fiber fabrication method known as the molten-core method to realize a new class of optical fibers: all-glass optical fibers free from the effects of SBS.[1,2]

We used a common material—sapphire (Al_2O_3)—on our first attempt to create such a fiber.[3] In our molten-core approach, a solid material, like a crystal rod, is sleeved with glass, such as silica. The resulting structure is drawn at a temperature above the melting point of the core, during which some cladding dissolves into the core and, following rapid quenching, results in an all-glass fiber.

Sapphire-derived optical fibers clad in pure silica possess a core that is a binary aluminosilicate glass, which can be compositionally tailored to have extraordinary Brillouin properties. Interestingly, alumina has a number of desirable characteristics—like large acoustic velocity, mass density and acoustic attenuation—that result in fibers with reduced Brillouin gain relative to their Ge-doped counterparts.

However, large concentrations of alumina are needed for substantial reductions in Brillouin gain. This has been unachievable through conventional modified chemical vapor deposition methods. We have used the molten core approach to demonstrate alumina concentrations as high as 55 mole percent, thus gaining access to alumina's desirable acoustic characteristics in a fiber form.[3]

Furthermore, silica and alumina's opposite-signed photoelastic constants can be balanced, leading to a wide range of compositions with near-zero Brillouin activity (ZEBRA). These compositions are ideally suited for the narrow-linewidth fiber applications described above.



Brillouin gain coefficient plotted as a function of the alumina concentration in mole percent on a linear (a) and log (b) scale. The log plot identifies the composition required for a ZEBRA optical fiber. SMF-28 is a commercially available optical fiber.

We produced four fibers with varying compositions (A to D), with the lowest Brillouin gain reported to be 3.1×10^{-13} m/W from fiber D—a value nearly 100 times lower than that seen with commercially available optical fiber.

Aside from the record-low Brillouin gain, we also observed Brillouin frequencies above 14 GHz in the 1,550 nm wavelength region. In addition, since the dependence of the acoustic velocity on the temperature has opposite signs for silica and alumina, we also demonstrated a fiber whose Brillouin frequency was independent of temperature. We expect these fibers to be of great utility when implemented in Brillouin-based distributed sensing systems.

We are currently investigating ZEBRA fibers with unique compositions. We are also working on novel core and cladding materials for applications where unconventional compositions give rise to extraordinary fiber performance.[4] OPN

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