# Photonic band-gap fiber gas cell fabricated using femtosecond micromachining

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**Abstract:** Femtosecond laser drilling is used to produce a variable-pressure fiber gas cell. Tightly focused laser pulses are used to produce micrometer-diameter radial channels in a hollow-core photonic band-gap fiber (HC-PBGF), and through these microchannels the core of the fiber is filled with a gas. The fiber cell is formed by fusion splicing and sealing the ends of the HC-PBGF to standard step-index fiber. As a demonstration, acetylene is introduced into an evacuated fiber at multiple backing pressures and spectra are measured.



**OCIS codes:** (060.2310) Fiber optics; (220.4000) Microstructure fabrication

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Hollow-core photonic band-gap fibers (HC-PBGF's) are a unique class of photonic crystal fibers that guide light in air [1]. Interest in HC-PBGF's arises from the unmatched combination of tight confinement and interaction length, allowing for detailed investigations of both intense and low-level light-matter interactions. Since the reduction of transmission losses in HC-PBGF's [2, 3], these fibers have found use in areas such as wavelength conversion, pulse compression and delivery, gas sensing, and resonant optical interactions [4–11]. These applications all require the introduction of an alternative gas medium into the fiber air-core. Typically in these experiments, the fiber is enclosed in a vacuum cell and light is coupled in and out of the fiber through windows with microscope objectives. Recent work [13, 14], has focused on creating all-fiber gas cells using HC-PBGF's. However, a compact system that allows for variable filling of fibers over a wide range of pressures has yet to be achieved.

Here, we present a noninvasive approach to filling and evacuating HC-PBGF via a micrometer-sized channel drilled through the fiber wall with focused femtosecond laser pulses. With this process a very compact, low-loss, fiber gas cell can be produced by splicing the ends of the HC-PBGF to step-index fiber. The section of the fiber containing the microchannel is sealed with epoxy in a small vacuum chamber, with the remaining fiber exposed allowing for easy manipulation and light coupling. This HC-PBGF gas cell can then be evacuated and filled with gas at pressures both far below and far above one atmosphere.

Optical breakdown with tightly-focused ultrafast laser pulses can produce highly deterministic structural changes in transparent materials [15]. This mechanism has been used to induce a change in refractive index for writing waveguides [16, 17] or to form vacancies [18] in fused silica. Recent work has demonstrated the ability to create sub-micrometer diameter capillaries in molded poly(dimethyl) siloxane [19], as well as in glass [20]. Unlike machining with an excimer laser, the microexplosions produced by a femtosecond laser are a result of a multiphoton process [21], which allows for the production of large aspect ratio channels. With material removal occurring only at the focus of the beam, the sample can be translated to make channels

with a length limited only by debris removal, which can be facilitated by adding a fluid that wicks in the channel during drilling [22].

The system used for drilling is a commercial, regeneratively amplified Ti:Sapphire laser (Spectra-Physics, Hurricane) capable of producing 90-fs, 1-mJ, 800-nm pulses, at a 1-kHz repetition rate. These pulses are focused through a Zeiss Neofluar 0.9-NA multi-immersion objective onto the fiber. This objective has a correction collar designed for use with immersion oil, water, and glycerine, which has an index of refraction similar to that of fused silica. The fiber is held in index-matching fluid ($n = 1.45$) and translated through the focus of the objective at a rate of 1 $\mu$m/s using a Newport PM-500 stage at 100-nm step sizes. The index-matching fluid acts both to reduce aberrations from tightly focusing into the cylindrical fiber and to assist with debris removal by wicking into the forming capillary. Circularly-polarized light is used to produce a more rounded hole through the fiber [24]. As an initial proof-of-principle demonstration, a microchannel is created in a Corning SMF-28E fiber. By translating the step-index fiber upward through the laser focus, drilling is performed from the surface toward the core of the fiber. The threshold energy for surface void formation is found to be $\sim$50 nJ. Microchannel formation in conventional step-index fiber with femtosecond laser-irradiation followed by etching has previously been demonstrated for potential sensing applications [23].

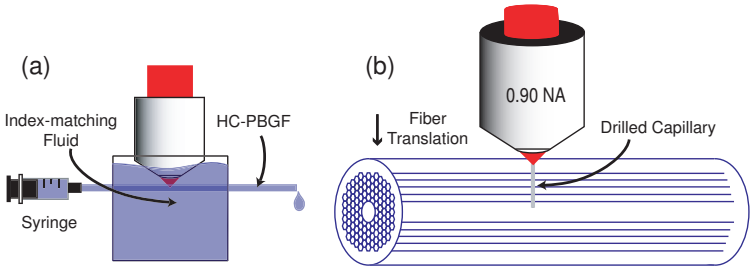


Fig. 1. (a) Experimental setup for laser-drilling. (b) Schematic showing the drilling orientation for HC-PBGF.

The presence of multiple glass-air interfaces poses a problem in transferring this method to laser drilling through a HC-PBGF. To overcome the scattering and optical aberrations due to these surfaces, index-matching fluid is continuously pumped through the core and the surrounding capillaries of the fiber during the laser drilling. This fluid flow has the added benefit of removing debris within the fiber core and the surrounding capillary structure. To take advantage of this flowing removal of debris, laser-drilling in the HC-PBGF is performed from the core to the surface (Fig. 1), so that any ejected debris is swept down the capillaries and out of the fiber. After drilling, the index-matching fluid is removed by flushing the air-core and surrounding capillaries multiple times with methanol and nitrogen gas, which re-establishes optical transmission through the fiber. To determine the threshold energy required for vacancy formation, a series of holes are drilled into a single length of HC-PBGF. SEM images of entry holes produced with pulse energies between 50 and 280 nJ show little increase in hole diameter with pulse energy. However, by imaging the fluid-filled fiber perpendicular to the drilling axis during the drilling, additional structural damage is observed to occur at higher pulse energies. Minimizing the energy required to form a microchannel in the HC-PBGF reduces the impact on optical transmission caused by this collateral damage within the guiding structure. In the work presented here, all channels are drilled with 80-nJ pulse energy, which is slightly above threshold for void formation.

In order to be a viable means of filling and evacuating the HC-PBGF for gas-cell applications, the microchannel must not substantially reduce the optical transmission of the fiber. To measure

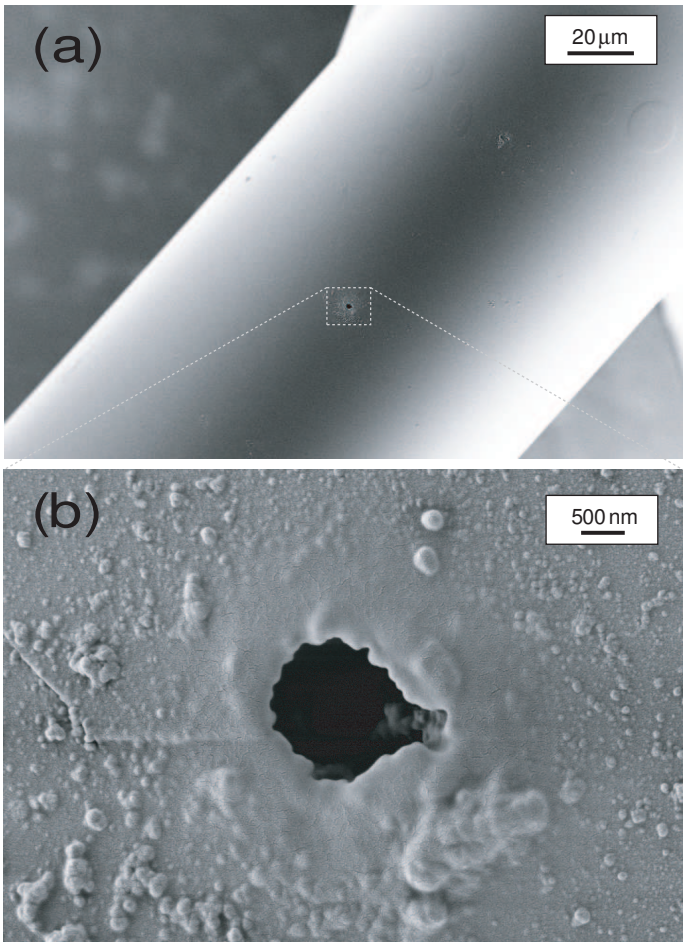


Fig. 2. (a) SEM image of HC-1550-02 fiber laser drilled with 80-nJ pulses. (b) Closeup image of drilled capillary formed in the side of fiber, the surface diameter of the channel is 1.5 $\mu$m.

the loss produced by drilling through the side of the fiber, a cutback method is employed. Six evenly spaced holes are drilled over a 2-mm section of a 33-cm length of HC-PBGF (Crystal Fibre, HC-1550-02). Fusion splicing the HC-PBGF to a fiber-coupled broadband source allows for a consistent measure of throughput without altering the input coupling. Spectral transmission measurements are then taken before and after the laser-drilled region is cutback (Fig. 3). The measured loss due to the drilled region of the fiber is found to be approximately 2.1 dB from 1500-1550 nm. Since the intrinsic loss of the fiber at these wavelengths is negligible (¡ 0.1 dB/m), this yields an estimated loss of 0.35 dB for a single drilled microchannel. We have no explanation, at this time, for the spectral dependence of the loss due to the microchannels.

To create the hollow-core fiber cell, a microchannel is drilled from the core to the surface of a HC-PBGF (Crystal Fibre, HC-1550-01), and the index-matching fluid is removed from the fiber as described above. Each end of the HC-PBGF is then fusion spliced to step-index fiber using the parameters recently described in the literature [25]. Holding the drilled section of the fiber in a small vacuum chamber allows for a long, variable-pressure interaction length, while readily connecting to fiber-coupled devices (see Fig. 4). After evacuating the system for 30 minutes to a pressure of several mTorr, it is then filled at two different backing pressures. Several minutes

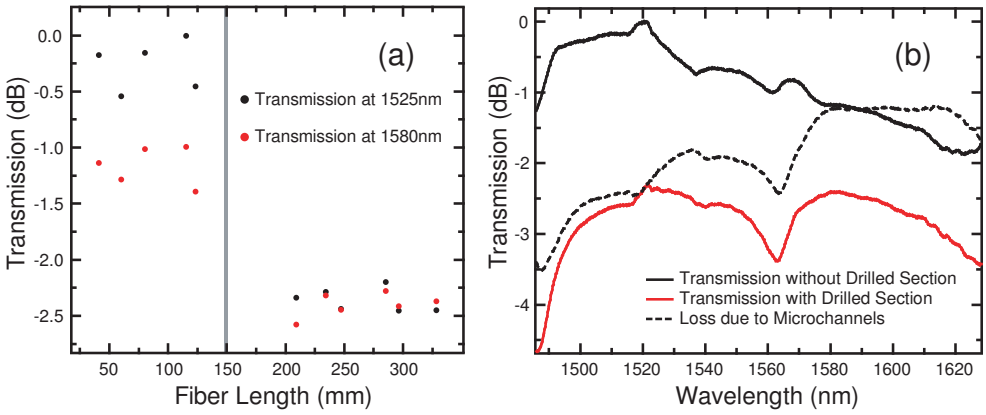


Fig. 3. (a) Cutback measurements taken along the length of the fiber. The drilled section is located at 150 mm (gray). (b) Averaged HC-1550-02 spectral transmission with (red) and without (black) laser-drilled section, both spectra are normalized to peak transmission before drilling. Subtracting these two plots gives the loss due to the drilled section (dashed line).

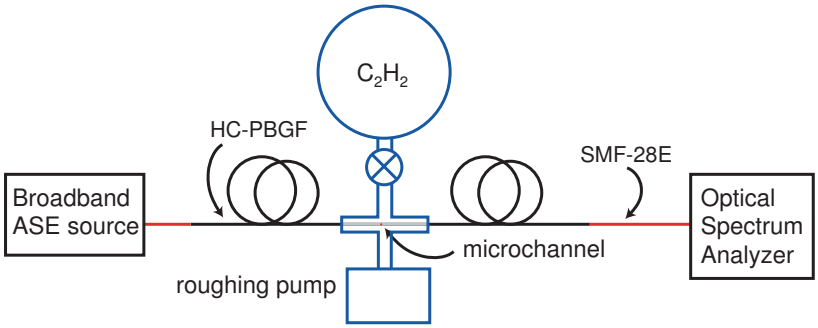


Fig. 4. Experimental setup for acetylene filling. The laser-drilled hole is held inside a vacuum cell, which is evacuated with a roughing pump. The fiber jacket to vacuum chamber is sealed with a low vapor-pressure epoxy resin.

following the introduction of acetylene a steady-state in pressure is achieved and transmitted spectra are measured. As shown in the spectra normalized to the band-gap transmission of the evacuated fiber, increased absorption occurs with increased pressure (see Fig. 5). These spectra are consistent with similar measurements from previous HC-PBGF acetylene gas cell work [13]. The measured loss through the system is found to be 5.6 dB, which is due primarily to the splice loss between the HC-PBGF and the step-index fiber.

In summary, we have used femtosecond pulses to drill microchannels into the side of a hollow-core photonic band-gap fiber. As a demonstration of its capability as a fiber cell, acetylene spectra were measured at two different backing pressures. We also measured the loss due to a single drilled microchannel to be approximately 0.35 dB. Still to be investigated are possible high pressure applications for this all-fiber variable-pressure gas cell, where a compact, tunable source of nonlinearity is required. These include tunable gain in a Raman scattering source or tunable pulse compression following a fiber laser. At low pressures this system has the potential for a myriad of spectroscopic and gas sensing applications.

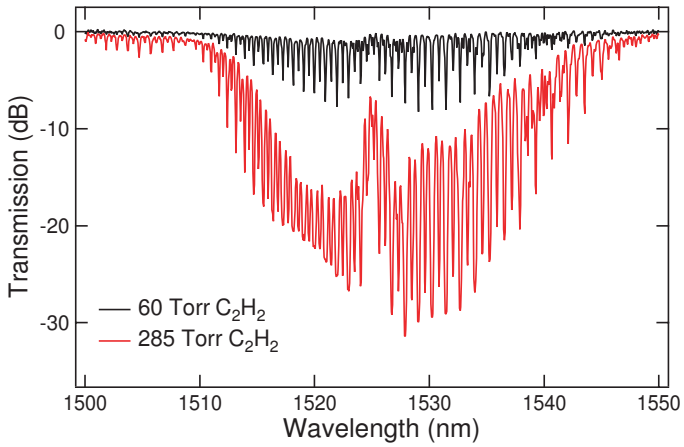


Fig. 5. Vibrational-rotational spectra of acetylene filled HC-PBGF. These spectra are taken by measuring transmission through a 72-cm length of hollow core fiber and are normalized to the fiber band-gap transmission.

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