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Low loss hollow optical-waveguide connection from atmospheric pressure to ultra-high vacuum

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A technique for optically accessing ultra-high vacuum environments, via a photonic-crystal fiber with a long small hollow core, is described. The small core and the long bore enable a pressure ratio of over 10^8 to be maintained between two environments, while permitting efficient and unimpeded delivery of light, including ultrashort optical pulses. This delivery can be either passive or can encompass nonlinear optical processes such as optical pulse compression, deep UV generation, supercontinuum generation, or other useful phenomena. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4860947>]

Optical transmission between two isolated environments at highly different pressures is often required for scientific and industrial processes, such as atom trapping and photolithography. To facilitate this, glass or crystal windows are routinely employed. Their presence in the beam-path can however be detrimental to the transmission. For example, for high peak pulse intensities, the damage threshold of the window material can be exceeded, leading to degradation of the transmission. Even when the material is not damaged, high intensities can induce undesirable nonlinear optical effects. Although it is possible to mitigate these by placing the window far from the optical focus, the result is an undesirably long beam-path. In addition, for wavelength ranges such as the soft x-ray and deep UV, suitable window materials that do not degrade over time may not even be available. The usefulness of windows, and by extension solid-core fibers, for optically transparent pressure isolation is thus limited.

To alleviate many of these problems, delivery of radiation is often made via a differentially pumped open channel whose diameter is millimeter in scale.^{1,2} However, despite reasonable success in achieving ~ 8 orders of magnitude pressure difference in applications such as synchrotron injection, such open channels require complicated and cumbersome multi-stage (3-4 stages) pumping mechanisms (needing 3-4 vacuum pumps), which adds to the size, cost, and complexity of the systems. Further alternatives include the use of a plasma channel as an interface between vacuum and atmospheric pressure.³ Although this helps increase the pressure difference attainable by differential pumping by 2 orders of magnitude, maintaining a plasma window requires multi-kilowatt power levels.

In this Letter, we present an alternative approach to providing an open optical channel between ultra-high vacuum and ambient pressures: hollow-core photonic-crystal fiber (HC-PCF). The use of HC-PCF not only allows direct delivery of light with negligible gas flow but also makes it possible concurrently to tailor the spectral and temporal characteristics of the light. For example, this permits temporal compression of ultrashort laser pulses or generation of tunable deep-UV light.^{4,5} If required, the hollow-core could

also potentially be used to transport micro-particles in and out of a high vacuum environment.⁶ Previous studies on gas dynamics in HC-PCF have mainly focused on the gas-filling time,^{7,8} which is a critical parameter in gas-sensing applications. Here, we study the feasibility of utilizing the restricted gas-flow in HC-PCF to provide a light-guiding open channel into a high vacuum environment.

The fluidic conductance of a narrow cylindrical tube can be approximated as the sum of its conductance in the molecular (first term) and in viscous (second term) regimes⁹

$$C \approx \frac{\pi \bar{c} d^3}{12 l} + \frac{\pi}{256 \eta} \frac{d^4}{l} (p_1 + p_2), \quad (1)$$

where p_1 and p_2 are the pressures at the entrance and exit of the tube [mbar], d is the tube diameter and l its length [m], $\bar{c}$ is the mean thermal speed of the gas molecules or atoms [m/s], and η is the viscosity [mbar·s]. The corresponding volumetric flow q_{pv} is related to the conductance by $q_{pv} = C(p_1 - p_2)$.

It is self-evident that isolating ultra-high vacuum from ambient pressure requires the gas flow to be reduced to a minimum. Equation (1) confirms intuition by showing that, if the gas flow is to be limited, the diameter should be as small as possible and the length as long as possible. A glass capillary is thus a potential candidate for combining pressure isolation with well-controlled optical beam and/or particle delivery. The leakage rate of light guided in a capillary, α , is however also a strong function of the core diameter¹⁰

$$\alpha_{nm} \approx \left(\frac{u_{nm}}{2} \right)^2 \frac{\lambda^2}{d^3} \frac{1}{2} \frac{(v^2 + 1)}{\sqrt{(v^2 - 1)}}, \quad (2)$$

where u_{nm} is the m^{th} root of the $(n - 1)$ th order Bessel function, λ is the wavelength, and v is the refractive index of the capillary glass. The inverse cubic dependence on core diameter means that a flow-restricting smaller core will simultaneously inhibit optical transmission. Furthermore, it is essential for a capillary to remain straight if additional bending loss

FIG. 1. Scanning electron micrographs of the cross-sections of kagomé-PCFs with (a) 37 μm core diameter and 3 layers of cladding channels, and (b) 28 μm core diameter with 5 cladding layers.

and (at high power levels) associated optical damage are to be avoided.¹¹

In contrast, HC-PCF provides low loss optical guidance at core diameters where a capillary would be unusable, allowing one to restrict the gas flow while maintaining good optical guidance. Optical losses of order 1 dB/m or less are routinely achieved over bandwidths of hundreds of nm in small-core (20–50 μm diameter) kagomé-PCF,^{12,13} with negligible bend losses. Figure 1 shows scanning electron micrographs (SEMs) of the kagomé-PCFs used in the experiments reported here. The kagomé-like lattice of channels in the cladding not only provides the fiber with attractive optical properties (pressure-adjustable dispersion and a high damage threshold¹³) but also contributes significantly to the restriction of the gas flow. Even though the total area of the cladding channels is greater than that of the central core, the strong dependence of the conductance on channel diameter (Eq. (1)) means that the gas flow through the cladding is comparable to the flow through the core in a typical kagomé-PCF.

The achievable equilibrium end-point pressure p_2 , which is simply q_{pV} divided by the effective pumping speed S_{eff} [m^3/s] of the vacuum pump, can be calculated straightforwardly. As q_{pV} and potentially the effective pumping speed S_{eff} are functions of p_2 ,⁹ we obtain p_2 by numerically solving

$$q_{pV}(p_2) - p_2 \cdot S_{eff}(p_2) = 0. \quad (3)$$

Figure 2 shows the capillary lengths and bore diameters required to achieve different end-point pressures when connected to a vacuum pump with 2000 l/s pumping speed, the other end being held at 1 bar and 20 °C. Also illustrated (shaded region on the right) is the parameter region in which the optical transmission at 800 nm is better than 50% (3 dB loss). At such a high pumping speed (corresponding to a very strong vacuum pump), it is a challenge to transmit a satisfactory amount of near-infrared light using a glass capillary if the end-point pressure is to be below 10 nbars. This problem becomes even more acute at longer wavelengths, as the capillary loss is proportional to the square of the wavelength. In comparison, kagomé PCF offers equilibrium pressures below 0.1 nbar while still offering good optical transmission over m-lengths.

Equation (2) indicates that the length of capillary yielding 50% transmission falls as the inverse square of the

FIG. 2. Capillary length and bore diameter required to achieve four different end-point pressures when connected to a vacuum pump with 2000 l/s pumping speed, the other end being held at 1 bar and 20 °C.⁹ The shaded region on the right indicates the range of parameters, where the optical loss is below 3 dB at 800 nm. A typical kagomé-PCF has a bore diameter less than 50 μm and a loss lower than 1 dB/m.

wavelength. The reduced capillary 3 dB loss length, plotted in Fig. 3 (right-hand axis) for a silica capillary with 20 μm bore diameter, results in increased gas flow and end-point pressure p_2 , as shown in Fig. 3 (left-hand axis) for a 2000 l/s pump. For capillary bore diameter of 20 μm , even this high pumping rate is inadequate for reducing the end-point pressure below 1 nbar at common laser wavelengths.

On the other hand, kagomé-PCF offers broad-band low loss (~ 1 dB/m or less), so that, at a given pumping speed, the minimum achievable pressure from a 3 dB-length kagomé PCF is at least one order of magnitude lower than that of a capillary at UV wavelengths and over two orders of magnitude better in the IR. Compared with the much shorter length of a capillary (< 1 cm for $\lambda > 400$ nm), which needs to be kept straight, the long (> 1 m) and flexible kagomé PCF can be conveniently positioned both inside a vacuum chamber or between two pressure systems, providing sufficient length for controlled nonlinear gas-light interactions.

To verify these calculations, we measured the equilibrium pressure inside a $22 \times 17 \times 15$ cm³ vacuum chamber pumped by a turbo-molecular pump with a speed of 225 l/s and connected to a capillary or kagomé-PCF. The 45 cm long connection between the pump and the chamber has a diameter of 10 cm. The chamber was first evacuated with all flanges sealed to establish a baseline pressure, which was found to be 3.2 nbars after 6 h.

A 0.5 mm diameter hole was drilled through one of the vacuum-sealing blanking plates, and a capillary tube with a bore diameter of 125 μm and a length of 30 cm inserted, only 1 cm of which protruded into the vacuum chamber. It was sealed in place with epoxy. Both ends of the capillary were cleaved using a ceramic blade to ensure a clean opening. The equilibrium pressure was measured at various cut-back lengths, each after 40 min of evacuation. As a comparison, the procedure was repeated for a capillary with a 200 μm bore diameter, and a kagomé-PCF with an inner cladding diameter of 125 μm and a core diameter of ~ 37 μm (Fig. 1(a)). The end-point pressures are plotted in Fig. 4. For the kagomé-PCF, the hexagonal core and cladding channels were approximated as circles with diameters equivalent to

FIG. 3. Achievable end-point pressure (in nbar) versus wavelength at the pumped end of a capillary (bore diameter 20 μm , 3 dB optical loss length), the other end being held at 1 bar and 20 $^{\circ}\text{C}$. The pumping speed of the vacuum pump is 2000 l/s.⁹ Also plotted is the 3 dB optical loss length of the capillary. The end-point pressure for a 1 m long kagomé-PCF (core diameter 20 μm) is between 10 and 1000 times lower than the capillary, while offering only ~ 1 dB loss over the entire wavelength range (apart from narrow loss bands due to anticrossings with cladding modes¹³).

the mean value between their flat-to-flat and corner-to-corner diameters. (Although the hydraulic diameter $d_h = 4A/P$, where A is the cross-sectional area and P is the length of the perimeter,⁹ is frequently used, it actually equals the flat-to-flat diameter of a hexagon, so is likely to underestimate the true flow rate.)

As expected, the larger bore diameter leads to an increased gas-flow, resulting in an achievable p_2 for the 200 μm capillary that is almost 7 times higher than for the 125 μm capillary.

Although the kagomé-PCF has approximately the same inner cladding diameter (Fig. 1(a)) as the bore of a 125 μm capillary, the segmentation of the cross-section into numerous narrow channels results in much lower conductance and end-point pressure. The calculated results show very good agreement with the measurements, apart from slight deviations in the vicinity of 1 μbar , where the pressure gauge switches between a Pirani and a cold-cathode sensor.

We further analyzed the effects of the cladding channels on the conductance. Kagomé-PCFs with core and inner cladding diameters of (a) 29 and 95 μm (3 layers of cladding channels), (b) 28 and 160 μm (5 layers of cladding channels),

FIG. 4. Measured (symbols) and calculated (curves) length-dependences of the equilibrium end-point pressure for two different capillaries and a kagomé PCF (core diameter 37 μm core and inner cladding diameter 125 μm) when evacuated at a maximum pumping speed of 225 l/s at one end and open to atmospheric pressure at the other.

FIG. 5. Measured (markers) and calculated (solid lines) equilibrium end-point pressures for kagomé-PCFs with different core/inner-cladding diameters, plotted against fiber length. The pumping speed is 225 l/s and the other fiber end is held at atmospheric pressure.

and (c) 37 and 125 μm (3 layers of cladding channels) were compared. Scanning electron micrographs of two of these PCFs are shown in Fig. 1.

As shown in Fig. 5, the increased number of cladding area between the fibers with similar (28 and 29 μm) bore diameters raises the achievable end-point pressure by approximately a factor of 2. However, a fiber with a 37 μm core diameter and inner cladding diameter of only 125 μm shows an equally large increase of end-point pressure. This results from the strong dependence of the conductance on the core and cladding diameters.

The experimental data matched very well with calculations, and the measurements are largely within the calculated upper and lower bound (Fig. 6), deduced by over- and under-estimating the diameter of the circles used in modeling the hollow channels (Fig. 6 inset).

To ensure that equilibrium pressure had certainly been reached, the measurements were repeated using an evacuation time of 8 h for the PCF with 5 inner cladding layers, where the additional narrow channels could potentially lengthen the evacuation time in the molecular flow regime. The results agree closely with those measured after 40 min of evacuation.

An end-point pressure of 7.9 nbars, approaching the baseline level of the system, was measured for a 30 cm

FIG. 6. Measured (dots) and calculated (dashed black curve) equilibrium end-point pressures plotted against fiber length for a kagomé-PCF with a flat-to-flat core diameter of 28 μm , evacuated at a maximum pumping speed of 225 l/s, the other end being held at 1 bar. The upper (green curve) and lower (orange curve) bounds for the pressures are deduced by over- and under-estimating the diameter of circles used in modeling hexagonal conductance (SEM in the inset).

length of kagomé-PCF with a $29\text{ }\mu\text{m}$ core, the other end being held at atmospheric pressure. This represents a pressure ratio of over eight orders of magnitude at only moderate pumping speed. If a 1 m length of the kagomé-PCF is connected to a 2000 l/s pump, an end-point pressure of ~ 0.1 nbar could be expected. Fibers with smaller cores could also be used to further reduce the gas flow.

Apart from simple optical transmission between pressure environments, the use of kagomé-PCF also enables the modification of optical pulses (e.g., duration, bandwidth, and chirp) as they propagate along the fiber. By replacing air with a suitable gas (e.g., Ar or Xe) and adjusting the external pressure, controlled manipulation and delivery of light can be simultaneously achieved in a single set-up. Examples of useful linear and nonlinear processes available in gas-filled PCFs include temporal pulse compression,^{14,15} generation of tunable vacuum-UV and deep-UV emission,⁵ multi-octave spanning supercontinuum generation,¹⁶ frequency blue-shifting,^{17,18} and high harmonic generation of XUV and x-ray radiation.¹⁹ Furthermore, since the transverse profile of the guided mode remains stable even if the fiber is bent or twisted, the transmitted light has excellent spatial coherence and so can be focused to a diffraction-limited spot inside the vacuum chamber.

In summary, hollow-core kagomé-PCF allows one to limit the gas flow into an ultra-high-vacuum environment, while maintaining a pressure ratio of eight orders of magnitude (or better) and simultaneously allowing the delivery of light with tailored characteristics. The system could also be used for laser delivery and manipulation of micro-particles⁶ and atoms.^{20,21} The results will apply equally well to other types of hollow-core PCF (e.g., ultralow loss band-gap guiding PCF) and seem likely to dramatically improve the flexibility of high-vacuum optical systems.

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