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Hollow Core Fiber Optics for Mid-Wave and Long-Wave Infrared Spectroscopy

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ABSTRACT

We describe the development and testing of hollow core glass waveguides (i.e., fiber optics) for use in Mid-Wave Infrared (MWIR) and Long-Wave Infrared (LWIR) spectroscopy systems. Spectroscopy measurements in these wavelength regions (i.e., from 3 to 14 μm) are useful for detecting trace chemical compounds for a variety of security and defense related applications, and fiber optics are a key enabling technology needed to improve the utility and effectiveness of detection and calibration systems. Hollow glass fibers have the advantage over solid-core fibers (e.g., chalcogenide) in that they are less fragile, do not produce cladding modes, do not require angle cleaving or anti-reflection coatings to minimize laser feedback effects, and effectively transmit deeper into the infrared. This paper focuses on recent developments in hollow fiber technology geared specifically for infrared spectroscopy, including single mode beam delivery with relatively low bending loss. Results are presented from tests conducted using both Quantum Cascade Lasers (QCL) and CO_2 lasers operating in the LWIR wavelength regime. Single-mode waveguides are shown to effectively deliver beams with relatively low loss (~ 1 dB/m) and relatively high beam quality. The fibers are also shown to effectively mode-filter the "raw" multi-mode output from a QCL, in effect damping out the higher order modes to produce a circularly symmetric Gaussian-like beam profile.

Keywords: Infrared fiber optics, hollow waveguides, infrared spectroscopy, long-wave infrared (LWIR), mid-wave infrared (MWIR), mid-infrared, quantum cascade laser.

1. INTRODUCTION

Fiber optics in the visible, near infrared, and short-wave infrared wavelength regimes (i.e., 0.4 μm to 2 μm) are extremely useful for many applications by enabling convenient, compact, remote delivery of laser beams. There is a similar need for fiber optics deeper in the infrared [1]. Using terminology from the remote sensing community we refer to the relevant wavelength regimes as the Mid-Wave Infrared (MWIR), 3 to 6 μm, and the Long-Wave Infrared (LWIR), 7 to 14 μm; these wavelength ranges are also often referred to as being part of the Mid-Infrared regime, spanning roughly 2 to 25 μm (5000 to 400 cm^{-1}). Recent advances in Quantum Cascade Laser (QCL) technology, have made laser based techniques at these wavelengths increasing appealing [2]. In this paper, we describe the testing of hollow core glass waveguides for use as a fiber optic solution for MWIR and LWIR laser applications. In particular, we examine the mode properties of the waveguides demonstrating single-mode beam delivery, which can be essential for many applications such as infrared counter measures, spectroscopy, and laser-based calibration.

1.1 Chemical Gas Sensing and Other MWIR/LWIR Laser Applications

Most gaseous chemical substances exhibit unique absorption bands in the MWIR and LWIR wavelength regions. In particular, spectral features in the so-called fingerprint region of the infrared spectrum (corresponding roughly to the LWIR range) can be exploited to enable the detection and identification of specific molecular species of interest in trace amounts. For example, the Pacific Northwest National Laboratory (PNNL) has an active program to develop field-deployable chemical sensing systems for proliferation detection [3]. A primary goal of this work is to develop small, lightweight systems for accurate field detection of trace gases indicative of weapons of mass destruction (WMD). Fiber optic components are an essential enabling technology in efforts to miniaturize the systems, which would increase their

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utility and effectiveness for Non-Proliferation Treaty verification and the Comprehensive Nuclear-Test-Ban Treaty on-site inspection efforts.

Another potential application for MWIR/LWIR fibers includes a convenient means for performing in-situ calibration of various infrared detectors and sensors in field use. Desired characteristics in this case are that fibers are robust and the beam exiting the fiber is stable both spatially and temporally. For such applications, single mode beam delivery is essential.

1.2 Chalcogenide Fiber Optics

Fibers based on chalcogenide glasses are the most widely used solid-core fiber option for the MWIR and LWIR ranges. Single mode chalcogenide fibers have been developed for astronomical interferometry applications [4], but despite being designed to work at the longer wavelengths, the losses are still relatively high (about 10 dB/m at 10.6 μm). Employing a photonic band gap structure is also an active area of research with chalcogenide fibers [5]; however, even these fibers attenuate strongly for $\lambda > 9$ μm due to the absorption of LWIR radiation by the chalcogenide glass at the edge of the fiber core. In general, chalcogenide based fibers have several significant drawbacks [6]:

- The transmission typically cuts off sharply for $\lambda > 9$ μm
- They are extremely brittle and fragile
- End reflections can cause feedback and destabilize the source laser
- Cladding modes can cause system noise, and are difficult to mitigate.

Hollow core glass waveguides, as described in the following section, essentially solve all of these problems.

2. HOLLOW CORE GLASS WAVEGUIDES

2.1 Structure and Fabrication

The basics structure of hollow glass waveguides for MWIR and LWIR applications is shown in Figure 1. The waveguides are fabricated by depositing a reflective silver (Ag) layer followed by a dielectric silver iodide (AgI) layer inside a hollow glass capillary tube using wet chemistry techniques [7]. The inside diameter of the hollow core is relatively large (e.g., 300 μm), yet single mode beam delivery of LWIR lasers is still possible as demonstrated in Section 3.2. A protective jacket on the outside of the tube helps with mechanical structure, but does not contribute to the optical properties.

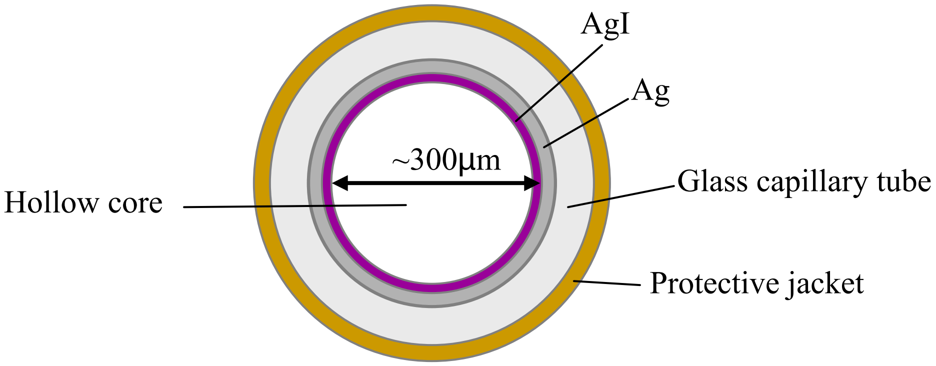


Figure 1. Cross section view of hollow waveguide showing basic structure and coating layers (not to scale).

The spectral properties of the waveguides can be modified by varying the thickness of the AgI dielectric layer (typically about 0.5 μm thick), which in turn is controlled by the deposition time of an iodine (I_2) solution. Figure 2 demonstrates that the transmission spectrum of the waveguides can be made to be broadband or tuned for specific spectral regions within the MWIR and LWIR regimes. The absorption peak at the shorter wavelength end is due to a thin film interference effect and for the longest deposition time shown, two peaks are visible. We note that the absorbance measurements shown in Figure 2 are on a relative scale, where each curve is scaled separately by its respective maximum, thus it does not give an indication of the overall losses of the waveguides. For example, contrary to the appearance in the graph, waveguides made with the longest deposition time shown, actually have the lowest loss in the LWIR region.

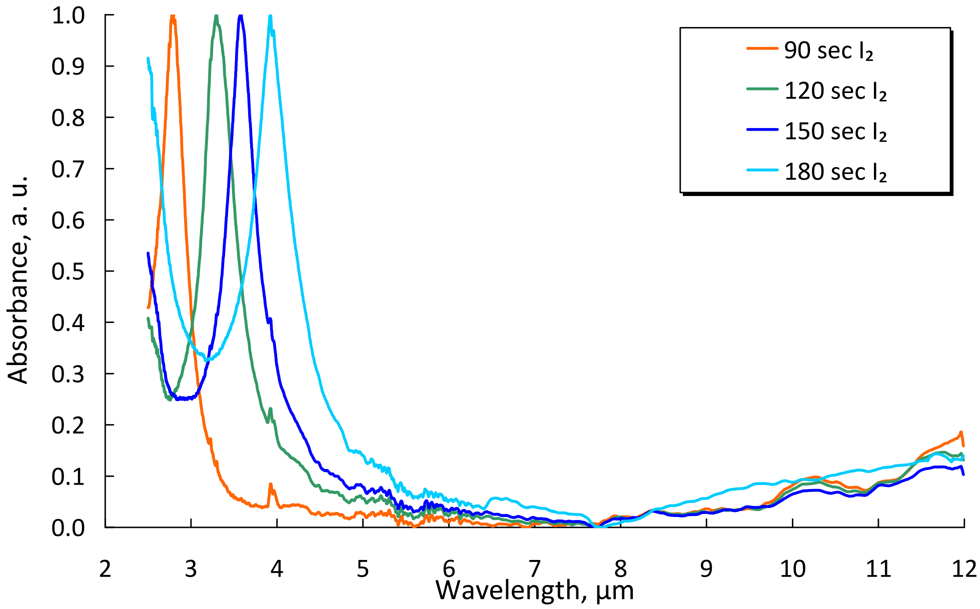
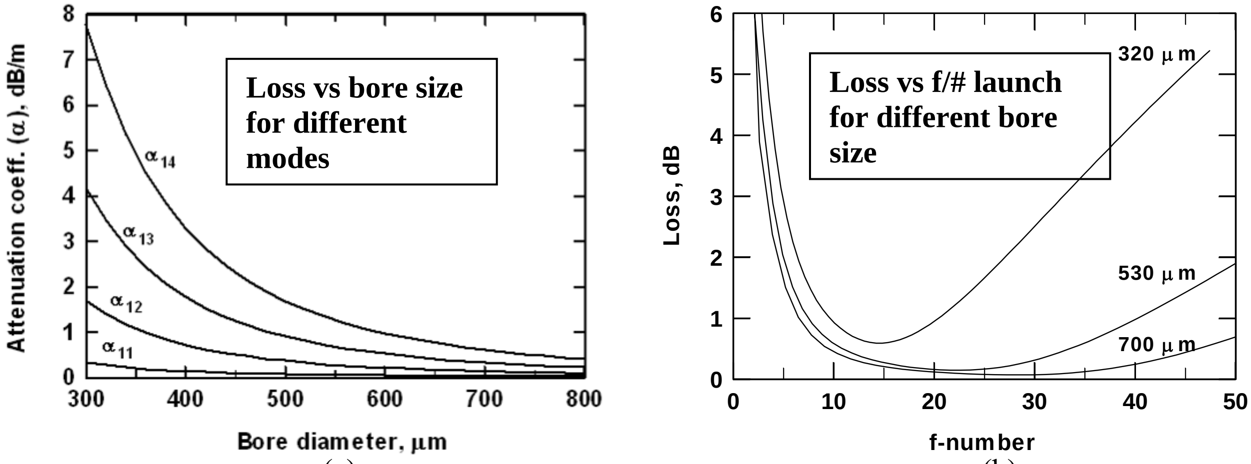


Figure 2. Scaled FTIR measurements of waveguide absorbance for different iodine (I_2) deposition times, which in turn determines the thickness of the AgI dielectric layer.

2.2 Loss and Coupling

In addition to the dielectric coating, waveguide loss (attenuation) depends strongly on two factors: (1) the diameter of the hollow bore and (2) the mode of the beam [8]; both of these factors are illustrated by Figure 3(a). The loss increases with smaller bore diameter (d) varying as $1/d^3$, and is greater for higher order waveguide modes. The strong dependence on mode has the consequence that higher modes are damped (i.e., mode filtering), as demonstrated in Section 3.3. In addition, when higher order modes are excited due to poor coupling or excessive bending, the losses are increased.



(a)

(b)

Figure 3. (a) Dependence of loss on bore diameter for different HE_{nm} modes; (b) Dependence of loss on f/# of launch for 1 m long waveguides with different bore sizes.

For example, the dependence of loss on the f/# launch for different bore sizes is shown in Figure 3(b). When the launch is not optimal, the losses are greater due to higher order modes being excited. Note, that the optimum launch conditions occur at relatively large f/# values (e.g., ~ f/15 for 320 µm bore waveguides). In other words, the waveguides have relatively small effective numerical aperture (NA) values in the range of $0.01 < NA < 0.05$.

The primary drawback with hollow core waveguides is that typically there is an additional loss on bending. This loss occurs due to the fact that bends can couple energy from lower to higher order modes, which consequently damp out. However, by using specific glass tubing, which is chosen to result in a waveguide with lower mode coupling, single mode performance and lower bending loss can be achieved.

3. MEAUREMENTS WITH QUANTUM CASCADE AND CO$_2$ LASERS

The properties of hollow core waveguides for infrared laser delivery have been studied for many years [1]. The focus of the new studies presented in this paper are on testing the performance of waveguides produced for single mode beam delivery, specifically with QCL based spectroscopy applications in mind. The data in this section consists of related measurements conducted at 3 different locations (OKSI, Rutgers, and PNNL) using 4 different lasers (2 QCL's and 2 CO_2 lasers).

Most of the measurements presented in the following sub-sections were conducted using a setup illustrated by the diagram shown in Figure 4. In some setups the aperture was not present. In other setups two bend mirrors were used immediately after the laser to facilitate alignment of the laser beam. However, one benefit of using hollow waveguides with a relatively large bore is that coupling is fairly forgiving and the precise alignment typically required for much smaller core fiber optics is not needed. In general, the coupling efficiency can be very high, and in practice is typically greater than 90% for the low-loss f/# launch conditions specified by Figure 3(b).

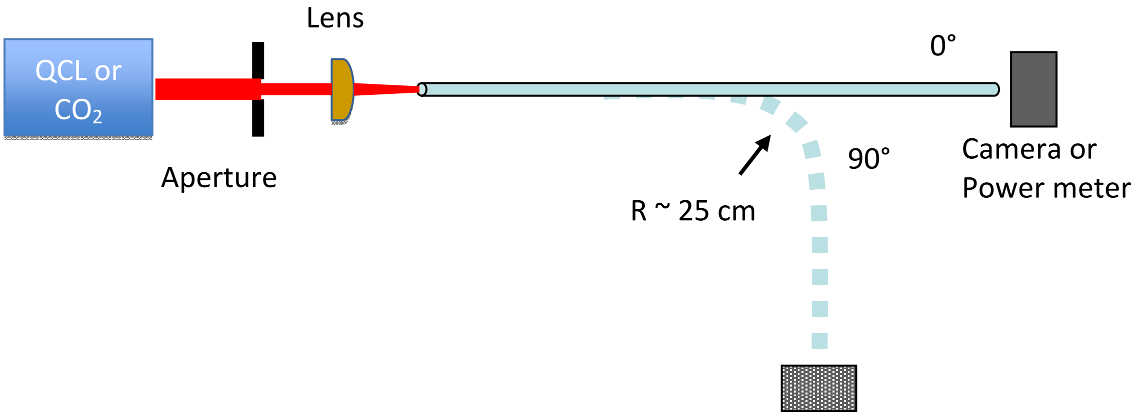


Figure 4. Diagram illustrating the setup for measuring power loss in the waveguide and beam profile exiting the waveguide.

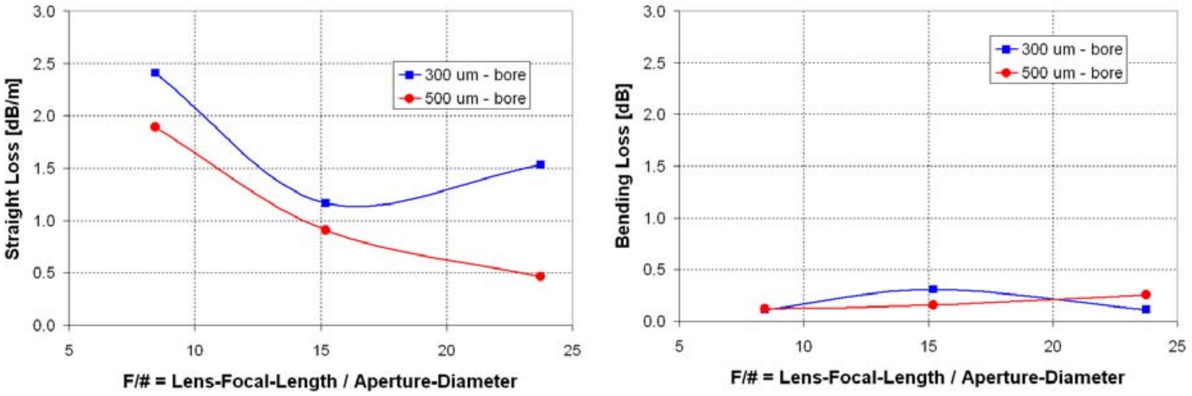
3.1 Transmission Loss and Additional Bending Loss

Sample loss measurements are shown by the plots in Figure 5. For these particular measurements a Daylight Solutions (model# 21088) pulsed QCL with an average output power of approximately 5 mW was used; this QCL is tunable over the wavelength range from 8.8 to 10.3 µm. The measurements shown in Figure 5 were all taken at $\lambda = 10.0$ µm. Measurements were also taken at $\lambda = 9.0$ µm and 9.5 µm, but do not differ significantly from those at 10.0 µm. The f/# of the launch was varied by using an iris (aperture) to spatially restrict the beam. Absolute loss values for the straight waveguides were determined using a "cut-back" method. With this method the power (P_0) is first measured exiting a full-length waveguide (e.g., $L_0 = 1$ m), then the waveguide is cut back to a smaller length (e.g., $L_S = 0.1$ m) and the output power (P_S) measured again. The waveguide is cut while keeping it in the test setup in an attempt to maintain identical coupling conditions for both the long and short pieces. The formula for calculating the straight loss is given in Equation (1) below and results shown in Figure 5(a). The variations of loss with f/# for the straight waveguides reflect the coupling conditions as shown in Figure 3(b), where the lowest loss occurs at about f/15 for a 320 μm bore waveguide and at about f/25 for a 530 μm bore waveguide.

$$Straight\ Loss[dB/m] = \frac{10\ Log(P_0/P_S)}{L_0 - L_S} \qquad Bending\ Loss[dB] = 10\ Log(P_0/P_B)\ . \tag{1}$$

The bending losses were measured in a similar manner as the straight losses except that instead of cutting the waveguide, it was simply bent while keeping the coupling fixed. The full length (unbent) power out is then compared to the power exiting a bent fiber (P_B). For the measurements shown in Figure 5(b), the fiber bend subtended an angle of 90^o with a radius of approximately r = 0.25 m over a section of the waveguide about 0.4 m long.

The magnitude of the additional bending loss in the single-mode waveguides is relatively low, ranging from about 0.1 to 0.3 dB for the bend tested, which when scaled by the length of the bend ranges from 0.2 to 0.7 dB/m. Previous measurements of bending loss for standard hollow waveguides were reported to be higher than this at about 1.0 dB for a 1 m long bend with radius = 0.25 m (these prior measurements were taken at λ = 10.6 μm with a 320 μm bore waveguide) [9]. These prior measurements also found that the loss due to bending scales linearly with the curvature of the bend (1/r), which is an effect that was not studied here.



(a) (b)

Figure 5. (a) Straight loss and (b) additional loss on bending as a function of the f/# launch conditions for waveguides with two different bore sizes. The laser used was a pulsed QCL operating at λ = 10.0 μm.

3.2 Single Mode Performance

Single mode beam delivery is important for many IR laser applications that require relatively high beam quality and/or beam stability over time. Waveguides were produced with improved single-mode performance compared to standard hollow core waveguides by using a proprietary choice of glass tubing that mitigates the effects of bending. Based on past empirical results, for single mode performance, the inner diameter (ID) of the waveguide should be chosen to be approximately 30 times the wavelength. For example, at λ = 10 μm, we find that waveguides with a bore size as large as 300 μm can be used to provide effective single mode performance. We are currently pushing this limit and working on single-mode waveguides that are significantly larger than 30λ, which would open up single-mode, low-loss waveguides for the MWIR regime as well as the LWIR.

Results of two different tests of the single mode performance in regard to bending are presented in Figure 6 and Figure 7. In Figure 6 a test showing the spatial profile of a beam exiting a larger bore (ID ~ 500 μm), multimode waveguide are shown along with the profiles for a beam exiting a smaller bore (ID ~ 300 μm), single-mode waveguide; both straight and bent conditions are shown for the two waveguides. The multimode fiber shows degradation in beam quality when bent; however, the single-mode waveguide maintains a Gaussian like beam profile. In Figure 7, spatial profiles from a grating-tuned CO_2 laser (Access Laser LASY-4G) tuned to 9.3 μm. are shown. These profiles were obtained from the output of a single mode waveguide under varying degrees of bend. At a bend angle of 90° and a radius of 0.28 m, the beam profile is slightly wider than the straight profile, but maintains a Gaussian-like shape.

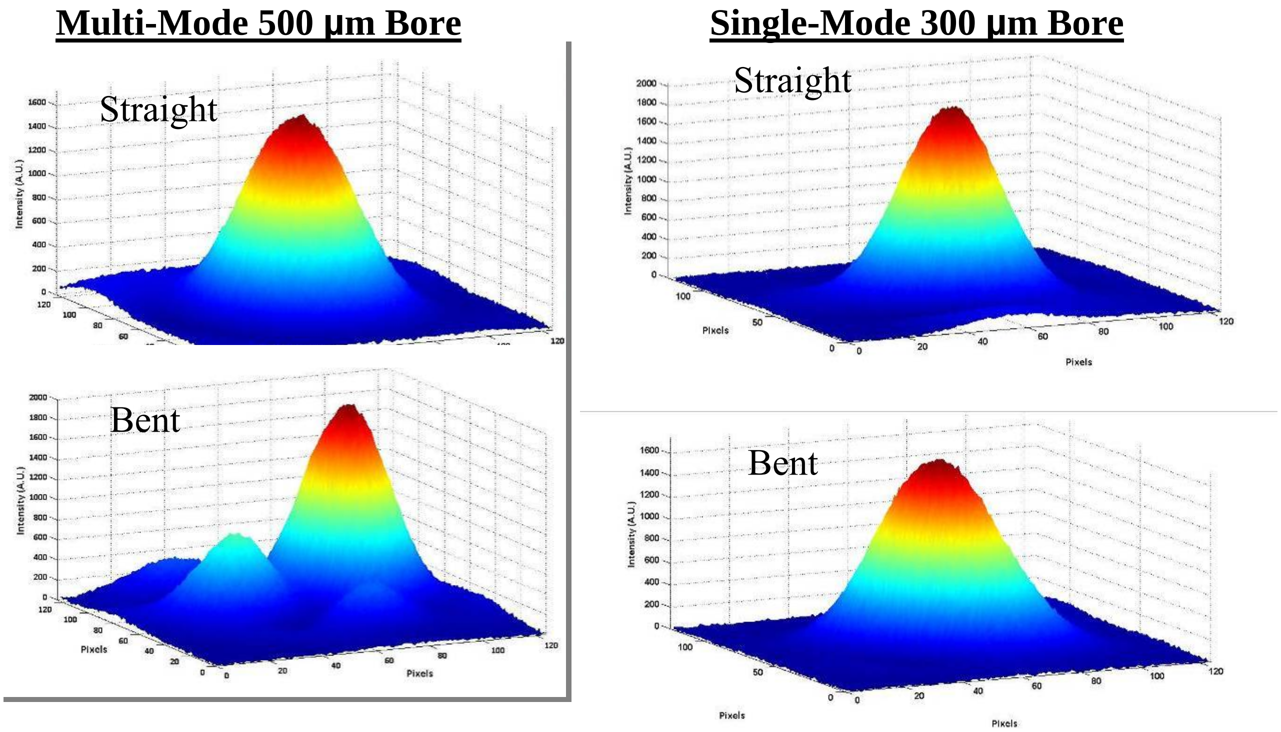


Figure 6. Two-dimensional spatial profile of a CO_2 laser ($\lambda = 10.6$ µm) delivered by two different sized waveguides under both straight and bent conditions.

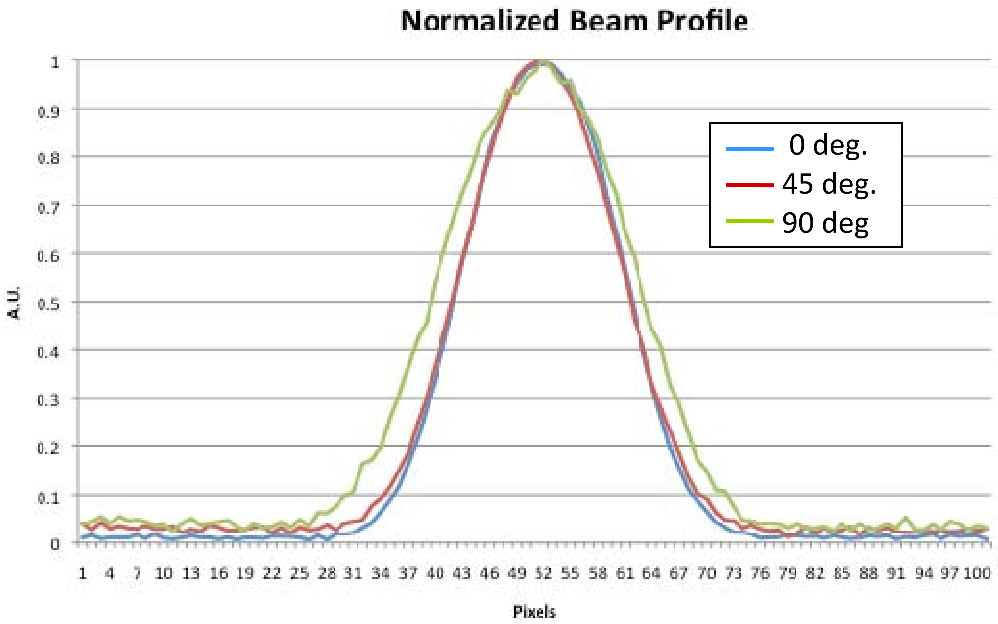
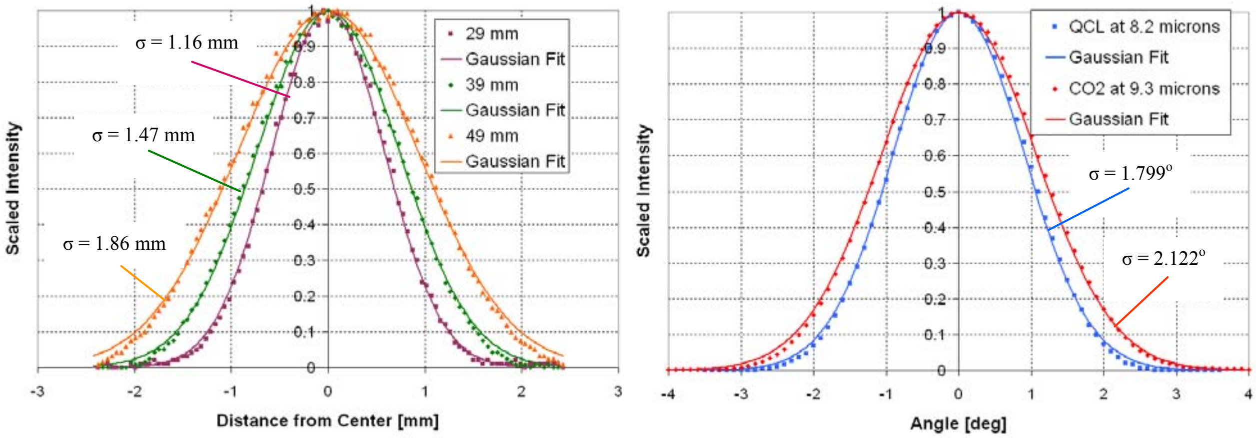


Figure 7. One-dimension spatial profile of a CO_2 laser ($\lambda = 9.3$ µm) delivered by a 300 µm "single-mode" waveguide undergoing different degrees of bending. For these measurements the bend radius was approximately 0.28 m.

Additional far-field spatial profiles from beams exiting a single-mode waveguide are shown in Figure 8. The measured data is displayed by the symbols, and Gaussian fits to the data, $exp(-2x^2/\sigma^2)$, are given by the solid lines. The measurements in Figure 8(a) were obtained from camera images of a CO_2 laser beam ($\lambda = 9.3$ μm) exiting the waveguide and were taken at 3 different distances from the end of the waveguide. The beam maintains a Gaussian shape as it diverges relatively slowly after exiting the waveguide.

In Figure 8(b), direct measurements of the divergence are shown taken at a distance of 65 mm from the end of the waveguide. In this plot, data is shown from both a $\lambda = 9.3$ μm CO_2 laser and a QCL operating at $\lambda = 8.2$ μm. These measurements were conducted by doing an angular scan of a single-element nitrogen-cooled HgCdTe detector rotating about the fiber end. Dwell time for each data point was 4 seconds, with a 0.1 deg scan increment; the input laser was chopped and detected using a lock in to reduce the effects of ambient thermal noise. The waist for the longer wavelength beam is larger, as expected for Gaussian beams.

Based on the far-field data shown in Figure 8, the beam waist at the exit plane of the 300 μm bore fiber is estimated to be about 80 μm and the effective numerical aperture (NA) is calculated to be NA = 0.031 at $\lambda = 8.2$ μm and NA = 0.037 at $\lambda = 9.3$ μm. We note that one must consider this relatively low NA to effectively design optics for coupling into and out of the waveguides.



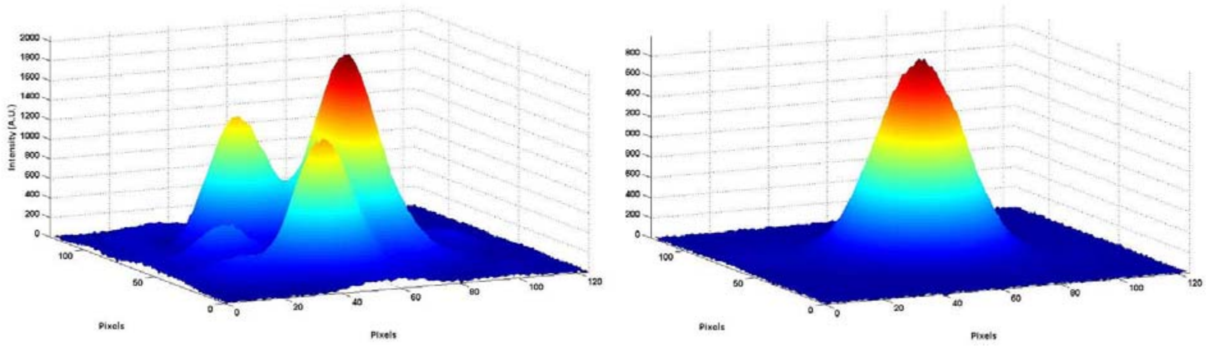
(a) (b)

Figure 8. Far field spatial profile data (symbols) of beam exiting single-mode waveguide, along with Gaussian fits (solid lines) labeled with their respective standard deviations. (a) Measurements of a $\lambda = 9.3$ μm CO_2 beam taken at 3 different distances from the waveguide: 29 mm, 39 mm, and 49 mm and (b) measurements of two different wavelength beams: 8.2 μm and 9.3 μm, both taken at a distance of 65 mm from the end of the waveguide.

3.3 Mode Filtering

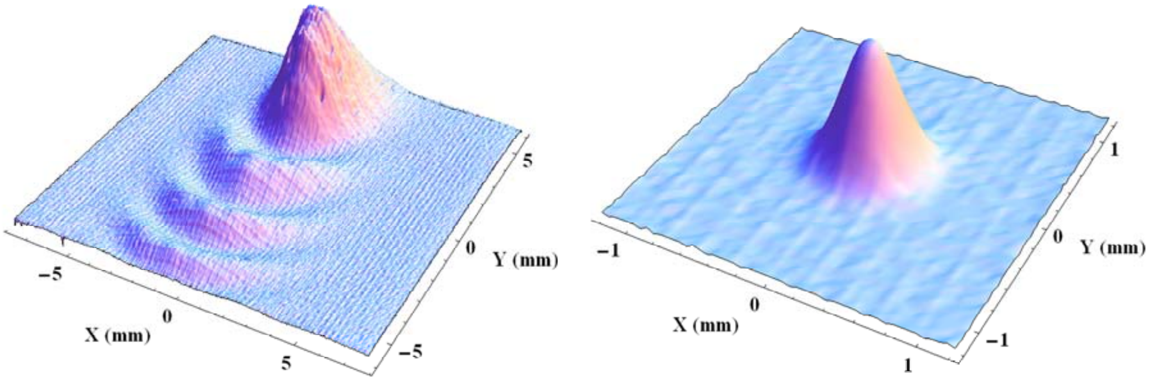
Two different demonstrations of mode filtering by a single mode (ID = 300 μm) waveguide are shown in Figure 9 and Figure 10. In Figure 9, a CO_2 laser beam ($\lambda = 10.6$ μm) was purposely misaligned with the waveguide (i.e., poor coupling) to excite higher order modes. When the waveguide is cut back to a short, 10 cm, long piece, evidence of the higher order modes is apparent in the spatial profile, Figure 9 (a). By comparison, the beam exiting a longer, 110 cm, waveguide is a smooth Gaussian indicative of the higher order modes being filtered out, Figure 9 (b).

In Figure 10, an example of mode filtering is shown for a QCL beam from a laser mounted in a high heat load (HHL) package by PNNL [10]. The collimated beam without the waveguide has an elliptical shape due to the approximately 2:1 divergence ratio between the fast and slow axes of the QCL. In addition, fringes are visible in the direct output from the QCL, which are believed to be due to the epi-down structure and reflection from the submount/heatsink. The image in Figure 10 (b) shows the output after exiting a single-mode hollow core waveguide. Both the elliptical shape and the fringes are "cleaned-up" by the waveguide as the beam is transformed into a circularly symmetric output. The filtering is not "free", of course, as there is a loss due to the higher order modes being damped out. One must consider this trade-off between beam quality and delivered power, when coupling in non-Gaussian beams.



(a) (b)

Figure 9. Spatial profiles of beams exiting a single mode (ID = 300 μm) waveguide. The laser was purposely misaligned with the waveguide (i.e., poor coupling) to excite higher order modes. (a) Beam exiting short waveguide, L = 10 cm and (b) beam exiting a longer waveguide, L = 110 cm, demonstrating mode filtering.

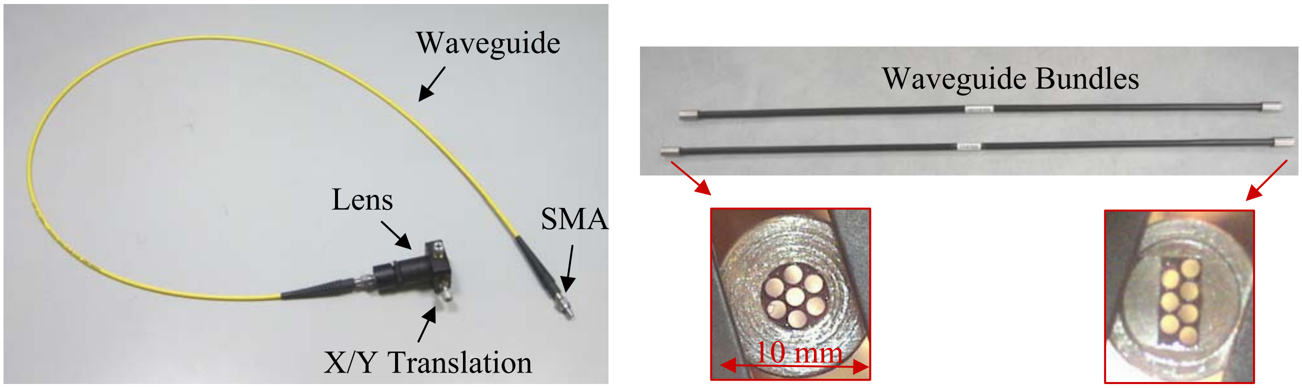


(a) (b)

Figure 10. Example of mode filtering of a QCL beam. (a) Camera image of output from HHL packaged QCL and (b) camera image of the same beam after exiting a single-mode waveguide (image taken 15 mm from end of waveguide).

4. RELATED AND FUTURE WORK

Optical packages are currently being optimized for various QCL coupling and beam delivery applications, e.g., Figure 11 (a). The coupling is simplified compared to single-mode fibers in other wavelength regimes and requires only X/Y translation due to the hollow core being relatively large. In addition to using the waveguide for beam delivery, it can also act as the gas cell for high sensitivity spectroscopy applications [11][12]. In such devices, the hollow core waveguide acts as a relatively small volume cell, within which a strong interaction between the probe beam and the gas under study can occur. Furthermore, bundles of waveguides have also been constructed for both signal collection, Figure 11 (b), and infrared imaging applications.



(a) (b)

Figure 11. Images of packaged hollow core waveguides. (a) Single mode waveguide with QCL coupling optics and (b) Waveguide bundles for signal collection applications.

The authors (OKSI and Rutgers) are actively pursuing improvements in the waveguide technology on a variety of fronts and for a range of applications. One major goal of this ongoing work is to reduce the overall loss in the waveguides, which can be accomplished using a multilayer dielectric structure [13], instead of just a single layer as shown in Figure 1. With such a multi-layer stack, theory predicts that the losses can be reduced by a factor of 100 times or more. This loss reduction is particularly important for applications that would benefit from smaller bore waveguides (e.g., ID < 300 μm), such as single-mode delivery of shorter wavelength beams (e.g. MWIR lasers) and for high resolution imaging bundle applications. In addition to the reduction in losses, hollow core waveguides are also currently undergoing shake/vibe testing to verify the stability of the output under a range of conditions.

5. CONCLUSIONS

Hollow core glass waveguides can be a useful tool for MWIR and LWIR (i.e., Mid-Infrared) laser applications. Waveguides specifically developed for single mode delivery of QCL beams have been produced and tested. Such waveguides have been demonstrated to deliver Gaussian like beams when the fiber is straight, when it is bent, and even for an elliptical QCL input beam (i.e., the waveguide mode filters). Waveguide probes are currently being developed for applications in beam delivery, trace gas detection, signal collection, and IR imaging applications.

6. ACKNOWLEDGEMENTS

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