Fiber delivery of mid-IR lasers

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Hollow-core waveguides enable effective, single-mode fiber delivery of mid-IR laser beams.

Fiber optics for the visible to near infrared (NIR) wavelength regimes (i.e., $\lambda = 0.4$–2$\mu$m) have proven to be extremely useful for a myriad of applications—such as telecommunications, illumination, and sensors—because they enable convenient, compact, and remote delivery of laser beams. Similarly, there is a need for fiber optics operating at longer wavelengths. For example, systems operating in the mid-IR regime (i.e., $\lambda = 3$–14$\mu$m) are being developed to detect trace molecular species with far-reaching applications, such as detecting explosives on surfaces, pollutants in the environment, and biomarkers in the breath of a patient. Furthermore, with the increasing availability of quantum cascade lasers (QCLs)—which are semiconductor lasers that operate in the mid-IR regime—additional uses are rapidly being developed. Here, we describe the development of hollow-core fibers for delivery of high-quality mid-IR laser beams across a broad spectral range.

Currently, the most widely used fibers for mid-IR applications are solid-core fiber optics comprised of chalcogenide glasses. Based on sulfur, selenium, and tellurium—along with elements such as germanium, arsenic, and antimony—these stable glasses transmit well in the mid-IR and can be drawn into fibers. However, chalcogenide glass fibers have serious drawbacks for use in molecular spectroscopy applications. For example, reflections off the fiber end can cause laser feedback, and cladding modes are supported in these waveguides. Both of these effectively reduce the signal-to-noise ratio in measurement systems. Current solutions—such as angle cleaving, anti-reflective coatings, and mode stripping—are cumbersome and do not effectively mitigate the resulting system noise. Furthermore, chalcogenide fibers are extremely brittle if impurities are not controlled, and transmission is attenuated strongly at long wavelengths, with a working limit of about $\lambda \lesssim 6\mu$m for sulfide and $\lambda \lesssim 9\mu$m for selenide glass.

Since solid-core fiber options are generally inadequate for mid-IR range laser beam delivery, we fabricated hollow fibers with reflective silver and dielectric layers (see Figure 1). We achieved this by pumping a silver solution through glass tubing, which created a smooth silver layer on the inside of the tube. We then pumped an iodine solution through the tube, which forms a dielectric silver iodide (AgI) layer upon reaction with the silver. The glass tubing provides a smooth, robust, and flexible structure on which to deposit the coatings. For most mid-IR applications, AgI is used as the dielectric material, and its thickness can be optimized for specific wavelengths. The inner diameter (ID) of our hollow fibers determines the performance characteristics with improved beam quality—but higher loss—for smaller ID fibers. In many applications, high beam quality (i.e., single-mode) is desirable and can be readily achieved when the ID $\lesssim 30\lambda$.

Recently, we improved the smoothness and uniformity of the coatings of our hollow fibers and recently developed hollow fiber solutions specifically for QCL applications (see Figure 2). In general, we can produce two broad classes of fibers. The first class are single-mode fibers for long-wave infrared (LWIR) applications operating at $\lambda = 6$–14$\mu$m. The second class consists of multi-mode, low-loss fibers for broadband applications operating at $\lambda = 3$–14$\mu$m. Additionally, we can produce other hollow fibers tailored for specific wavelength regions and applications, including separate solutions for visible and terahertz regimes.

The development of a LWIR single-mode class of fibers was driven by the need for high-quality, stable beams. Thus, we...
Figure 2. Hollow fiber coupling package shown attached to a commercial mid-IR laser.

Figure 3. Example of mode filtering. A camera image of (a) a beam from a custom-packaged quantum cascade laser and (b) the beam after exiting a single-mode hollow fiber.

We fabricated fibers with ID of 300μm and tested the loss and output beam profiles using both carbon dioxide lasers and QCLs.\textsuperscript{8,9} We focused the laser beams into the fibers and measured the beam exiting the fiber with either a power meter (for loss measurements) or a camera (for beam profile measurements). The measured loss of these fibers was 1–3dB/m at λ=10μm, with an additional loss on bending of 0.1dB for a 90° bend with a radius of 0.25m. Despite this additional loss on bending, our single-mode fibers maintained an excellent Gaussian output profile even when bent, which is important for the delivery of high-quality beams to specific, convenient locations. Furthermore, the coupling is simple and highly efficient (\textasciitilde 95%), and the fibers can transmit relatively high power (30W). Additionally, our multi-mode class of fibers has a larger hollow bore (ID of 700μm), which results in lower loss (0.1dB/m) and the ability to transmit higher power beams (100W).

In addition to preserving a Gaussian profile on bending, our single-mode fibers exhibited mode filtering (see Figure 3). For example, a beam from a custom QCL—with an elliptical shape and fringes—was ‘cleaned-up’ by our hollow fiber, resulting in a circularly symmetric (Gaussian) output.\textsuperscript{10} However, the filtering is not without its drawbacks since there is a loss due to the damping out of higher-order modes.

In summary, we fabricated and tested hollow wave-guides for fiber coupling for mid-IR lasers. In particular, we demonstrated single-mode beam delivery of QCLs operating at LWIR wavelengths. In the future, we will develop new multi-layer dielectric coatings with significantly lower loss. These new coatings have the potential to enable single-mode delivery for shorter wavelength (λ= 3–5μm) lasers and will allow applications such as remote thermal imaging using a coherent bundle of small-ID hollow fibers.

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