Hollow waveguides for the transmission of quantum cascade laser (QCL) energy for spectroscopic applications

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Abstract

Spectroscopy in the long-wave infrared (LWIR) wavelength region (8 to 12 µm) is useful for detecting trace chemical compounds, such as those indicative of weapons of mass destruction (WMD). To enable the development of field portable systems for anti-proliferation efforts, current spectroscopy systems need to be made more robust, convenient, and practical (e.g., miniaturized). Hollow glass waveguides have been used with a Quantum Cascade Laser source for the delivery of single-mode laser radiation from 9 to 10 µm. The lowest loss measured for a straight, 484 µm-bore guide was 0.44 dB/m at 10 µm. The smallest 300 µm-bore waveguide transmitted single-mode radiation even while bent to radii less than 30 cm.

Keywords: Infrared fiber optics, hollow waveguides, infrared spectroscopy, long-wave infrared (LWIR).

INTRODUCTION

Hollow glass waveguides (HGWs) are an attractive alternative to conventional solid-core IR fibers for applications ranging from laser power delivery to broadband chemical sensing and thermal imaging. Hollow waveguides not only enjoy the advantage of high laser power thresholds but also low insertion loss, no end reflection, ruggedness, and small beam divergence. A disadvantage, however, is a loss on bending which varies as $1/R$ where R is the bending radius. In addition, the losses for these guides vary as $1/a^3$ where a is the radius of the bore and, therefore, the loss can be relatively high for small cores. The bore size and bending radius dependence of all hollow waveguides is a characteristic of these guides not shared by solid-core fibers. Initially these waveguides were developed for medical and industrial applications involving the delivery of CO_2 laser radiation, but they have also proven useful for transmitting incoherent light for broadband spectroscopic and radiometric applications.

One of the most popular HGW structures is comprised of a silica tube with an inner coating of Ag/AgI as shown in Fig. 1. These hollow guides have been thoroughly described in the literature and reviewed by Harrington.[1] Such HGWs are fabricated using wet-chemistry methods to first deposit a Ag layer on the inside of silica glass tubing and then to form a dielectric layer of AgI over the metallic film by converting some of the Ag to AgI. The thickness of the AgI is optimized to give high reflectivity at a particular laser wavelength or range of wavelengths. Using these techniques, HGWs have been fabricated with lengths as long as 13 m and bore sizes ranging from 250 to 1,300 µm.

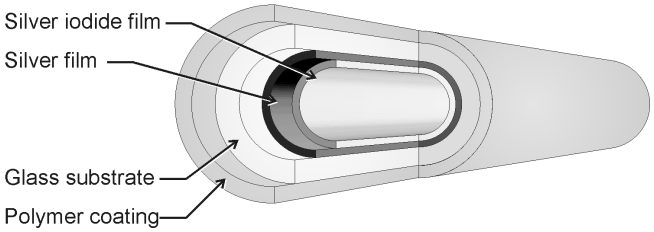

Figure 1 – Cross section of a Ag/AgI coated HGW.

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FABRICATION OF HGWS

The fabrication of HGWs begins with silica tubing, which has a polymer (UV acrylate or polyimide) coating on the outside surface that serves to preserve the strength of the silica tubing. A dynamic liquid-phase chemistry technique, shown in Fig. 2, is used to deposit the Ag and AgI films inside the glass tubing.[3] This technique is similar to that used by Croitoru and his co-workers[4] to deposit metal and dielectric layers on the inside of plastic tubing. The first step involves depositing a silver film using standard electro-less Ag plating technology as shown in the left half of Fig. 2. Next, a very uniform dielectric layer of AgI is formed through an iodization process in which some of the Ag is converted to AgI. The iodization step is shown in the right half of Fig. 2. As shown in Fig. 2, a peristaltic or suction pump can be used to force the silver and reducing solutions through the silica tubing. Generally, the Ag film is between 0.25 and 1 μm thick, and it is deposited at room temperature slowly over a period of about 1 hour. Immediately after the silver is deposited, an iodine solution is pumped through the tubing and, through a subtraction process, a layer of AgI is formed. By controlling the concentration of the iodine solution and reaction time, an AgI film of the correct optical thickness can be deposited.

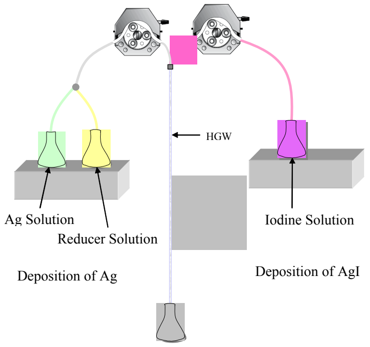

Figure 2 – Setup for silvering and iodizing silica tubing.

There are several key process parameters involved in the deposition of the metallic and dielectric films that dictate the quality and uniformity of the films. Among these are the flow rate, the reaction time, and the concentration of the solutions used. Because the AgI film is formed from the Ag layer, it is essential to have a sufficiently thick silver film otherwise the Ag layer will be too thin for the formation of a sufficiently thick AgI film over Ag. To improve the quality of the Ag film both in terms of smoothness and adhesion, we first sensitize the silica tubing using a dilute solution of stannous chloride. Then an appropriate thickness of Ag is deposited. For the AgI films we have determined the chemical kinetics necessary to correlate the iodization time and the thickness of the AgI layer. The data in Fig. 3 show how the thickness of the AgI films increase with increasing iodization time.

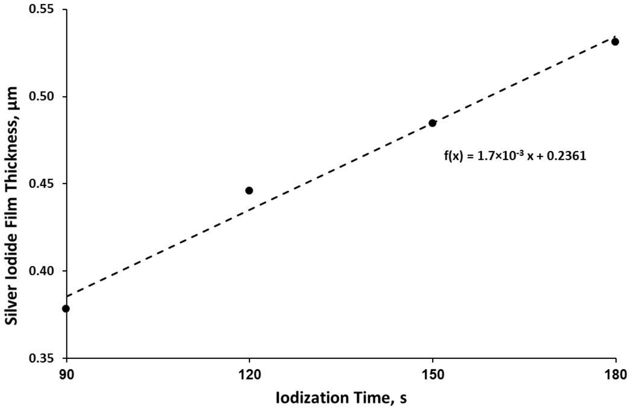

Figure 3 – Deposition times used to produce different AgI film thickness.

OPTICAL PROPERTIES OF AG/AGI COATED HGWS

1.1 Spectral loss

The spectral losses for different AgI film thickness are given in Fig. 4. This data shows the characteristic interference peaks that one would expect from AgI thin-film interference. This data was taken on one waveguide with a bore size of 1000 μm which had been successively coated to increase the thickness of the AgI layers. That is, the Ag-coated guide was iodized for 90 s and then the spectrum measured as shown in Fig. 4. The same guide was then iodized for another 30 s and remeasured. We have repeated this iodization for as many as 12 times and each time the guide is iodized the AgI layer becomes thicker and the interference peaks shift to longer wavelengths.

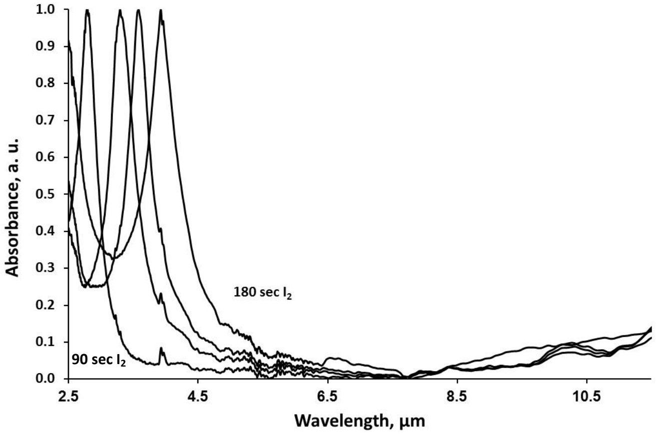

Figure 4 – Successive iodization of 1,000 μm bore HGW. The shortest time is 30 s and each successive deposition is for 30 s. The longest deposition time shown is 180 s.

The HGWs for this application were iodized for about 2 to 3 minutes. In this way we optimize the optical response for transmission from 9 μm to 10 μm. This is the operating region for the QCL used in this study. If we wished to have the guides transmit at shorter wavelengths then we would make thinner AgI films by reducing the iodization time accordingly.

1.2 Loss measured using QCL

We made measurements at 9.0, 9.5, and 10.0 μm using a Daylight Solutions, Inc. QCL laser. This laser ran in pulsed mode with an average power of 10 mW or less. In Fig. 5 we show the lowest measured straight loss at 10.0 μm for two HGWs each 110 cm in length. We expect the loss to increase with decreasing bore size or specifically as $1/a^3$. This strong dependence on bore size may be seen in the calculated loss at 10.6 μm, which is shown as the solid line in Fig. 5. The measured values for the 300 and 484 μm bore guides are those obtained for the QCL that was apertured to improve the mode quality. We note that the measured loss of 0.44 dB/m at 10.0 μm for the 484 μm-bore guide is reasonably close to the loss calculated at 10.6 μm.[2] We also measured the losses at 9.0 and 9.5 μm

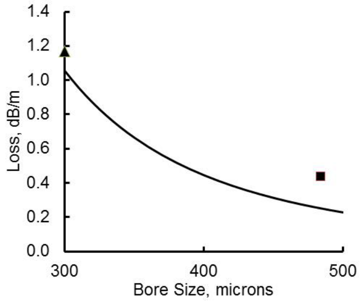

Figure 5 – Loss at 10.0 μm for two HGWs. The solid curve is the calculated loss at 10.6 μm.

and found that there was little difference from the losses measured at 10.0 μm. This is not unexpected as the spectra in Fig. 4 show that the spectral losses vary little over this rather small wavelength range.

1.3 Modal properties of the QCL and HGWs

The spatial mode of the output beam of the Daylight Solutions QCL is slightly elliptical. According to the manufacturer the beam profile 20 cm from the laser output is 2.2 × 2.5 mm. Coupling light most efficiently into HGWs means that we would like to launch a nearly perfect TEM_{00} mode into the guide with a spot size at the $1/e^2$ points equal to about 70% of the bore size. This will couple almost all of the energy into the lowest order HE_{11} waveguide mode. Nubling and Harrington[5] have shown that coupling into the lowest order mode depends somewhat on the bore size of the waveguide but that in general the most efficient coupling occurs with f/numbers between 20 and 25. For smaller f/numbers higher order modes will be coupled into the guide, which will result in higher loss.

The spatial output that we measured for the raw beam of the QCL is shown in Fig. 6. From the profile taken without an aperture it can be seen that the raw beam is indeed elliptical and clearly non-Gaussian. We then aperture the beam with a 1.6 mm diameter aperture to achieve the profile shown in Fig. 6. Adding an aperture in the output of the QCL cleans up the spatial profile and gives us the higher, more efficient f/number launch. We measured the loss for both the 300 and 484 μm-bore guides as a function of f/number which we controlled by aperturing the input beam. The loss at 10 μm is given in Fig. 7 for three different f/number launches. The reduction in loss as a result of increasing the f/number is significant. In fact we would expect an even a lower loss if we were to have launched with f/numbers closer to f/20 to f/25. [5]

Figure 6 – Raw beam from QCL. QCL beam with external 1.6 mm aperture.

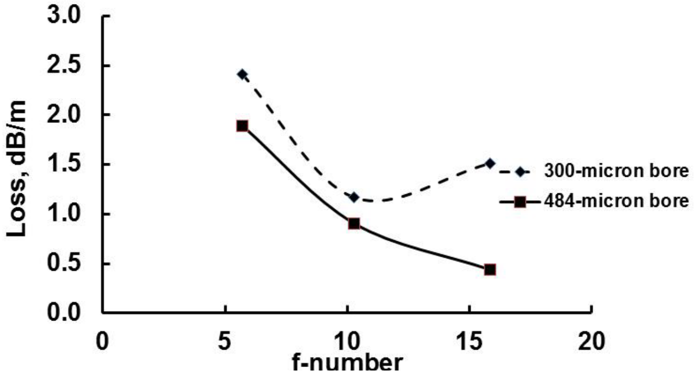

Figure 7 – Loss improves for 484 μm guide with better coupling to the lowest order mode. For 300 μm guide loss increases at f/16 as the beam size increases beyond the optimal coupling condition.

One of the primary objectives of this work was to deliver a single-mode (SM) output beam. A SM output provides nearly perfect coupling of the laser light into the multi-pass gas cells, e.g. Herriott cell, used for high sensitivity spectroscopy applications. Furthermore, it is critical that the input to such a multi-pass gas cell be SM, otherwise the beam would diverge too much for the long path lengths inherent in this type of gas cell. To achieve a SM output from a HGW requires a bore size of approximately 25 to 30 times the wavelength of the laser light. This is mostly an empirical result verified by studies of the SM behavior of HGWs used to transmit CO_2 laser radiation. Transmission and preservation of the SM property of the guides also depends on bending, which can couple light into higher order modes, and on the thickness of the glass wall. The most effective approach to propagating SM energy is to use a small bore waveguide, for example the 300 μm-bore by 665 μm guide for long wavelength radiation in the 10 μm range. In Fig. 8 we show the spatial profile of a straight and bent (R = 50 cm) 300 μm-bore guide. This data was taken with a CO_2 laser source launched into a 110-cm long guide. The mode remains nearly Gaussian even on bending. In Fig. 8, the profile of the bent guide appears narrower than that for the straight guide. We believe that this is due to measurement of the spatial profiles at slightly different distances from the Spiricon pyroelectric-array camera rather than any fundamental modal property. We have found that a similar experiment using the larger bore 484 μm-bore guide resulted in mode mixing and a multimode output.

Figure 8 – Spatial profile for straight 300 μm bore guide Same guide with a 50 cm bend radius

An interesting modal property of HGWs is their ability to mode filter. That is, if a multimode laser is focused into a small bore waveguide, the guide can filter the multimode radiation to produce only an SM output. Naturally, the mode filtering of higher order mode radiation to SM radiation comes at the expense of power. Yet the mode filtering properties of the guides can be very useful in some applications. To illustrate this property we show in Fig. 9 the spatial profile of a 300 × 665 μm waveguide for a short, 10-cm length compared to a 110-cm length. A CO_2 laser was used as the source and it was focused into the guide slightly off axis to propagate some low order modes as well as the lowest order HE_{11} mode. After 10 cm the mode is a mixture but, as seen in Fig. 9, after traveling 110 cm the mode is nearly Gaussian. Mode filtering works when the bore size is in the SM regime, i.e. a bore diameter equal to 25 to 30 times the wavelength. If the bore size is larger the guide will not produce the reliable mode filtering.

Figure 9 – 110-cm long, 300 μm bore guide 10-cm long, 300 μm bore guide

SUMMARY AND CONCLUSIONS

Flexible HGWs provide a convenient method of transmitting QCL radiation. Hollow silica waveguides with inner Ag/AgI coatings transmit well the IR radiation that is most common for current QCLs. We have shown that when the input beam from a QCL has a near Gaussian spatial profile that the loss for the guides is nearly equal to the value calculated for the lowest order HE_{11} mode. To preserve the SM qualities of the input beam and deliver a SM output even under bending requires a smaller bore size guide. For the QCL used in this study we found that a 300 μm-bore guide did deliver a SM output. This is very important for applications in gas sensing in which the guide must deliver QCL radiation to a multi-pass gas cell. We also showed that the HGWs could be used as mode filters to filter out low order modes to obtain an SM output.

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