Coherent hollow-core waveguide bundles for infrared imaging

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Abstract. Coherent IR fiber optic bundles for use in IR imaging from 2 to 12 μm are fabricated from rigid hollow-glass waveguide arrays. The bore of each hollow glass tube in the bundle is coated with thin films of metallic Ag followed by AgI for enhanced reflectivity. The coating of the rigid bundle is done using liquid phase chemistry techniques applied to all tubes simultaneously. The hollow-glass arrays are composed of up to 900 individual tubes with bore sizes as small as 50 μm. Several rigid hollow-core arrays are used to transmit an IR image of a small loop of hot wire and a sample of tissue heated by a CO_2 laser. [DOI: 10.1117/1.1687729]

Subject terms: hollow waveguides; IR fiber optics; IR imaging; coherent fiber bundles.

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1 Introduction

Coherent fiber optic arrays composed of oxide glass fibers have been fabricated for many years using mandrel wrapping and leached bundle technologies.[1] These coherent fiber bundles have been used to transmit high-resolution images for a variety of applications, including endoscopic medical imaging of tissue and industrial borescopes for remote inspection systems. There has, however, been very little work to extend the wavelength range of fiber image bundles to wavelengths greater than 2 μm. This is due in part to the lack of IR transmissive fibers with optical and mechanical properties analogous to the oxide glass fibers currently employed in the visible fiber bundles. Nevertheless, if an IR fiber image bundle could be made, it would have significant applications for thermal imaging, especially for low temperatures where blackbody radiation is most intense. To date, most IR fiber arrays have been fabricated from chalcogenide glass fibers. Nishi et al.[2,3] and Hilton[4] have made coherent IR fiber bundles consisting of several thousand As_2S_3 fibers. More recently, Rave, Katzir, and Paiss[5,6] have extruded polycrystalline silver halide fibers into coherent bundles. In this work, we employ our Ag/AgI-coated hollow-glass waveguide (HGW) technology to form coherent bundles for IR imaging.[7–9] An advantage of the HGWs is that we may use either mandrel wrapping or leach bundle methods to make the coherent fiber array. Once the bundle has been fabricated, we coat all tubes simultaneously with Ag/AgI coatings. This oxide glass structure is simple in design, low in cost, and quite rugged. We report our results for rigid coherent bundles, not flexible fiber bundles. In the past, we have reported on some low fiber count, flexible HGW arrays made from silica capillary tubing.[9] These flexible HGW arrays had a high loss resulting from the small bore size of the individual tubes comprising the bundle. Therefore, we have temporarily abandoned work on the flexible bundles in favor of rigid coherent arrays. Once we have lowered the losses, we intend to return to producing longer-length flexible hollow waveguide arrays. The rigid, coherent bundles may be employed in short lengths for some medical IR imaging and image transfer applications. Recent *in-vivo* studies have emphasized the importance of IR imaging of human tissues for two purposes[10]: 1. screening neoplastic superficial tissue layers, based on significant thermal gradients observed between healthy, benign, and malignant cells; and 2. facilitating laparoscopic surgery, as it sharply visualizes the localization of anatomic structures and simplifies the assessment of tissue viability and blood perfusion throughout the procedure. Such physiologic parameters are not attainable with visible techniques.

2 Fabrication of Rigid, Coherent HGW IR Bundles

Rigid arrays composed of ordered glass capillary tubes were purchased from Collimated Holes, Incorporated. Two bore size bundles were used in the study. One array had 500 holes with an individual bore size of 150 μm, and the other had 900 holes with a bore size of 50 μm. The length of the

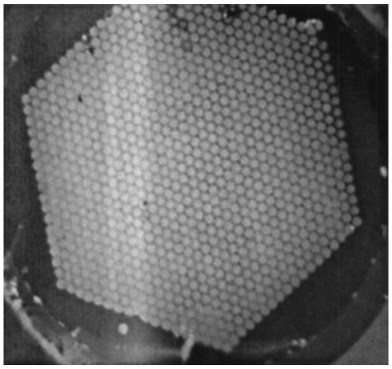

Fig. 1 Uncoated collimated hole rigid bundle with 900 capillaries, each with a 50-μm bore size.

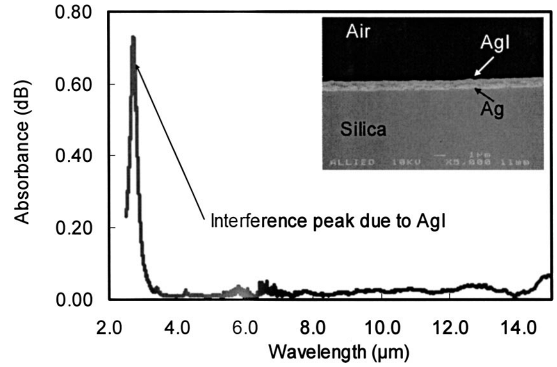

Fig. 2 Spectral response of a single Ag/AgI-coated HGW made using silica tubing. The thickness of the AgI film determined from averaging the optical and FESEM data is 0.38±0.02 μm.

as-received tubing was as long as 1 m, but the arrays that were coated varied in length from 2 to 20 cm. An image of the capillary array containing 900 capillaries with a bore size of 50 μm is shown in Fig. 1.

The active core area of the bundles determines the actual imaging area. The calculated core areas for the two capillary arrays that we used are given in Table 1. Normally, for good resolution, a bore size nearer 25 μm is desirable, but for our first bundles we decided to first deposit coatings in somewhat larger bore bundles and then proceed to the smaller bore sizes once the coating technology had been well established. Additionally, it is generally desirable to have an active core region greater than 50%. This would involve fabricating bundles made from tubing with a smaller capillary wall thickness. In the bore size tubing that we have used, the wall thickness should be between 5 and 10 μm to achieve an active core area of at least 50%.

The same liquid phase chemistry procedure used to make single bore HGWs is used to coat the rigid coherent bundles. The first thin film deposited is silver, followed by a conversion of some of the silver film into AgI for enhanced reflectivity. The thickness of the AgI film is tailored to give low loss across a broad spectral range. This is generally desirable for most IR imaging applications. As an example, we show in Fig. 2 the spectral response for a single Ag/AgI-coated HGW with the thickness of the AgI film optimized for low loss near 3 μm. This spectrum was measured using a Nicolet Protégé 460 FTIR. Light from the spectrometer was coupled into a short ($\sim$2 cm) HGW launch tube. The launch tube was then butt-coupled to a 1-m-long HGW for the spectral measurement. This particular AgI film yields low loss over a reasonably flat spectral region for wavelengths greater than about 3 μm. The AgI film produces interference peaks, from which we can estimate the film's thickness using

$$d_p = \frac{m\lambda_p^m}{4\sqrt{n^2-1}}, \tag{1}$$

where m is the order of the interference maxima; λ_p is the wavelength of the m'th interference peak; and n is the refractive index of the dielectric film.[11] From Fig. 2 we see that the position of the first interference peak is at $\lambda_p^1 = 2.9$ μm. Using Eq. (1) and a refractive index of AgI, $n = 2.21$, gives an AgI film thickness of 0.36 μm. As an independent check on film thickness, we used a FESEM to determine the thickness of both the metal and dielectric layers. The insert in Fig. 2 shows a cross section of the Ag/AgI films on silica tubing. A direct measurement of thickness from the FESEM gives an AgI film thickness of 0.4 μm, which is in good agreement with the optical measurements.

3 Optical Losses in Coherent Bundles

The spectral response of the two coherent bundles was measured using the same FTIR spectrometer and launch optics used for single HGWs. Figure 3 shows the spectra of the rigid coherent bundle containing 500 capillaries, each with a bore size of 150 μm. The top curve in Fig. 3 was measured on the uncoated, as-received glass bundle. This spectrum of the uncoated sample shows a decrease in attenuation between approximately 8 and 10 μm. Within this spectral range, the lead silicate glass used to make the bundle has a refractive index less than one.[12,13] Because the glass tubing wall has an index less than that of the air core, the loss will be less in this spectral region (Reststrahl region). This type of $n<1$ fiber-like structure has been studied in both glass[14] and crystalline hollow guides.[15] The first

Table 1 Active core area for rigid bundles madeby Collimated Holes, Incorporated.

Collimated hole bundle	Bore, μm	OD bundle, mm	Number of fibers	% core area
CH50900	50	3	900	25
CH150500	150	6	500	31.2

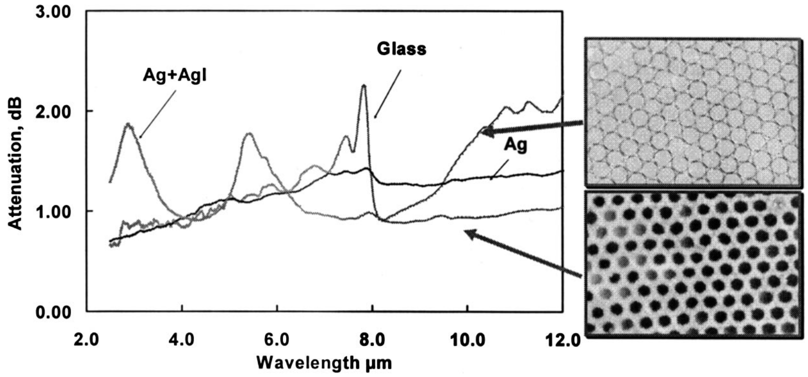

Fig. 3 FTIR spectra of rigid coherent HGW IR bundle made from Collimated Holes, Incorporated, capillary arrays having 500 holes with bore size 150 μm and length 2.5 cm.

thin film deposited is Ag, and the spectrum of the bundle with Ag only is also shown in Fig. 3.[7] Finally, the AgI layer is deposited over the Ag film and the losses are reduced, as shown in the same figure. Note also the photographs of the ends of uncoated and Ag/AgI-coated bundles in Fig. 3.

Figure 4 shows the spectral response of the two rigid coherent bundles that have been coated with Ag/AgI films. The smallest bore bundle has 900, 50-μm holes. This spectrum is contrasted with the results for the Ag/AgI bundle with 500, 150-μm holes, also shown in Fig. 3. Both coherent bundles show sharp absorption peaks due to thin-film interference in the AgI thin-film coatings.[16] The relative sharpness of these peaks is an indication of the good AgI film uniformity in all of the capillary tubes making up the bundle. This is an important result, because nonuniform film thicknesses would lead to a smearing of the interference peaks and increased attenuation.[11] The coherent waveguides shown in Fig. 3 have good transmission beyond about 6 μm and, therefore, would be a good choice for imaging in the 8- to 12-μm region. The losses for the bundles, however, are rather high. This is due in large part to the small bore size. We have measured the loss of individual Ag/AgI-coated HGWs with a bore size of 150 μm similar to that used in the bundle. The loss measured using a CO_2 laser, was found to be 0.097 dB/cm for the single 150-μm bore waveguides. Here, the loss is given in dB/cm because the length of the bundles and small bore samples was only a few centimeters.

4 Thermal Imaging of Coherent HGW Bundle

A small-bore rigid coherent bundle with a capillary bore size of 65 μm and 900 holes was used to image a hot wire. The spatial resolution was estimated to be 85 μm based on the ability to just image two hot wires with an 85-μm spacing. All images were obtained at Tel Aviv University using a FLIR ThermaCam SC500 IR camera with a 5-cm focal length imaging lens between the object and bundle and a 2.5-cm focal length magnifying lens between the bundle and camera. The setup is shown in Fig. 5. The IR camera operated over the wavelength range from 7.5 to 13 μm. Figure 6 shows the image transmitted by the bundle. The hot tungsten wire imaged had an OD of 0.2 mm and the loop was 2 mm in diameter. The temperature of the wire was about 700°C. The temperature scale in the figure corresponds to the camera's reading after the attenuation caused by the optical coupling. Figure 7 shows a thermal image of a CO_2 laser interacting with an *ex-vivo* porcine stomach. This image illustrates the ability of the system to record the temperature changes in the tissue sample. This is important, as this thermal information may be used in the future as a feedback signal to control tissue temperature.

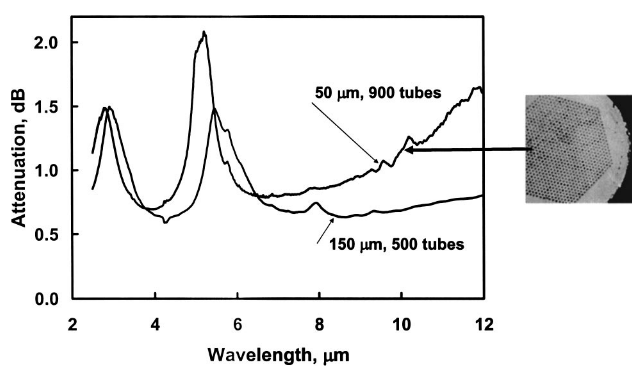

Fig. 4 FTIR spectra of two rigid coherent Ag/AgI HGW bundles, made using capillary arrays from Collimated Holes. The length of both the 50- and 150-μm rigid bundles is 2.5 cm.

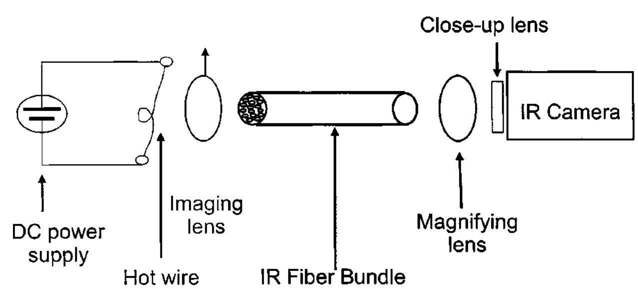

Fig. 5 Experimental arrangement for IR imaging of a hot wire through the 900 hole×65-μm bore HGW bundle. The tungsten wire was electrically heated and focused by a 5-cm IR lens onto the bundle's left end. The image emitted from the bundle's right end was magnified by a 2.5-cm IR lens and the IR camera's close-up lens (×5), then recorded.

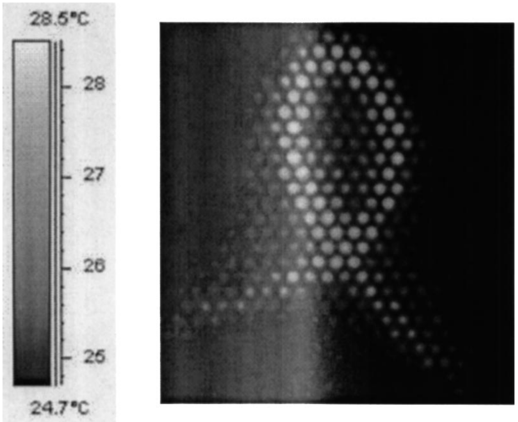

Fig. 6 Thermal image of a heated tungsten wire transmitted by the rigid Ag/AgI HGW bundle. The rigid Ag/AgI HGW bundle contains 900 holes of bore size 65 μm. About 550 of the holes are used in this image.

5 Conclusions

IR coherent bundles are potentially very useful for thermal imaging. The bundles that we have coated with the Ag/AgI films transmit in the long 8- to 12-μm wavelength region. The results of imaging a small hot wire are encouraging, but the lengths of the waveguide bundles were only about 2.5 cm. The primary reason for the short lengths is the high loss for these bundles. Since the loss increases as $1/a^3$, where a is the bore radius, the losses for such very small bore, single dielectric layer HGWs are rather high.[8] For example, the loss for the best 250-μm single-bore HGW at 10.6 μm is about 2.0 dB/m.[16] This means that decreasing the bore size by a factor of 5 to 50 μm would lead to an increase in the attenuation by $(5)^3$ or 125 to an almost untenably high value of about 250 dB/m. Thus, these early experiments had to employ short lengths and hotter sources to observe any image through the bundles. The approach for lowering the loss of either a rigid or flexible bundle is to use multiple dielectric layers composed of alternating high/low refractive index materials. Recently, we developed CdS and PbS coatings for deposition over Ag films as a means of substantially lowering the loss of the hollow waveguides.[17] For example, if we were to use a three-layer dielectric stack of these sulfide materials, we would expect a reduction of about 5 in the attenuation over a single-layer structure. At the moment, we are only able to use the Ag/AgI-coated HGW bundles in short lengths for image transfer in applications involving image transfer faceplates or other short-length biomedical imaging applications.

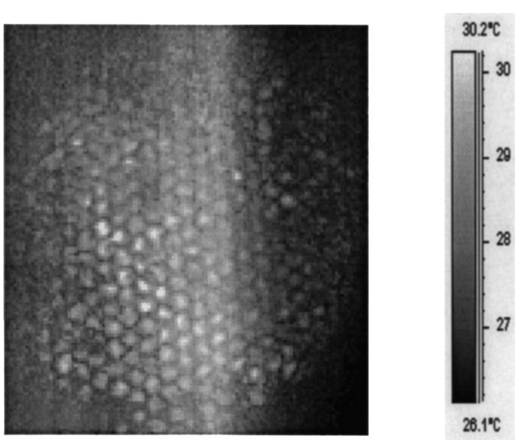

Fig. 7 2-D thermal image of a CO_2 laser interaction with tissue *ex-vivo* (porcine stomach) via a 900-hole$\times$65-μm bore HGW IR bundle. Intensity of the CO_2 laser beam was 127 W/cm^2 on the tissue.

Acknowledgment

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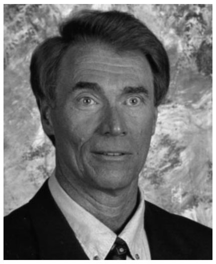

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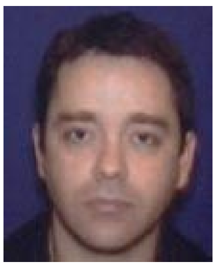

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