Loss and modal properties of Ag/AgI hollow glass waveguides

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Hollow glass waveguides, composed of Ag/AgI coatings, have been studied at 10.6 μm. The losses for different bore sizes equal the theoretical loss, which for the 700 μm bore guide was about 0.15 dB/m. The losses for the guides increase upon bending, varying linearly with increasing curvature. These hollow guides propagate a single mode when the bore size of the guide is approximately 30λ. In addition, the best single-mode transmission is obtained when the thickness of the glass wall is large. These smaller bores, thick wall hollow guides, can also be used to filter higher order modes from poor quality input laser beams. © 2012 Optical Society of America

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1. Introduction

Hollow-core waveguides are being used for a variety of applications ranging from laser power delivery to broadband chemical sensing and thermal imaging. Hollow waveguides not only hold 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 by $1/R$ where R is the bending radius. In addition, losses for single-bore, hollow guides, i.e., one-dimensional, vary by $1/a^3$ where a is the radius of the bore. In practice, this means that the loss can be relatively high for core sizes less than about 250 μm. The bore size and bending radius dependence of all hollow waveguides is a characteristic of hollow waveguides 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 [1].

One of the most popular structures is the hollow glass waveguide (HGW) 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 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 [2].

In addition to the loss properties of the HGWs, it is also important for many applications to have good mode quality. A particular advantage of the hollow guides is that they can transmit a single mode (SM) even when the size of the core is 20 to 30 times larger than the wavelength. For example, in past work we have shown that small bore HGWs with bore sizes of 250 μm preserve the mode of a 10.6 μm CO_2 laser even when bent [3]. Furthermore, we have shown that the wall thickness of the silica tubing affects

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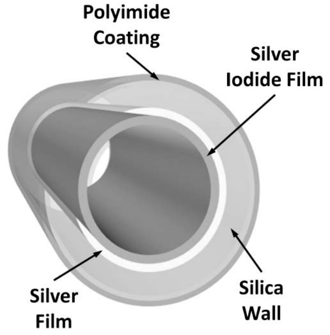

Fig. 1. Cross section of an Ag/AgI coated HGW.

the modal properties [4]. In this paper we show that guides with bore sizes up to 500 μm can be SM at 10.6 μm if the wall thickness is sufficiently large. Furthermore, an interesting and potentially important modal property is the ability of the guides to mode filter. That is, when a multimode laser beam is launched into a sufficiently small-bore waveguide the output of the guide will be SM. Naturally, the resultant mode filtering occurs at the expense of higher loss. However, for some applications it may be important to improve the beam quality, so the use of a small-bore guide might prove to have advantages.

2. Fabrication of HGWs

The fabrication of HGWs begins with capillary 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 [2]. This technique is similar to that used by Croitoru *et al.* [5,6] to deposit metal and dielectric layers on the inside of the plastic tubing. The main processing parameters that determine the film quality, and thus optical response, include fluid flow rate, solution concentrations, and deposition times. 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 over a period of about 25 minutes. Immediately after the Ag 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.

There are several key process parameters involved in the deposition of the metallic and dielectric films dictating 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 Ag 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 acidic solution of stannous chloride. Then, an appropriate thickness of Ag is deposited. The thickness of the deposited AgI films depends on the chemical kinetics. This includes the iodization time, the concentration of the iodine solution, and the flow rate. In Fig. 3 we show the spectra of the Ag/AgI coated guides as a function of coating time. As may be seen in the data presented in Fig. 3, the first interference peak shifts to longer wavelengths as the thickness of the AgI layer increases due to increasing iodization times.

The actual thickness, d, of the AgI film is calculated from the Fourier transform infrared spectroscopy (FTIR) spectra using Eq. 1:

$$d = \frac{\lambda_{\mathrm{opt}}}{4\sqrt{n_d^2 - 1}}, \tag{1}$$

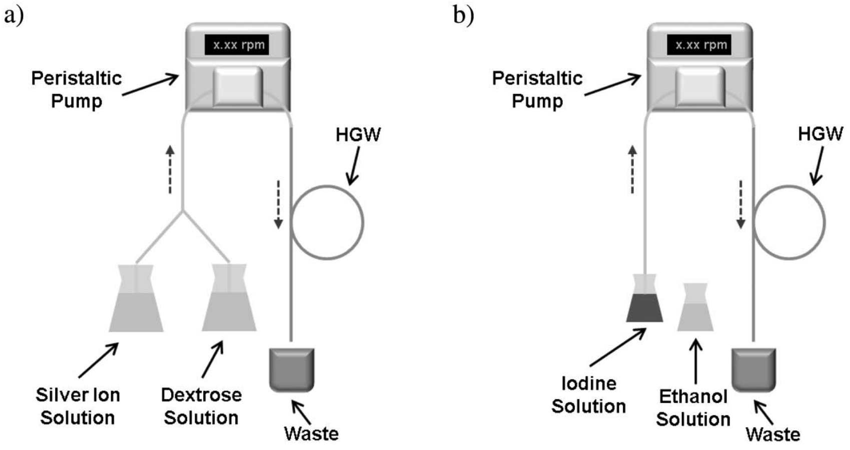

Fig. 2. Setup for (a) silvering and (b) iodizing silica capillary tubing.

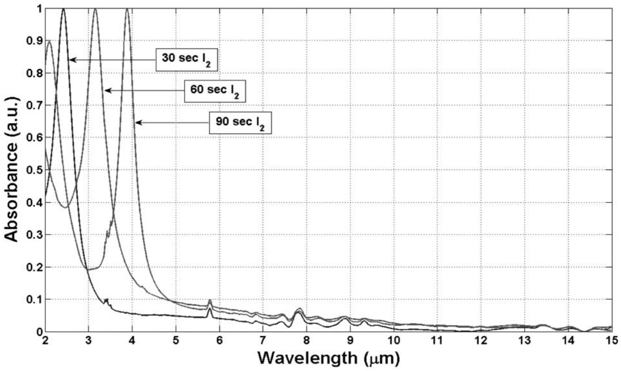

Fig. 3. Fourier transform infrared spectroscopy spectra of Ag/AgI HGW at different iodization times.

where λ_{opt} is the wavelength of the first interference peak and n_d is the refractive index of the dielectric film. The growth kinetics of the AgI dielectric film, formed during the iodization process, depends primarily on solution concentration, fluid flow rate, and deposition time. Matsuura *et al.* [7] have shown that the film thickness follows an mth root dependency with respect to iodization time for a fixed solution concentration. The dependency of the AgI film thickness as a function of iodization time for an iodine solution at a concentration of 10 g/L in cyclohexane is presented in Fig. 4.

The optimal dielectric film thickness can be found for any desired wavelength region and in the case of a single dielectric film is given by:

$$d_0 = \frac{\lambda_d}{2\pi\sqrt{n_F^2 - 1}} \tan^{-1}\left(\frac{n_F}{(n_F^2 - 1)^{1/4}}\right), \tag{2}$$

where n_F is the refractive index of the dielectric film material and λ_d is the design wavelength. For this particular study we seek an HGW which has low loss in the 10 μm region, therefore a target AgI thickness of about 0.65–0.75 μm is desired. Losses for HGWs at 10.6 μm depend primarily on the dielectric film material used, the film thickness itself, the bore size, the degree of applied bending, and film surface roughness.

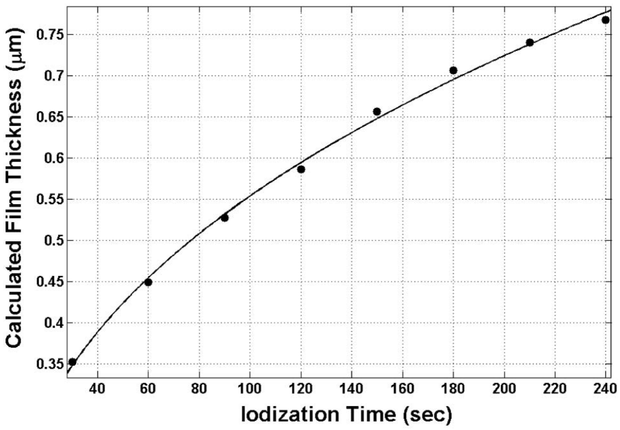

Fig. 4. AgI film growth kinetics as a function of iodization time.

The loss for one-dimensional metal-only, hollow waveguides may be calculated using the theory of Marcatili and Schmeltzer [8]. In this work we need to use the theory developed by Miyagi and Kawakami [9] for metallic/dielectric coated guides. Thus, to calculate the attenuation coefficient, α, we use

$$\alpha_{\text{lm}} = \left(\frac{u_{\text{lm}}}{2\pi}\right)^2 \frac{\lambda^2}{a^3} \left(\frac{n}{n^2 + k^2}\right)_{\text{metal}} \cdot F_{\text{film}}, \tag{3}$$

where u_{lm} is the mode parameter, n and k are the optical constants of the metal film, and F_{film} is a term, which accounts for the loss due to the dielectric film (s). From Eq. (3) we see that α depends on (λ^2/a^3) and the loss increases as the square of the mode parameter u_{lm}. The lowest loss modes are the HE_{lm} modes for the metal/dielectric coated structures.

The losses for different bore sizes were made using a stabilized 10 W Synrad continuous wavelength CO_2 laser with beam coupling conditions optimized as necessary [10]. This loss data is shown in Fig. 5 for core diameters ranging from 300 to 700 μm. We also show in Fig. 5 the calculated loss using Eq. 3 for the lowest order HE_{11} mode.

From the data we clearly see the strong $1/a^3$ dependence of α and that the measured losses are close to those calculated.

The bending losses are expected to increase linearly as the curvature increases when the amount of waveguide under bend is kept constant [1]. In this study, the length of the samples under applied bending conditions was held constant at 100 cm for all measurements. The bending losses for four different bore sizes and silica wall thicknesses are shown in Fig. 6.

The straight losses (curvature equals 0) are close to theoretical as shown in Fig. 5, and the bending loss varies by $1/R$ as expected. It can be seen in Fig. 6 that there are clear differences in the linear bending loss slopes for the different bore sizes. The thinner wall HGWs (320/450 μm and 500/850 μm) exhibit a higher bending loss than the thicker wall guides (300/665 μm and 510/1125 μm). This higher loss

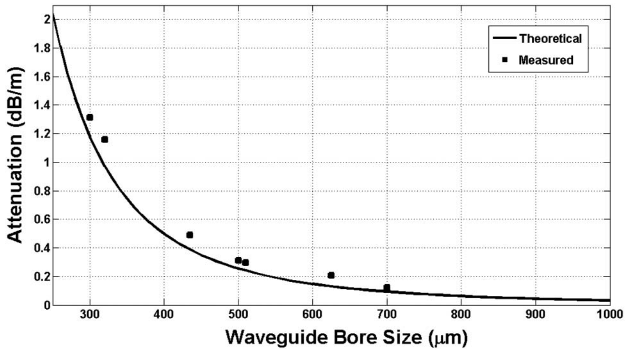

Fig. 5. Measured and theoretical attenuation of HE_{11} in Ag/AgI HGWs.

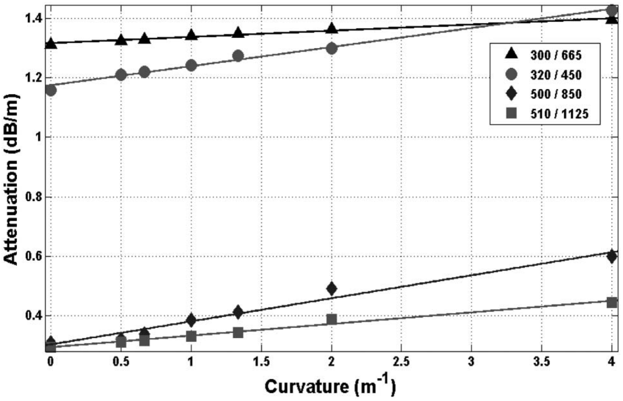

Fig. 6. Bending losses for Ag/AgI HGWs with different bore size and outer dimensions. The sizes are given in terms of the bore/outer diameter in microns.

for the thinner wall guides is a result of the excitation of a greater number of higher-order modes compared to the thicker wall guides. Higher-order modes have losses, which increase by $(u_{\mathrm{lm}})^2$, as seen in Eq. (3). That is, the propagation of higher modes resulting from either the macrobending type losses generated by virtue of the thin wall, or as a result of the larger bore size, which lead to a higher overall loss. In contrast, the slopes of the bending loss for the 300/665 μm and 510/1125 μm are similar as a result of the low-order mode propagation.

3. Modal Properties for HGWs at 10.6 μm

Hollow glass waveguides, in principle, are highly overmoded structures, but in practice they are essentially low-order mode guides. This is a result of the strong dependence of the attenuation on the mode parameter, u_{lm} as may be seen in Eq. (3). An interesting aspect of this is the ability of small-bore waveguides to preserve an SM for wavelengths 30 or more times its wavelength. Matsuura *et al.* [4] not only described this behavior for small-bore HGWs transmitting CO_2 laser radiation, but also the relationship between the thickness of the glass wall and the SM properties of the guides. In Fig. 7 the spatial profiles, measured using a CO_2 laser source and a Spiricon Pyrocam *I*, of two HGWs are shown. One is a thick wall, 1.45 m long, guided with a core diameter of 300 μm and a glass outer diameter (OD) of 665 μm, and the other has a slightly larger bore size of 320 μm but a thin glass wall with an OD of 450 μm. In Fig. 7(a) and 7(b) we see the excellent mode for the

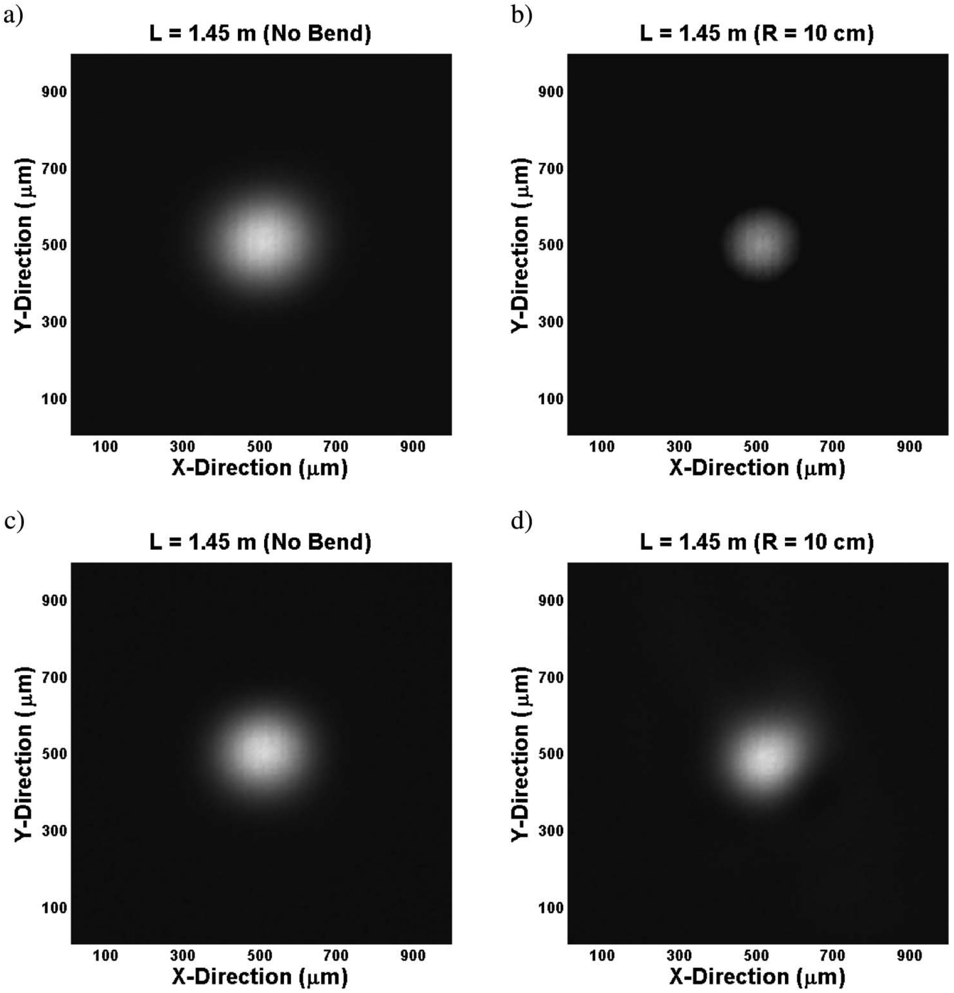

Fig. 7. Mode profile for a 300/665 μm (a) straight and (b) bent HGW and a 320/450 μm (c) straight and (d) bent HGW.

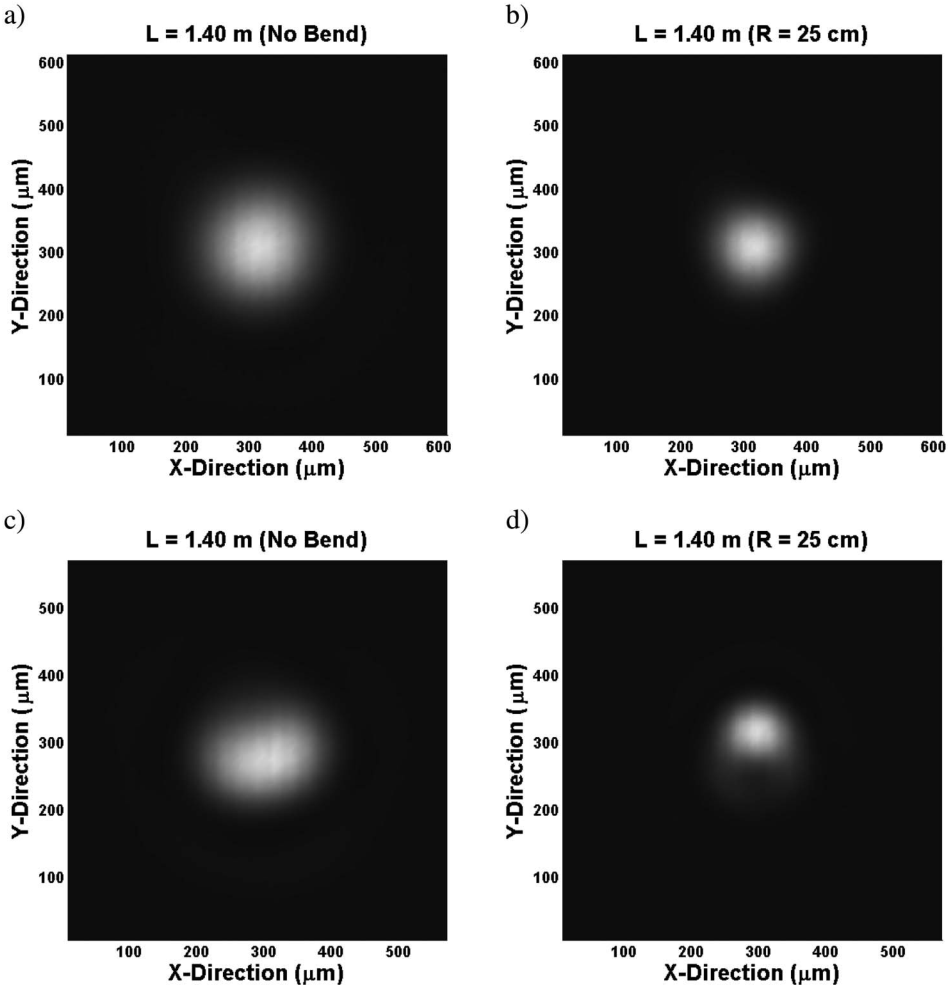

Fig. 8. Mode profile for HGWS for a 510/1050 μm (a) straight and (b) bent HGW and a 625/850 μm (c) straight and (d) bent.

thick wall guide even when the guide is bent to a radius of 10 cm. In contrast, it can be seen in Fig. 7(c) and 7(d) that the same bore size guide has a good mode when straight but that this mode becomes distorted due to the mixing of higher-order modes when the guide is bent. The reason that the mode is not preserved in the thin-wall guide is that the glass wall of this waveguide is rather thin. It was shown by Matsuura *et al.* [4] that a thin wall could be more easily distorted than a thicker wall leading to macrobending, which in turn manifests itself in mode coupling.

It is important in some applications that the waveguide deliver a nearly Gaussian output mode. One way to ensure good mode quality is to have a core size that is approximately 25 to 30 times the wavelength. The good mode shown, qualitatively in Figs. 7(a) and 7(b) for the 300 μm core (30λ) illustrates this concept for both the straight and bent waveguide.

However, with a smaller core comes higher loss. Therefore, it is most desirable to employ the largest bore that can still maintain SM transmission. To this end we looked at larger bore tubing with a thick wall. In Fig. 8 we show a composite two-dimensional plot of the mode profiles of two large bore, thick wall waveguides measured straight and bent. The data in Fig. 8 shows that even though these HGWs have bore sizes significantly greater than 30λ the modal purity is still quite good. This is a result of a thicker wall for these guides. The output of the waveguides, shown in Fig. 8, was measured at a fixed distance of 8 cm from the Spiricon beam profiler for both the straight and bent configurations. The spot size of the bent guide is smaller than when measured straight. This is a result of less power being transmitted when the guide is bent.

The modal properties of the HGWs, discussed above, suggest that it should be possible to use these guides to filter out higher-order modes. For instance, it may be that the output of the IR laser is multimode, but what is desired is a SM output. That is, if a poor quality mode is launched into a small bore guide it can be expected that the guide itself will filter or attenuate the higher-order modes as the laser power propagates down the guide. In Fig. 9 we show this mode filtering ability in a 300/665 μm guide.

The mode of the CO_2 laser is nearly Gaussian, but we have scrambled the output mode of the laser by applying a small load to the input end of the fiber. In Fig. 9(a) the output of a short, 8-cm length of a

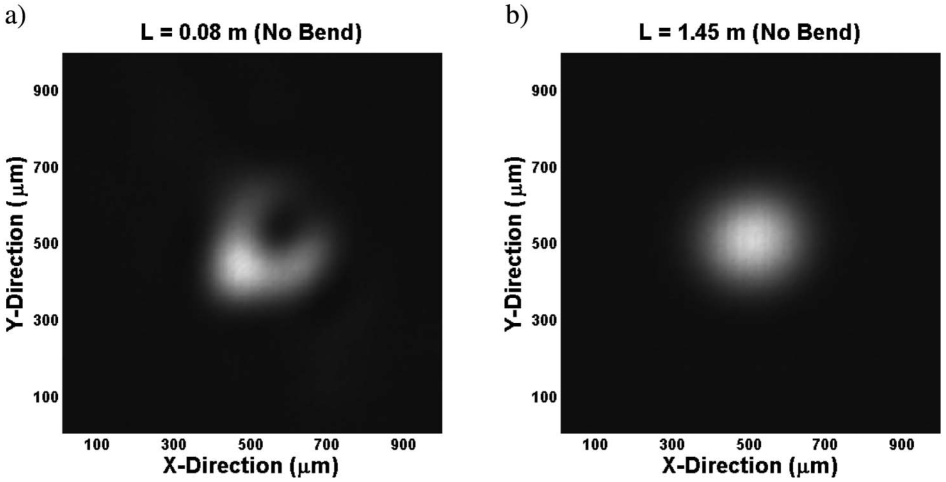

Fig. 9. Mode filtering by 300/665 μm HGW: (a) scrambled input and (b) filtered output.

300 μm bore waveguide clearly shows the very multimode output from this short length. However, when a long, 145 cm waveguide of the same construction is used we see the nearly excellent Gaussian output mode shown in Fig. 9(b). Naturally, this mode filtering comes at the expense of some power as the higher-order modes are damped out. Yet, this can be a very useful technique to easily improve the beam quality of a multimode laser.

4. Conclusion

The losses in Ag/AgI coated HGWs are shown to be nearly equal to the theoretical loss calculated for the lowest-order HE_{11} modes at 10.6 μm. Furthermore, the bending loss for these single-dielectric coated guides is linearly dependent on the curvature. Therefore, both the theoretical dependence of the loss on bore size, $\alpha \sim 1/a^3$, and on bending, $\alpha \sim 1/R$, are confirmed experimentally. However, the bending loss is seen to be greater for the thinner-wall guides compared to the thick-wall guides. This can be explained by the fact that bending the thinner-wall HGWs leads to coupling of the high loss, high-order modes. In general, to ensure SM behavior it is best to employ a guide with a bore size that is about 30 times the wavelength, although we have shown that it is still possible to propagate a single HE_{11} mode with bore sizes that are sometimes as large as 50λ. To achieve SM propagation with low loss one should select a tubing with a thick wall and a large bore diameter. Finally, we note that it is possible to filter out the higher-order modes, which may be present in the source laser. Mode filtering was shown to be excellent for the 300 μm bore guide when a poor quality CO_2 laser beam is incident on the guide. Naturally, any mode filtering is at the expense of reduced transmission.

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