Investigation of silver-only and silver / TOPAS® coated hollow glass waveguides for visible and NIR laser delivery

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ABSTRACT

Hollow Glass Waveguides (HGWs) present a viable option for the low-loss transmission of radiation over a broad range spanning from visible to far-infrared wavelengths. Cyclic Olefin Copolymer (COC), a commercially available polymer known as TOPAS®, is chosen for this study due to its exceptionally low absorption losses throughout the spectrum, particularly in the visible and near-infrared (NIR) regions. While silver-coated HGWs are capable of transmitting visible and NIR radiation with low losses, theory predicts that the addition of a uniform dielectric thin film of quarter-wavelength thickness will reduce these losses for both straight and bent configurations, while additionally providing a potentially more desirable modal output for laser applications. In this paper, the procedures for the deposition of the silver and subsequent COC films are outlined. Spectroscopy is used to obtain the thickness of the polymer film. The theoretical attenuation losses of the silver and Ag/COC HGWs are explored and experimental values are obtained using various visible and IR lasers. Moreover, the modal output of the silver and Ag/COC HGWs is qualitatively compared. The possibility of use of these Ag/COC HGWs at mid- and far-IR wavelengths is discussed.

Keywords: hollow glass waveguides, fiber optics, cyclic olefin copolymer, TOPAS®, near infrared, visible

1. INTRODUCTION

Hollow Glass Waveguides (HGWs) have been extensively studied and successfully implemented for the low-loss transmission and mode discrimination of mid-infrared radiation.[1] These hollow waveguides typically consist of a metal/dielectric film structure to enhance radiation transmission over metal-only alternatives and to allow for low-order hybrid mode propagation. To ensure mode discrimination, the waveguide bore size must be sufficiently small with respect to the wavelength of operation.[2] At shorter wavelengths, the increase in transmission losses due to the pronounced effect of surface-roughness induced scattering often outweighs the reduction in losses originating from the enhanced surface reflection from the addition of a dielectric film. Thus, a metal-only structure presents a viable option for transmitting relatively short wavelengths in the visible to near-infrared range. In addition to the insignificant loss reduction from the presence of a dielectric coating at short wavelengths, the large bore size with respect to the wavelength of interest excludes the possibility of mode discrimination in either the metal-only or metal/dielectric waveguide. With this consideration, it is of interest to investigate and directly compare the attenuation and modal properties of metal and metal/dielectric waveguides at visible and near-infrared wavelengths.

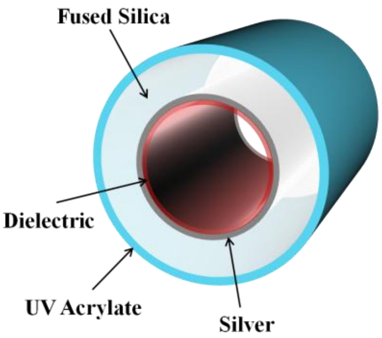

Figure 1. Representation of a typical HGW structure, including the fused silica capillary with protective polymer outer layer and deposited metal and dielectric thin films.

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A typical HGW structure is shown in Fig. 1. The HGWs used in this study have a constant inner diameter of 750 microns and use silver as the metallic film and TOPAS® as the dielectric film. Silver exhibits desirable reflection properties throughout the range of interest and its ease of deposition and extensive use in IR hollow waveguides make it an obvious choice.[1,3] TOPAS®, a cyclic olefin copolymer produced by TOPAS Advanced Polymers, is chosen due to its excellent transmission in the visible/NIR region. Furthermore, the transmission extends into the far-IR making TOPAS® a good candidate for future studies at longer wavelengths.

2. THEORETICAL CONSIDERATIONS

2.1 Dielectric Enhancement

The ideal thickness, d_{opt}, of a single dielectric film of refractive index, n, for optimal transmission at a desired operating wavelength, λ_{opt}, is given by Eq. 1.[1]

$$d_{opt} = \frac{\lambda_{opt}}{2\pi\sqrt{n^2-1}}\tan^{-1}\left(\frac{n}{(n^2-1)^{1/4}}\right) \qquad [1]$$

Taking $n = 1.53$ for the TOPAS® film throughout the visible/NIR region, the ideal dielectric thickness ranges between approximately 70 and 140 nanometers for the laser wavelengths of interest that will be investigated in this study (532 nm – 1064 nm). Due to the inherent limitations of the COC deposition process, to be discussed later in section 3.2, the minimal attainable COC film thickness is around 90 nm. As such, less than optimal dielectric thin films must be deposited for the HGWs designed for operation at 532 nm and 635 nm. The theoretical spectra of the Ag-only and Ag/COC coated HGWs are shown in Fig. 2, assuming a uniform dielectric film thickness of 90 nm and a propagation angle of $\theta = 0.5°$. The calculated spectrum further assumes completely smooth interfaces in the film structure, and thus the absence of any roughness-induced losses. The loss is modeled with a ray-optics approach using the transfer matrix method to obtain the reflection coefficient of the structure as a function of wavelength.[4] From the reflection coefficient, R, the attenuation coefficient, α, can be obtained using Eq. 2, as follows:

$$\alpha = \frac{1-R}{4a\cot\theta} \qquad [2]$$

where a is the bore radius.[5] At wavelengths longer than around 550 nanometers, for this particular propagation angle, it is predicted that the losses of the Ag/COC HGW will be lower than the Ag-only alternative.

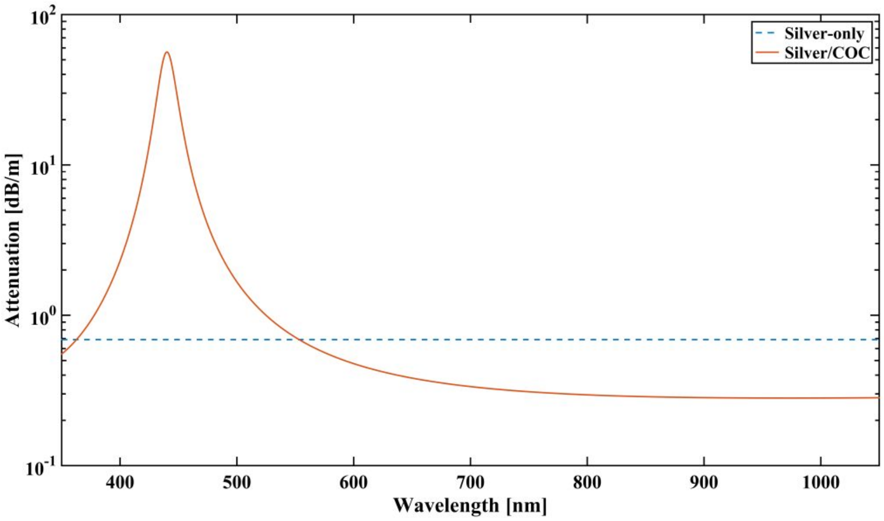

Figure 2. Theoretically calculated spectra of the Ag-only and Ag/COC HGW for a COC thickness of 90nm and a propagation angle of 0.5°.

Due to the large difference between the wavelength of light and the bore size of the hollow waveguide (bore diameter$\sim 1000\lambda$) it is predicted that the waveguide will exhibit multimode behavior.[1] Therefore, this mode mixing will lead to a distribution of propagation angles in the waveguide. This in turn requires an understanding of the effect of propagation angle on calculated attenuation values. Figure 3 shows the effect on loss for the same Ag/COC HGW modeled in Fig. 2 in a straight configuration for propagation angles ranging from ~0°-10°. As expected, a greater propagation angle and a corresponding higher order mode, leads to larger values of attenuation.

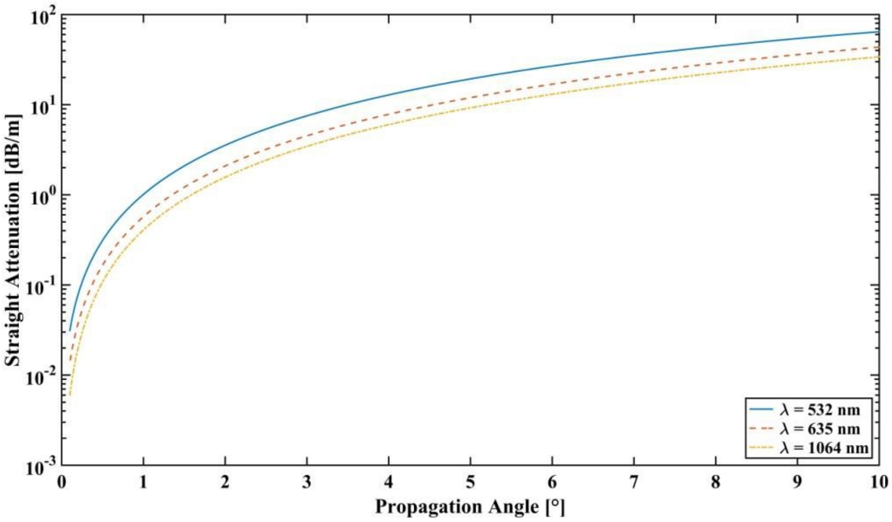

Figure 3. The effect of propagation angle on straight attenuation losses in an Ag/COC coated HGW at various wavelengths.

2.2 Surface Roughness

The presence of surface roughness is a significant loss mechanism that must be considered when operating at short wavelengths. In this analysis, the loss reduction factor is considered, in such a way to account for both the enhanced surface reflection from the dielectric film and the scattering losses contributed by the surface roughness of the additional film. Thus, the loss reduction factor is defined as the ratio between the attenuation coefficients for the Ag-only HGW and the Ag/COC HGW. A value exceeding unity indicates an improvement in transmission quality of the waveguide, while anything less than unity corresponds to higher losses with the additional film. To incorporate surface roughness into the calculation, the Fresnel coefficients in the transfer matrix are modified to contain a roughness term.[4]

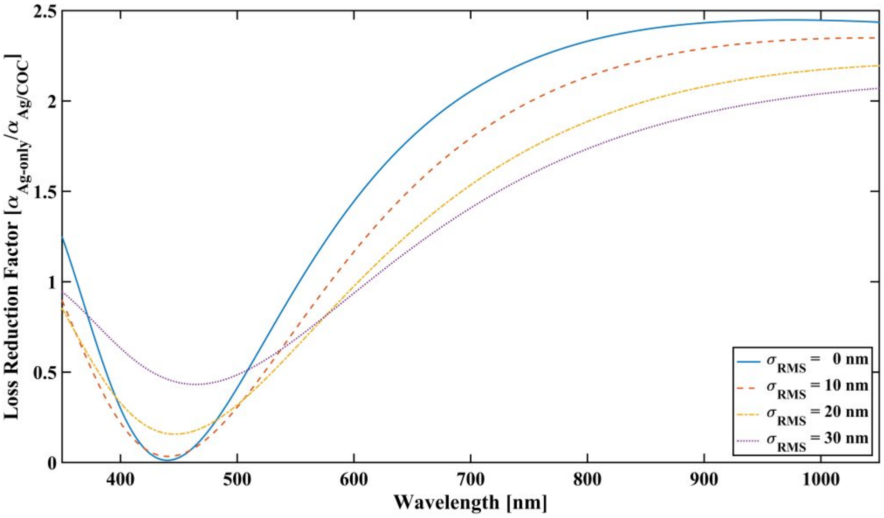

Figure 4. The effect of surface roughness scattering losses on the loss reduction factor of Ag-only and Ag/COC HGWs.

Figure 4 shows the loss reduction factor for different values of root-mean-square surface roughness of the dielectric film, ranging from zero to 30 nm. Loss reduction approaches zero at around 440 nm as it is the location of the primary interference peak, as seen in Fig. 2. For wavelengths greater than ~600 nm, an increase in surface roughness corresponds to a decrease in loss reduction.

3. EXPERIMENTAL METHODOLOGY

3.1 Silver Film Deposition

The silver film is deposited on the inner capillary wall using wet chemistry techniques by flowing solutions through the hollow capillary with the aid of a peristaltic pump. This process consists of two separate steps, namely sensitization and silvering. In the sensitization step, a stannous ion solution is used to sensitize the fused silica substrate, facilitating a more rapid silvering in the subsequent step.[6] The setup for the silvering procedure is shown in Fig. 5, in which an ammonia-complexed silver (I) ion solution is flown in conjunction with a reducing dextrose solution to react and form a reflective silver film on the sensitized silica surface. The waveguides are silvered for 5 minutes to ensure a sufficiently thick silver film is deposited such that radiation does not penetrate through the wall. Naturally, a longer silvering time contributes a greater degree of surface roughness related scattering losses, so it is important that the silver thickness only be a little greater than the skin depth at the operation wavelength.

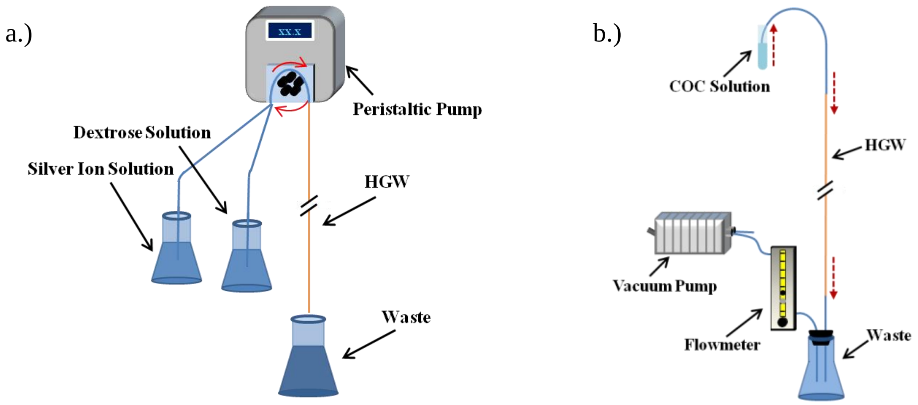

Figure 5. a.) The setup for the silvering procedure of fused silica capillaries and b.) the setup for the deposition of a dielectric polymer thin film.

3.2 TOPAS Film Deposition

The COC (5013L-10 from TOPAS Advanced Polymers), comes in pellet form and is dissolved in a suitable organic solvent to enable liquid phase deposition. Specifically, the pellets are dissolved in toluene by placing the solution in an ultrasonicating bath until full dissolution is obtained. In the deposition procedure, a desired amount of solution is pulled through the silvered hollow waveguide using a vacuum pump to provide the suction required. To gain control of the deposition speed, a flowmeter is used to regulate and reduce the strong, constant pull of the vacuum pump. The detailed setup is shown in Fig. 5. In contrast to the peristaltic pump used in the silvering procedure, a vacuum pump is utilized in the polymer deposition to guarantee a uniform, homogenous flow of solution, as opposed to the pulsating nature encountered with the peristaltic pump. Due to the viscous properties of the polymer solution, a pulsating flow leads to significant non-uniformity in the resulting polymer film, and therefore poor film quality and high transmission losses. Another integral part of the procedure is the post-deposition time, which refers to the time after the polymer solution exits the waveguide and before the vacuum pump is turned off and the HGW is removed. Previously, the HGW was immediately removed and allowed to dry with low-pressure forced air. However, it was determined that removing the waveguide directly after the solution exits the capillary causes cohesion of the solution, ruining the film. By incorporating a post-deposition time, much of the toluene will evaporate, stabilizing the film structure prior to any movement or handling of the waveguide.

The film thickness dependency on solution concentration is experimentally determined by creating several solutions of variable volume percent TOPAS® and flowing them through the silvered waveguide, with the following parameters held relatively constant for each trial; effective pull of the vacuum pump, post-deposition time, waveguide length, tubing system lengths, and solution volume. Each resulting HGW is tested spectroscopically using an Ocean Optics HR4000 UV-VIS spectrometer to determine the thickness of the polymer film. Based on the primary peak location in the spectrum, λ_p, Eq. 3 is used to calculate the corresponding film thickness, d.[1]

$$d = \frac{\lambda_p}{4\sqrt{n^2 - 1}} \qquad [3]$$

where n is the refractive index of the dielectric film, taken to be 1.53 for TOPAS®. The experimentally determined relationship between the film thickness and solution concentration is shown in Fig. 6. The plot exhibits a parabolic relation between the data for the particular range of solution concentrations investigated. At the low concentrations, the film thickness reaches a lower limit of approximately 90 nanometers. As the concentration of polymer approaches zero, the solution viscosity approaches the solvent viscosity. Since the film thickness is primarily dependent on solution viscosity, this suggests that the small variation in viscosity at very dilute concentrations is the reason for this limit on minimum attainable film thickness.

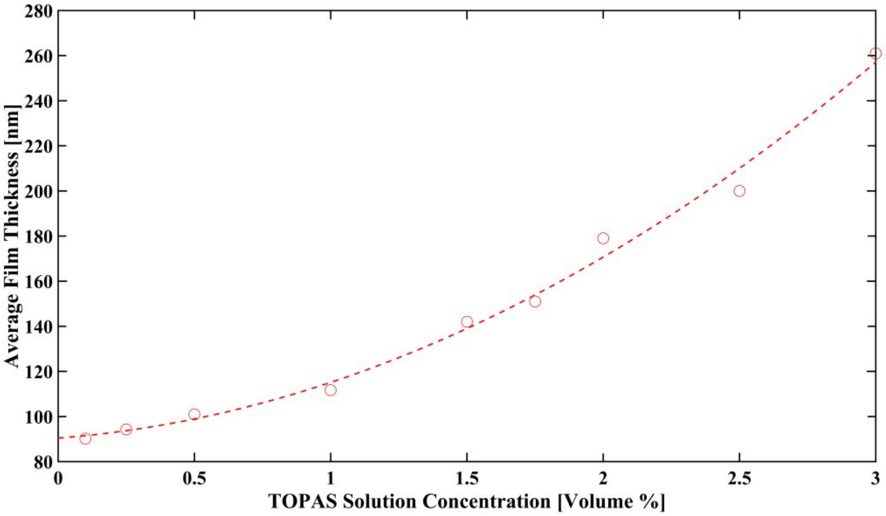

Figure 6. Experimentally determined relationship between TOPAS solution concentration and thickness of deposited film.

4. RESULTS AND DISCUSSION

4.1 UV-VIS Spectral Analysis

The spectra of the particular HGWs used in the attenuation and mode measurements discussed in Sections 4.2 and 4.3 were taken with a UV-VIS spectrometer in the 350-1050 nm range. As mentioned previously, a lower limit of 90 nm is set on the TOPAS® film thickness due to the inherent restriction on viscosity introduced by the organic solvent, toluene. As such, the HGWs for use at 532 nm and 635 nm are fabricated such that the primary peak location is at the shortest possible wavelength at around 420 nm, even though the ideal thicknesses are determined from Eq. 3 to be 70 and 87 nm, respectively. The 1064 nm HGW has an ideal COC thickness of 140 nm and thus its primary peak is placed at a longer wavelength. Due to the expected natural non-uniformity of the film along the waveguide length, the deposited thickness of the 1064 nm HGW film is reduced to 100 nm, with a corresponding peak location of 480 nm. The Ag-only spectrum is taken as well for comparison, and shows a small linear increase in attenuation at shorter wavelengths, likely the result of increased scattering as wavelength decreases. The three Ag/COC HGW spectra are shown in Fig. 7 for the three laser wavelengths, along with an Ag-only spectrum. The broadness of the interference peaks demonstrates the non-uniformity of the TOPAS® film, furthered by the fact that an approximately 1.5 meter HGW is used for the measurement. It is important to note that the spectra are arbitrarily displaced along the ordinate axis, and that the relative positions of the distinct spectra along the axis have no significance.

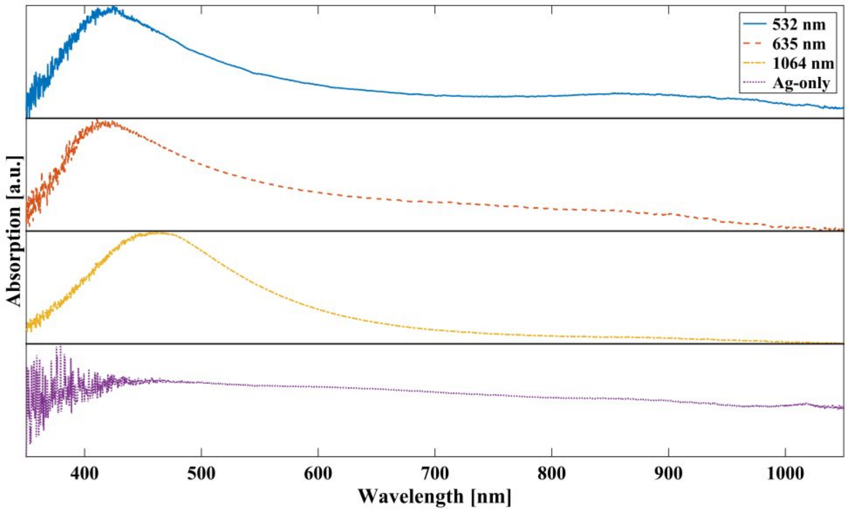

Figure 7. Experimental spectra of the silver and Ag/COC HGWs taken in the UV-VIS region with an Ocean Optics HR4000 Spectrometer.

4.2 HGW Attenuation Measurements

The attenuation losses for the Ag-only and Ag/COC HGWs were measured using the cutback method at the following three laser wavelengths: 532 nm, 635 nm, and 1064 nm. In each case, the Ag-only HGW was 2 meters in length, while the Ag/COC HGW was roughly 170 cm. For the bending measurements, a constant length of 130 cm was kept in the bent configuration for both waveguides. The following procedure was followed in each instance: first, the Ag-only waveguide losses were measured; next, the same silver HGW was coated with an appropriately thick COC film; lastly, the Ag/COC HGW losses were measured. In this way, a direct and accurate comparison between the two waveguide film structures is obtained.

Figures 8a.)-c.) show the measured losses of the Ag-only and Ag/COC HGWs for each laser. At all wavelengths, it is found that the Ag/COC HGW has lower loss than the Ag-only HGW in the straight configuration (zero curvature). For the green laser wavelength (532 nm), the losses for the Ag/COC HGW exceed the Ag-only waveguide only when bent. This is a result of the additional scattering losses from the COC film encountered as the bend radius increases, which arises as a result of due to an increased number of reflections along the waveguide at larger curvature. At this short wavelength, it is clear that the negative effect of surface roughness outweighs the positive effect of reflection enhancement from the presence of the dielectric. At the red laser wavelength (635 nm), the losses for the Ag/COC waveguide are slight better than the Ag-only HGW at all bend radii. The attenuation measurements indicate that the Ag-only HGWs are very good candidates for transmission of green and red laser light. For the 1064 nm laser, the Ag/COC HGW gives a significant reduction in attenuation with respect to the Ag-only HGW.

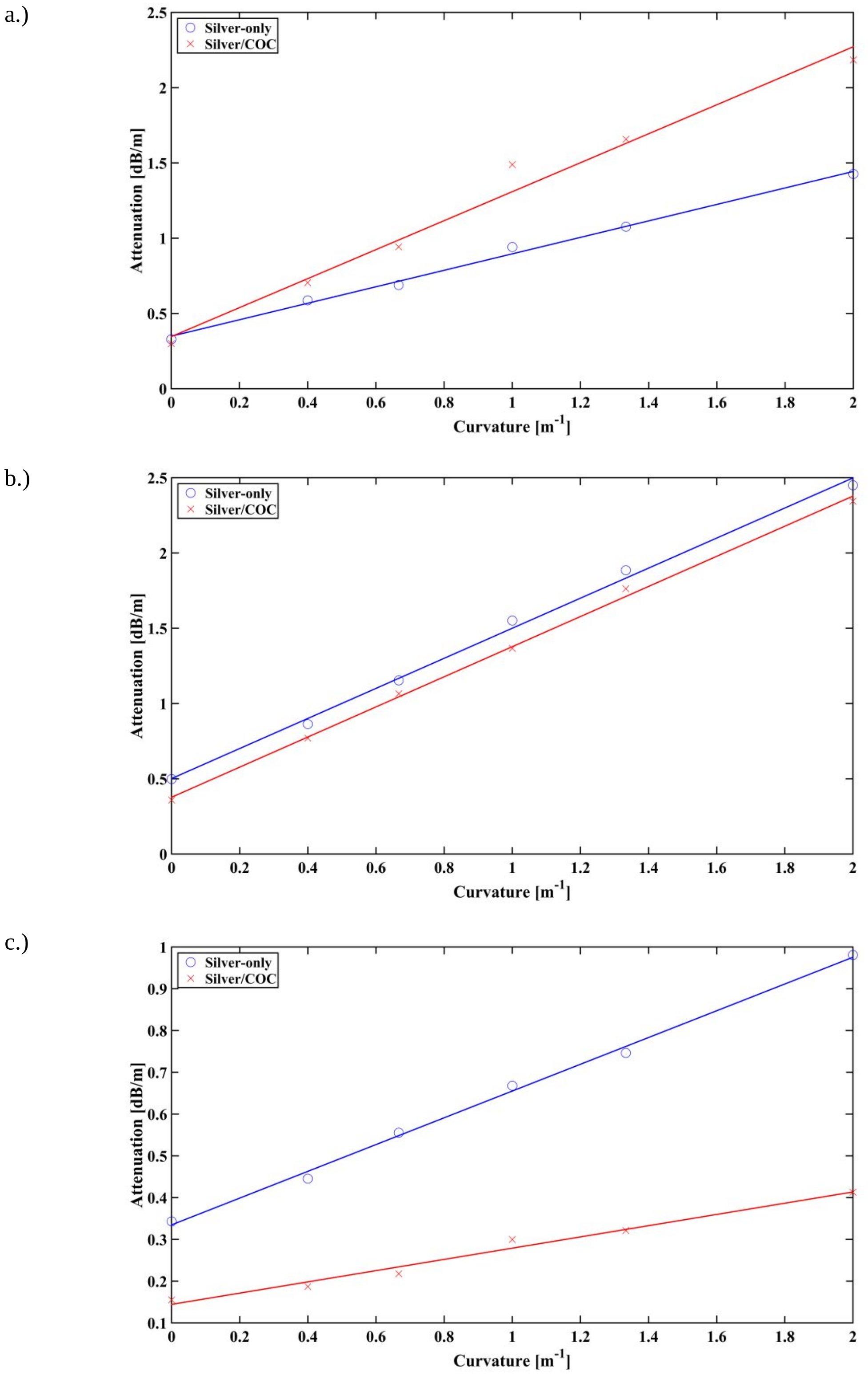

Figure 8. Attenuation losses of Ag-only and Ag/COC HGWs as a function of waveguide curvature for (a.) 532 nm, (b.) 635 nm, and (c.) 1064 nm.

4.2 HGW Modal Analysis

The modal outputs of the HGWs were obtained using a Spiricon SP503 camera interfaced with BeamGage software. As expected, both the Ag-only and Ag/COC waveguides demonstrated highly multimodal behavior due to the extremely large bore size with respect to the operating wavelength of light. Furthermore, there was no perceivable difference between the modes of the Ag-only and Ag/COC waveguides for each wavelength, independent of whether the HGW was in the straight or bent configuration. The modal outputs of the two HGWs are shown for the straight configuration on the green (532 nm) laser in Fig. 9.

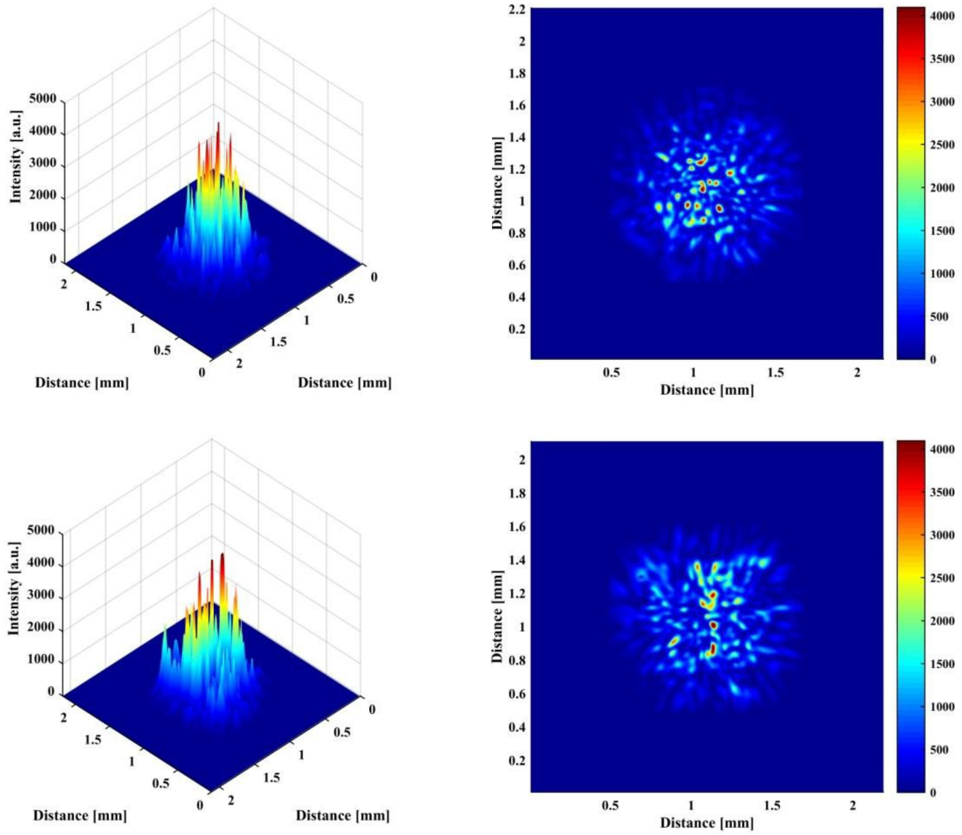

Figure 9. Beam profiles of the outputs of Ag-only (top) and Ag/COC (bottom) HGWs in 2D and 3D views.

As can be seen in the figure, there is no clear difference between the top and bottom profiles, corresponding to the Ag-only and Ag/COC waveguides respectively. Thus, contrary to the benefits of TEM_{00} mode propagation in metal/dielectric waveguides with mode discrimination used in the mid and far-infrared, the presence of a dielectric film does not pose any significant advantage with respect to the modal quality at short wavelengths.

5. CONCLUSION

The modal and attenuation properties of Ag-only and Ag/COC coated hollow glass waveguides have been thoroughly investigated in the visible and NIR regions of the spectrum. The large HGW bore size with respect to the operating wavelength excluded the possibility of mode discrimination within these guides, leading to no modal differentiation between the silver and Ag/COC structures. However, the attenuation measurements did show variation between the Ag-only and Ag/COC HGWs. In particular, the 532 nm Ag/COC waveguide showed a general increase in loss on bending with respect to the Ag-only HGW, while the 635 nm waveguide showed a small reduction in attenuation at all curvature, and the 1064 nm Ag/COC HGW showed significant transmission improvement over the Ag-only HGW. Thus, at visible wavelengths, it appears that the addition of the dielectric TOPAS® film did not lead to significant advantages in either loss or modal quality. It must be noted, however, that the COC film thickness is not actually ideal for the operating wavelengths, which likely leads to increased attenuation that would not be encountered with a more optimally deposited film. It is clear that in the NIR, the addition of a dielectric poses significant benefits, particularly on the application of external curvature of the HGW, mimicking real-life waveguide configurations in many operations. Future studies will investigate the possibility of use of COC as a dielectric thin film at larger wavelengths, and additionally, in multilayer structures to exploit its relatively low index of refraction.

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