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Low-loss modes in hollow metallic terahertz waveguides with dielectric coatings

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Cylindrical hollow-core metallic waveguides with an inner coating of polystyrene (PS) deposited over silver have losses less than 1dB/m for terahertz waves propagating in the HE_{11} mode. The thickness of the PS film determines whether the hybrid HE_{11} mode or the transverse TE_{01} mode exhibits the lowest loss. The mode selection is confirmed by studying mode profiles and transmission losses at 2.5 THz in waveguides with the dielectric coating thickness ranging from 0 to the optimum value of approximately 10 μm. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3013585]

Waveguides for terahertz electromagnetic waves can enable component integration. It will lead to development of compact systems for imaging and spectroscopy applications that do not require large free-space optics. Waveguides are also needed for delivering signals with terahertz carrier frequencies. Currently, guiding of terahertz waves is realized using free-space optics. The difficulty of developing waveguiding technology for terahertz waves is caused by the relatively high absorption in most dielectric materials and high Ohmic losses in metals. These losses are mitigated by designing a waveguide structure where the wave energy is mostly distributed in the air region and only a small fraction propagates inside the absorbing medium.[1–9]

In metallic waveguides the losses are caused by the electric field not vanishing entirely on the metallic surface but penetrating into the waveguide wall, where the wave is absorbed. As a result, transmission losses of practical metallic waveguides are still limited to several dB/m in the terahertz region.[1,3,6]

The residual losses in metallic hollow terahertz waveguides can be further reduced by adding a thin dielectric film on the inner wall surface.[10–12] The dielectric coating allows wave propagation of the hybrid HE_{11} mode, for which the normal electric field at the metal boundary can be substantially reduced.[10] We recently demonstrated that indeed cylindrical metallic waveguides with a thin polystyrene (PS) coating provide a lower loss compared to metal-only waveguides.[11] The transmission loss can be reduced below 1 dB/m, the lowest value reported for any terahertz waveguide to date. These waveguides also exhibit very efficient coupling to free-space beams (>80%).

In this work we address the impact of the waveguide mode on the transmission characteristics of the dielectric-lined waveguides. Specifically, we analyze the mode profiles and the corresponding transmission losses in cylindrical silver waveguides with PS coatings (Ag/PS waveguides). We show that the loss for the HE_{11} mode in a waveguide with the optimum PS coating thickness decreases below the TE_{01} and TE_{11} levels. This study confirms that the lower loss in the dielectric-lined waveguides compared to the metal-only waveguides is due to the change in the mode structure.

In a cylindrical metal-only waveguide, the lowest loss is expected for the TE_{01} mode,[10] while the TE_{11} mode, which has greater practical significance due to its TEM_{00}-like mode profile, suffers from higher losses because of a stronger penetration of the electric field into the waveguide walls. However, adding a thin dielectric film on the inner surface of the metallic wall changes the boundary conditions and can reverse the dominant mode order. The dielectric film forms the hybrid HE_{11} mode, for which the electric field at the boundary is reduced along the entire contour of the waveguide wall. The HE_{11} mode loss in an optimally designed waveguide can become lower than the TE_{01} mode loss even for practical dielectric coatings with a moderate absorption coefficient.

The optimal thickness d for a nonabsorbing dielectric coating was estimated to be only a small fraction of the wavelength λ. That is, $d=(\pi/4k)(1/\sqrt{n^2-1})$, where k is the wave vector and n is the refractive index of the dielectric.[10] For an absorbing dielectric film, the optimal thickness is slightly smaller as the overall loss increases with the film thickness. Specifically, the loss for a 2.2 mm bore diameter Ag/PS waveguides at 119 μm (2.5 THz) has been calculated to have a minimum value of 0.18 dB/m when the PS film thickness is 12.7 μm.[11]

At this minimum, the transmission loss for the HE_{11} mode loss is lower than that for the TE_{01} mode ($\sim$3–5 dB/m) and the waveguide should suppress the TE_{01} mode. Conversely, in a waveguide with a thinner dielectric coating (<3 μm) or no dielectric coating, the TE_{01} mode has the lowest loss and the HE_{11} mode (or the TE_{11} mode in a metal-only waveguide) is suppressed. This competition between the two low-loss modes raises an important question of the dominant mode in a real waveguide with a dielectric coating. To resolve this issue, we determine the mode profile

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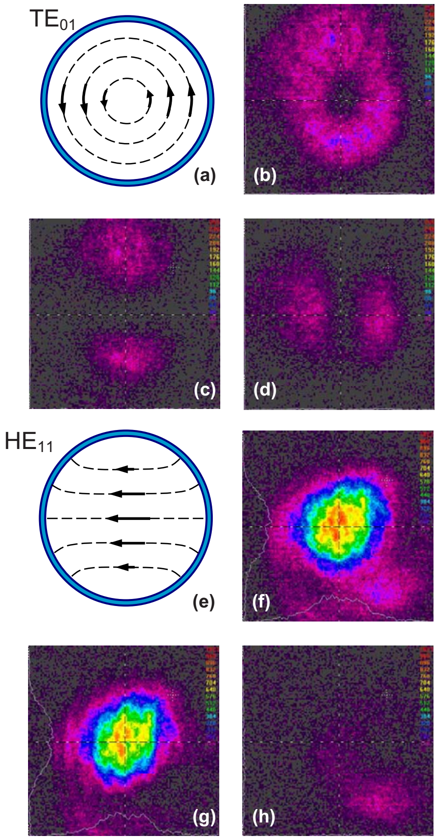

FIG. 1. (Color online) The far-field spatial intensity distribution of 2.5 THz radiation upon exiting a 45 cm long 1.6 mm bore diameter Ag waveguide with a 2 μm PS film [(a) and (b)] and a 90 cm long 1.6 mm bore diameter Ag waveguide with a 10 μm PS film [(e)–(h)]. The images show the total [(b) and (f)], horizontally polarized [(c) and (g)], and vertically polarized [(d) and (h)] intensity distributions. The schematics [(a) and (e)] of the corresponding waveguide modes show the electric field lines.

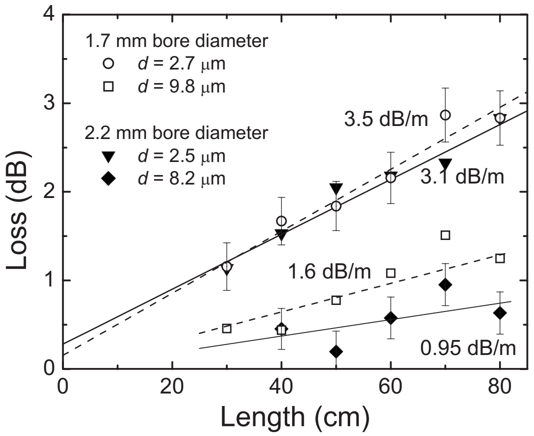

FIG. 2. Cut-back loss measurement data for 1.7 and 2.2 mm diameter waveguides (symbols) and corresponding linear fits (dashed and solid lines). The error bars show absolute maximum errors for each individual data point calculated using the standard deviations in the power measurements. The loss shown is calculated from the slope of each curve.

and characterize the absorption loss simultaneously in our cylindrical hollow core silver waveguides with the PS film thickness ranging from zero to the optimal thickness.

We use a CH_3OH laser (Coherent, Inc., SIFIR-50) tuned to 119 μm (2.5 THz). A horizontally polarized TEM_{00} cw beam (~25 mW) was coupled into the waveguides with a 7.5 cm focal length off-axis parabolic mirror, which focuses the laser beam into an ~1 mm (full width at half maximum) spot at the waveguide input. A pyroelectric camera, Spiricon Pyrocam I, is used to image the mode profile at the waveguide output (~6 cm away from the facet). For the cut-back loss measurements, the total power exiting the waveguide is measured using a power meter with a thermal sensor.

Waveguides are fabricated by depositing a 1 μm thick layer of silver followed by a layer of PS inside a 120 cm long glass tube. The fabrication details are given elsewhere.[11] Experimental results show that both fundamental modes are supported in our Ag/PS waveguides with a clear tendency for relatively thick PS films to maintain the hybrid HE_{11} mode and for the metal-only and thin-film waveguides to develop the TE_{01} mode.

Figure 1 shows two cases corresponding to almost complete suppression of one of the modes in 1.6 mm bore diameter waveguides. Separate images are collected with horizontal and vertical wire grid polarizers inserted between the output end of the waveguide and the pyroelectric camera. The doughnut-shaped mode at the output of the waveguide with a thin PS film (2 μm) is characteristic of the TE_{01} mode. The polarized radiation profiles confirm that the electric field is parallel to the waveguide walls. As the PS thickness increases, the HE_{11} component detected at the output increases significantly. Radiation propagates primarily in the HE_{11} mode in the waveguides with the thickest PS films (8–17 μm). The mode profile of the waveguide with a 10 μm PS film shown in Figs. 1(e)–1(h) is made up almost entirely of horizontally polarized radiation, and the intensity profile is characteristic of the HE_{11} mode.

It is important to note that the TE_{01} mode can develop in the waveguide if the PS film thickness is small. Although the TEM_{00} mode of the laser is not expected to couple efficiently to the TE_{01} mode, we observed a significant portion of the total energy propagating as the TE_{01} mode even after 20–40 cm in waveguides with the PS film thickness below ~3 μm. Waveguides with no PS coating have a large TE_{01} component.

To confirm the mode suppression effect we performed cut-back loss measurements on 1.6, 1.7, and 2.2 mm bore diameter waveguides with various PS film thicknesses. The initial length of each waveguides is 90 cm. After the output power measurement, 10 cm is cleaved from the input end for measurement of the input power. The power ratio corresponds to the loss in the 80-cm long section, excluding coupling losses. The remaining section is used for the next cut-back measurement. A total of six cut-back measurements is performed on each 90 cm waveguide. Thus the loss is measured for waveguide sections that are 80–30 cm in length. The data clearly show the trend of the decreasing attenuation with increasing film thickness. Figure 2 shows the loss for selected waveguides as a function of length for PS film thickness of ~2.5 and ~9 μm. The lowest loss of 0.95 ± 0.16 dB/m was measured from the linear fit to the data in Fig. 2 for a 2.2 mm bore diameter waveguide with an 8.2 μm thick PS film. The theoretical loss for this waveguide including an atmospheric absorption of 0.5 dB/m is 0.68 dB/m. The highest losses of 3.5–5.0 dB/m are measured for the metal-only waveguides. The full set of the transmission loss characteristics is summarized elsewhere.[11]

It is important to note that the coupling efficiency is high for these waveguides. Nine out of ten tested 1.7 and 2.2 mm bore diameter Ag/PS coated waveguides had coupling efficiencies between 78% and 84%. The outlier has a coupling efficiency of 66%.

The experimental results also confirm that the transmission loss decreases with the waveguide bore diameter since a larger fraction of the transmitted energy propagates in the air core. The loss coefficient is expected to decrease as $1/a^3$, where a is the bore radius.[13] Higher order modes, which are not present in the 1.6 or 1.7 mm bore Ag/PS waveguides, appear in the 2.2 mm waveguides.[11] The increase in the number of propagating modes is caused by reduced attenuation in large bore guides. To ensure the single-mode behavior at 2.5 THz, the waveguide bore diameter should be kept below ~1.6 mm.

These results allow us to make the following conclusions regarding the hollow dielectric-lined metallic waveguides. Terahertz transmission characteristics of cylindrical Ag waveguides improve after coating the inner waveguide walls with a thin PS film. The dielectric coating forces a reduction in the electric field at the boundary along the entire waveguide wall contour resulting in a smaller wall penetration and hence a lower transmission loss. The PS coating thickness determines whether the hybrid HE_{11} mode or the transverse TE_{01} mode exhibits the lowest loss. The optimum dielectric coating thickness of $\sim 10\ \mu m$ effectively suppresses the undesirable TE_{01} mode at 2.5 THz while keeping the dielectric absorption low. This waveguide design is particularly attractive for practical applications owing its low loss, the complete radiation confinement inside the waveguide, and efficient coupling to free-space propagating beams.

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