

# Dielectric-gap-metal waveguides for THz low-loss propagating wave with subwavelength mode width

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## ABSTRACT

For a good THz waveguide, both low propagating loss and small mode width are usually very important. However, the high ohmic loss of metals and the high absorption loss of dielectric materials result in that it still remains a challenge to obtain the two capabilities at the same time. In this paper, planar dielectric-gap-metal (DGM) waveguides are presented to guide THz wave. According to the dispersion equations of the waveguides, we calculate their mode characteristics by numerical calculation, and we find that THz wave can propagate in the waveguides with low loss and simultaneously subwavelength mode width. When compared with the parallel-plate waveguide, the mode losses of the DGM waveguide can be 1-3 orders of magnitude lower, but the mode widths do not increase. The combination of low propagating loss and subwavelength mode width makes the DGM waveguides particularly useful for many THz applications such as sensing, communication, and imaging.

Waveguides, Terahertz Wave

## 1. INTRODUCTION

Recent years have witnessed a rapid development of research on THz waveguides for their great importance in the THz science and technology<sup>[1-3]</sup>. For a good THz waveguide, low mode loss is a very important feature. A single metal wire can guide the broadband THz pulses with nearly no dispersion and with a loss of about  $3 \text{ m}^{-1}$ <sup>[4]</sup>, but the mode is weakly bound to the wire surface<sup>[5-8]</sup>. The metal/dielectric-coated hollow waveguide with an aperture much larger than the wavelength shows a low propagating loss of THz wave, and the loss coefficient is  $0.95 \text{ dB/m}$  at the frequency of  $2.5 \text{ THz}$ <sup>[9-12]</sup>. Recently, the parallel-plate waveguide<sup>[13,14]</sup> and the dielectric-pipe waveguide<sup>[15-18]</sup> were presented to guide the THz wave with very low losses, and their mode losses can be as low as  $2.6 \text{ dB/km}$  and  $0.08 \text{ m}^{-1}$ , respectively.

On the other hand, small mode width is also very important for a good THz waveguide. However, all the low-loss waveguides mentioned above have mode widths much larger than the wavelength. Of course, one can reduce the mode widths of these waveguides, but the corresponding mode losses will increase largely<sup>[3,9,15,19]</sup>.

In this paper, we present planar dielectric-gap-metal (DGM) waveguides to guide THz wave. When compared with the low-loss waveguides mentioned above<sup>[4,5,13,15]</sup>, the mode widths of the DGM waveguides are much smaller.

Compared with the parallel-plate waveguide <sup>[3]</sup> with small apertures, the mode widths of the DGM waveguide do not increase, but their mode losses can be 1-3 orders of magnitude lower. These results emphasize the high potential of the DGM waveguides for various THz applications including sensing, detection, communication, and imaging.

## 2. PLANAR DGM WAVEGUIDE

### 2.1 Dispersion equations of the planar DGM waveguide

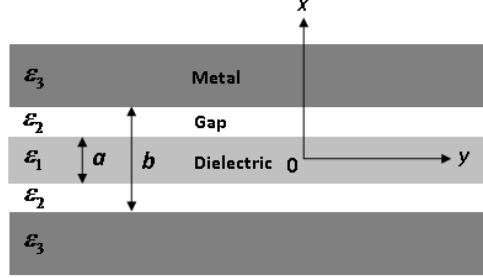


Fig. 1. The transverse cross-section of the planar DGM waveguide

The transverse cross-section of the planar DGM waveguide is shown in Fig. 1, and the waveguide width in the y-direction is large enough. This waveguide can guide two kinds of modes: transverse-electric (TE) modes and transverse-magnetic (TM) modes. When THz wave propagates in the waveguide, the dispersion equations of the even modes can be written as follows <sup>[20]</sup>:

$$\text{TE mode} \quad \tan\left(\frac{h_1 a}{2}\right) = -i \frac{h_2 h_3 - h_2 + (h_2 + h_3) \exp[ih_2(b-a)]}{h_1 h_3 - h_2 - (h_2 + h_3) \exp[ih_2(b-a)]} \quad (1)$$

$$\text{TM mode} \quad \tan\left(\frac{h_1 a}{2}\right) = \frac{1 - \frac{\varepsilon_3 h_2}{i\varepsilon_2 h_3} \tan\left[\frac{h_2(b-a)}{2}\right]}{\frac{\varepsilon_3 h_1}{i\varepsilon_1 h_3} + \frac{\varepsilon_2 h_1}{\varepsilon_1 h_2} \tan\left[\frac{h_2(b-a)}{2}\right]} \quad (2)$$

where  $A$  is a coefficient related with the mode power,  $h_n^2 = \varepsilon_n k_0^2 - \beta^2$ ,  $k_0$  is the wave vector in vacuum,  $\beta = \beta_1 - i\alpha$  is the complex propagation constant, and  $\varepsilon_1$ ,  $\varepsilon_2$ , and  $\varepsilon_3$  are relative permittivities of the dielectric, gap, and metal, respectively.  $\alpha$  and  $n_{\text{eff}} = \frac{\beta_1}{k_0}$  are the loss coefficient and effective refractive index of the guided modes, respectively.

### 2.2 Mode characteristics of the planar DGM waveguide

Copper is adopted as the material of metal plates, and its relative permittivity  $\varepsilon_3$  can be obtained by the Drude model

$$\varepsilon_3 = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - i\omega\omega_\tau} \quad (3)$$

where  $\omega$  is the angular frequency of THz wave,  $\varepsilon_\infty$  is the high-frequency permittivity of copper, which is negligible in the THz region, and  $\omega_p = 1.12 \times 10^{16}$  Hz and  $\omega_\tau = 1.38 \times 10^{13}$  Hz are the plasma oscillation frequency and damping frequency of copper<sup>[21]</sup>, respectively. The material of dielectric slabs is silicon, and its relative permittivity is adopted as  $\varepsilon_1 = 11.7 - 0.0001i$ . The gap between the copper plate and silicon slab is air of a relative permittivity  $\varepsilon_2 = 1$ .

When the frequency of THz wave is  $f = 0.5$  THz and the interval between two copper plates is  $b = \frac{\lambda}{2} = 0.3$  mm, according to Eqs. (1) and (2), we numerically calculate the dependence of both loss coefficients (solid lines) and effective refractive indices (dashed lines) on the silicon slab thickness for the TE<sub>1</sub> and TM<sub>1</sub> modes, respectively, as shown in Figs. 2(a) and 2(b). From Fig. 2(a), one can observe that the mode loss is always lower than 0.30 m<sup>-1</sup> in the range of  $a = 0.043 \sim 0.19$  mm. The minimum loss is 0.21 m<sup>-1</sup>, which is 452 times lower than that of the corresponding TE<sub>1</sub> mode in the parallel-plate waveguide (95 m<sup>-1</sup>).

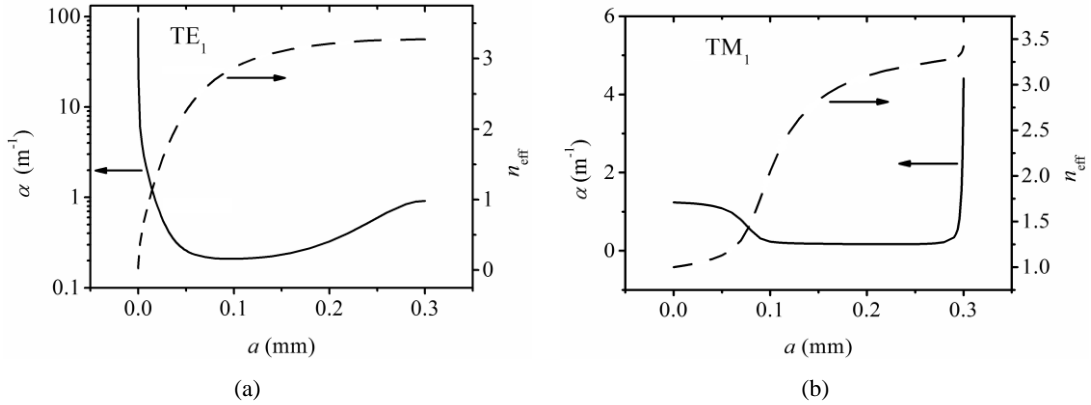


Fig. 2. The dependence of both loss coefficients (solid lines) and effective refractive indices (dashed lines) on the thickness of the silicon slab for (a) TE<sub>1</sub> and (b) TM<sub>1</sub> modes.

As shown in Fig. 2(b), when the thickness of the silicon slab is in the range of  $a = 0.092 \sim 0.28$  mm, the propagating loss of the TM<sub>1</sub> mode is always lower than 0.30 m<sup>-1</sup>. The minimum mode loss is 0.17 m<sup>-1</sup>, which is seven times lower than that of the corresponding TM<sub>1</sub> mode in the parallel-plate waveguide (1.2 m<sup>-1</sup>).

We further calculate the transverse electric field distribution of the TE<sub>1</sub> mode for  $a = 0.1$  mm and the transverse magnetic field distribution of the TM<sub>1</sub> mode for  $a = 0.15$  mm, respectively, as shown by the solid lines in Figs. 3(a) and 3(b). We also calculate the corresponding mode field distributions of the parallel-plate waveguide for comparison, as shown by the dashed lines in Figs. 3(a) and 3(b). As shown by the inset in Fig. 3(a), the electric field and the THz intensity at the interface for the DGM waveguide are much smaller than that for the parallel-plate waveguide, so the THz

power proportion inside copper plates for the former is much lower than that for the latter. As a result, the mode loss of the DGM waveguide is much lower than that of the parallel-plate waveguide.

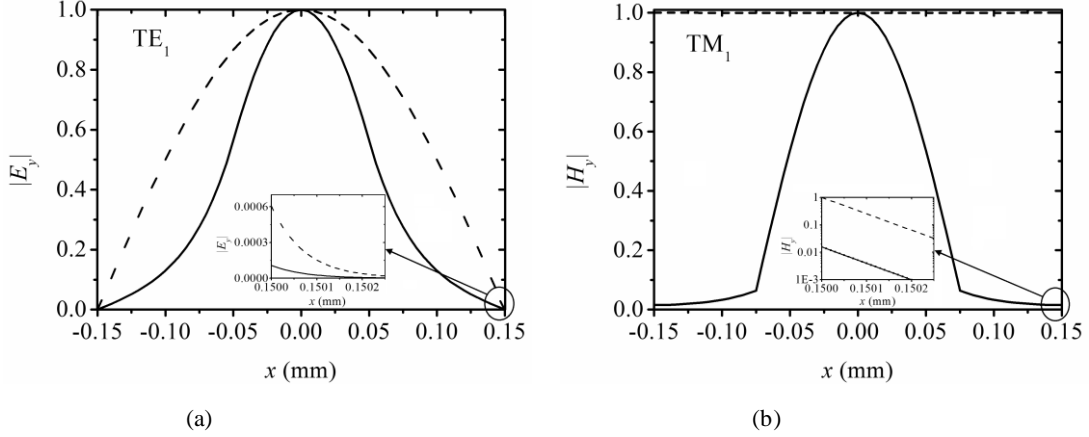


Fig. 3. (a) The transverse electric field distributions of  $TE_1$  modes in the DGM waveguide (solid line) and parallel-plate waveguide (dashed line). (b) The transverse magnetic field distributions of  $TM_1$  modes in the DGM waveguide (solid line) and parallel-plate waveguide (dashed line). The inset in (a) or (b) shows the corresponding electric or magnetic field distributions in copper plates.

As shown in Fig. 3(b), the transverse magnetic field of the  $TM_1$  mode in the parallel-plate waveguide is nearly unchanged between the two copper plates, but the mode field in the DGM waveguide decreases gradually from the slab center to the two copper plates. From the inset in Fig. 3(a), one can observe that the magnetic field and the THz intensity at the interface for the DGM waveguide are much smaller than those for the parallel-plate waveguide. Therefore, similar to the  $TE_1$  modes above, the loss of the  $TM_1$  mode in the DGM waveguide is also much lower than that for the parallel-plate waveguide.

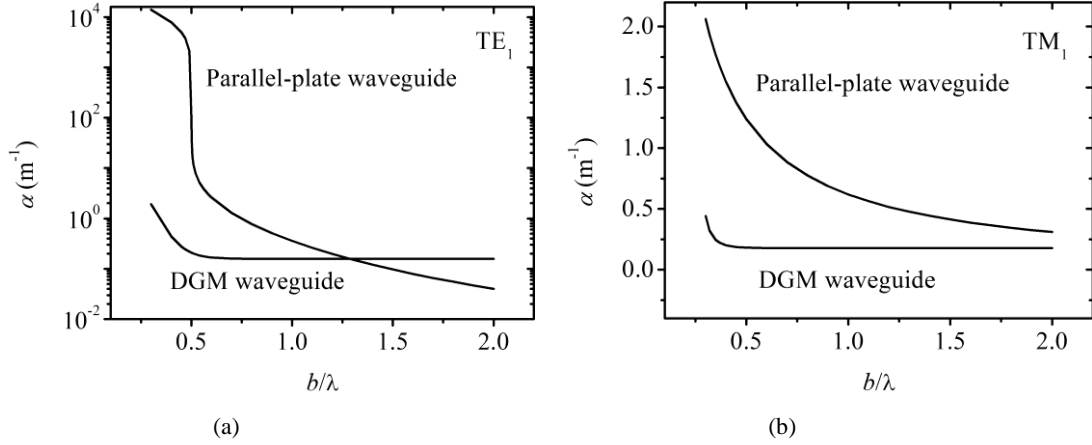


Fig. 4. The dependence of the loss coefficients on the interval between two copper plates for (a)  $TE_1$  and (b)  $TM_1$  modes.

When the frequency of THz wave is  $f = 0.5$  THz, we calculate the dependence of the propagating losses of both  $TE_1$  and  $TM_1$  modes in the DGM waveguide on the interval between two copper plates, as shown in Figs. 4(a) and 4(b). The thickness of the silicon slab is  $a = 0.1$  mm for the  $TE_1$  mode and  $a = 0.15$  mm for the  $TM_1$  mode, respectively. The dependence of the corresponding mode losses of the parallel-plate waveguide on the interval are also shown in Fig. 4 for

comparison. From Fig. 4(a), one can see that when the interval is smaller than  $1.3\lambda$ , the mode loss of the DGM waveguide is lower than that of the parallel waveguide. When the interval is larger than  $1.3\lambda$ , the mode loss for the former is higher than that for the latter. This is because the losses caused by copper plates for both  $TE_1$  modes are very low, and the absorption loss of the silicon slab in the DGM waveguide is larger. Therefore, when the interval is large enough, which means that the mode width is very large, the parallel-plate waveguide is a good choice for guiding the  $TE_1$  mode. However, when one wants to guide the  $TE_1$  mode with subwavelength width, the DGM waveguide is a better choice. For the  $TM_1$  modes, as shown in Fig. 4(b), the loss of the DGM waveguide is always lower than that of the parallel-plate waveguide. For both  $TE_1$  and  $TM_1$  modes, the smaller the interval is, the greater the advantage of the planar DGM waveguide is.

### 3. CONCLUSION

We propose the DGM waveguides to guide THz wave with low propagating loss and subwavelength mode width. For the planar DGM waveguide with an interval of  $b = \frac{\lambda}{2}$ , the minimum losses of  $TE_1$  and  $TM_1$  modes are 0.21 and  $0.17 \text{ m}^{-1}$ , respectively, which are 452 and seven times lower than those of the corresponding modes in the parallel-plate waveguide; at the same time, the mode widths of the planar DGM waveguide do not increase. The combination of low propagating loss and subwavelength mode width emphasizes the high potential of the DGM waveguides for many THz applications including sensing, detection, communication, and imaging.

#### Acknowledgement

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