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Double-dielectric-slab waveguides for guiding broadband THz wave with low propagation loss and small beam width

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Double-dielectric-slab waveguides for guiding broadband THz wave with low propagation loss and small beam width

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Abstract: A double-dielectric-slab waveguide is proposed to guide broadband THz waves. We derive the dispersion equations of both the even mode and odd mode of the waveguide, which are used to study the relationships between the mode propagating characteristics and the waveguide structure, as well as the THz wave frequency. Furthermore, the mode field distribution characteristics of the two modes are studied. The results obtained show that this simple waveguide can guide the broadband THz wave with relatively low loss and small beam width simultaneously.

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1. Introduction

The development of the low-loss waveguides is essential for facilitating terahertz (THz) science and applications [1-4], but they are limited by the high ohmic loss of metals and the high absorption of dielectric materials. It seems that dry air is the most appropriate medium to transmit THz waves. Hitherto, most low-loss THz waveguides are based on the propagation of a large portion of field in air, such as metal wires [5-9], dielectric-coated metallic hollow fibers [10-13], parallel-plate waveguides [14,15], and dielectric pipe waveguides [16-19]. The metal wire can guide the broadband THz pulses with nearly no dispersion and the loss coefficient is about 3 m^{-1} [5]. The silver/PS-coated hollow waveguide exhibits a loss coefficient of 0.95 dB/m at the frequency of 2.5 THz [10]. The parallel-plate waveguide [14,15] and the dielectric pipe waveguide [16-19] both can guide the THz with very low losses, and their loss coefficients are as low as 2.6 dB/km and 0.08 m^{-1}, respectively. However, the beam widths for the two waveguides, which are much larger than the wavelength of the THz wave, may be a limiting factor for many applications.

In this paper, we present a double-dielectric-slab waveguide for broadband THz wave propagating. We derive the dispersion equations of both the even modes and odd modes of the waveguide and numerically study the relationships between the propagating characteristics and the waveguide structure, as well as the THz wave frequency. Furthermore, the mode field distribution characteristics of the two modes are studied. The results obtained show that this simple waveguide can guide the broadband THz wave with small beam width and relatively low loss. We expect the waveguide plays an important role in many THz applications such as communication, sensing and detection.

2. Mode dispersion equations of the double-dieletric-slab waveguide

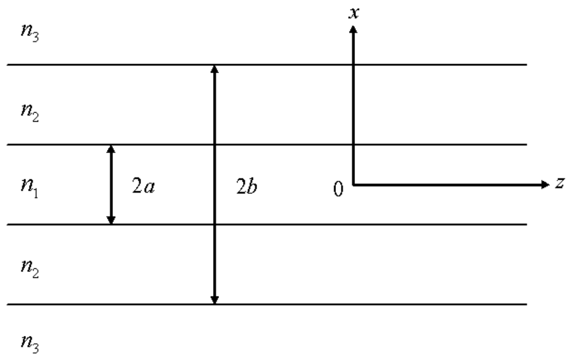

Fig. 1. The double-dielectric-slab waveguide structure

The double-dielectric-slab waveguide structure and the coordinate system are shown in Fig. 1, and the waveguide width is large enough. When transverse electric (TE) modes propagate in the positive z-direction, the field components of the even mode and odd mode can be written as [20]

Even mode:

$$E_y(x)=\begin{cases} A\cos(h_1 x) & |x|<a \\ \frac{A}{2}\{[\cos(h_1 a)+\frac{h_1}{h_2}\sin(h_1 a)]e^{-h_2(|x|-a)}+[\cos(h_1 a)-\frac{h_1}{h_2}\sin(h_1 a)]e^{h_2(|x|-a)}\} & a<|x|<b \\ \frac{A}{2}\{[\cos(h_1 a)-\frac{h_1}{h_2}\sin(h_1 a)]e^{-h_2(-b+a)}+[\cos(h_1 a)+\frac{h_1}{h_2}\sin(h_1 a)]e^{h_2(-b+a)}\}e^{-h_3(|x|-b)} & |x|>b \end{cases} \quad (1),$$

and

Odd mode:

$$E_y(x)=\begin{cases} A\sin(h_1 x) & |x|<a \\ \frac{A}{2}\frac{x}{|x|}\{[\sin(h_1 a)-\frac{h_1}{h_2}\cos(h_1 a)]e^{-h_2(|x|-a)}+[\sin(h_1 a)+\frac{h_1}{h_2}\cos(h_1 a)]e^{h_2(|x|-a)}\} & a<|x|<b \\ \frac{A}{2}\frac{x}{|x|}\{[\sin(h_1 a)-\frac{h_1}{h_2}\cos(h_1 a)]e^{-h_2(b-a)}+[\sin(h_1 a)+\frac{h_1}{h_2}\cos(h_1 a)]e^{h_2(b-a)}\}e^{-h_3(|x|-b)} & |x|>b \end{cases} \quad (2),$$

respectively, where A is a coefficient related with the mode power, $h_1=(n_1^2 k_0^2-\beta^2)^{1/2}$,

$h_2 = (\beta^2 - n_2^{\,2} k_0^{\,2})^{1/2}$， $h_3 = (\beta^2 - n_3^{\,2} k_0^{\,2})^{1/2}$ ， n_1、n_2、n_3 are refraction indices, β is the complex propagation constant, and k_0 is the wave vector in vacuum.

As the tangential components of the electromagnetic fields on interfaces are continuous, we can obtain the dispersion equations of both the even mode and odd mode as follows

$$\text{Even mode:}\quad h_1 a = \tan^{-1}[\frac{h_2}{h_1}\frac{h_2 + h_3 + (-h_2 + h_3)\exp[2h_2(-b+a)]}{h_2 + h_3 - (-h_2 + h_3)\exp[2h_2(-b+a)]}] \tag{3}$$

$$\text{Odd mode:}\quad h_1 a = \tan^{-1}[\frac{h_1}{h_2}\frac{-h_2 + h_3 - (h_2 + h_3)\exp[2h_2(b-a)]}{-h_2 + h_3 + (h_2 + h_3)\exp[2h_2(b-a)]}] \tag{4}$$

By using Eqs. (3) and (4), we can calculate the propagation constants β for the even mode and odd mode, respectively. Then the loss coefficient α and effective refractive index n_{eff} can be gotten accordingly. Based on the propagation constants, we can also obtain the field distributions of the modes by using Eqs. (1) and (2).

3. Mode characteristics of the TE modes in the double-dielectric-slab waveguide

The material adopted here for the slabs in the waveguide is doped silicon with a refractive index $n_2 = \sqrt{\varepsilon_2}$, and the spaces between and outside the slabs are air with a refractive index $n_1 = n_3 = 1$. The relative dielectric constant of silicon ε_2 can be calculated by the Drude model

$$\varepsilon_2 = \varepsilon_\infty - \frac{\omega_p^{\,2}}{\omega^2 - i\omega\omega_\tau} \tag{5}$$

where $\varepsilon_\infty = 11.7$ is the high frequency dielectric constant, ω_p is the plasma oscillation frequency, ω_τ is the damping frequency, and ω is the angular frequency of the THz wave. Here we adopted the doped silicon which has a parameter as $\omega_p = 0.01 \times 10^{12}$ Hz , $\omega_\tau = 0.67 * 10^{12}$ Hz .

3.1 Relationships between the propagating characteristics and the slab thickness

When the space between the two silicon slabs is d = $2a$ = 0.3 mm and the THz wave frequency is f = 0.15 THz, the dependences of α and n_{eff} of the even mode and odd mode, respectively, with the lowest order on the slab thickness t are calculated by numerical calculation, as shown in Fig. 2 (a) and (b). It is indicated that the loss coefficients of the two modes are always very low (less than 0.025 m^{-1}) for the given thickness range, and they both decrease with the decreasing of the slab thickness. When the slab thickness becomes small enough, the loss coefficients tend to zero. The slab thicknesses of 0 and 0.06 mm correspond to the zero loss points for the even mode and odd mode, respectively. When the propagation losses tend to the zero loss points, the beam widths go to infinity for the effective refractive indices tend to the refractive index of air. When the slab thickness increases, the effective refractive indices also increase, and gradually go to the refractive index of silicon, and thus the beam widths decrease correspondingly. For this waveguide, the propagation loss and the beam width are a contradiction. The lower the propagation loss is, the larger the beam width is. However, in applications, a trade-off can be considered between the two aspects.

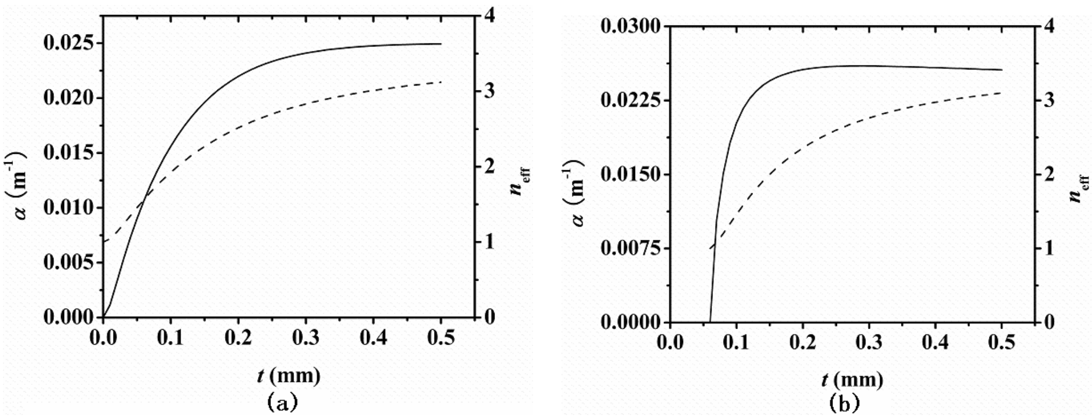

Fig. 2. The dependences of both the amplitude loss coefficients (solid line) and effective refractive indices (dashed line) of the even mode (a) and odd mode (b) on the slab thickness

3.2 Relationships between the propagating characteristics and the space between the two slabs

When the slab thickness is t = 0.15 mm and the THz wave frequency is f = 0.15 THz, the dependences of α and n_{eff} of the even mode and odd mode on the space between the two slabs d are shown in Fig. 3. As shown in Fig. 3 (a), when the space between the two slabs increases, the loss coefficient of the even mode decreases first, and then increases, and then tends to a stable value finally. When the space is d = 0.3 mm, the loss coefficient reaches the minimum, which is 0.0196 m^{-1}. On the contrary, with the space increasing, the loss coefficient of the even mode, as shown in Fig. 3 (b), increases first, and then decreases, and then tends to a stable value finally. When the space between the two slabs goes to zero, the loss coefficient of the odd mode tends to zero, but its beam width tends to infinity. The characteristics of the effective refractive indices of the even mode and odd mode are also different. With the increasing of the space, the effective refractive index of the even mode decreases gradually and tends to a stable value finally, while that of the odd mode increases gradually and tends to a stable value finally.

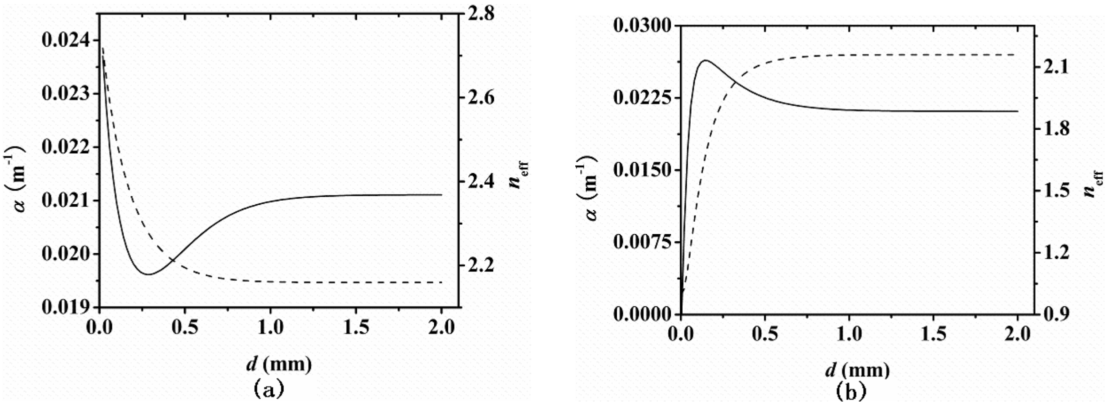

Fig. 3. The dependences of both the amplitude loss coefficients (solid line) and effective refractive indices (dashed line) of the even mode (a) and odd mode (b) on the space between the two slabs

3.3 Relationships between the propagating characteristics and the THz wave frequency

When the slab thickness is t = 0.15 mm and the space between the two slabs is d = 0.3 mm, the dependences of α and n_{eff} of the even mode and odd mode on the THz wave frequency f are shown in Fig. 4. It is indicated that, with the increasing of the frequency, the effective refractive indices of both the even mode and odd mode increase and their propagation losses first increase and then decrease. The loss coefficient of the even mode tends to zero as the frequency goes to zero, but that of the odd mode tends to zero as the frequency goes to 0.08 THz. It is pointed that the propagation losses of the two modes are both very low in the given frequency range, so one can guide the broadband THz wave with low loss by using the double-dielectric-slab waveguide.

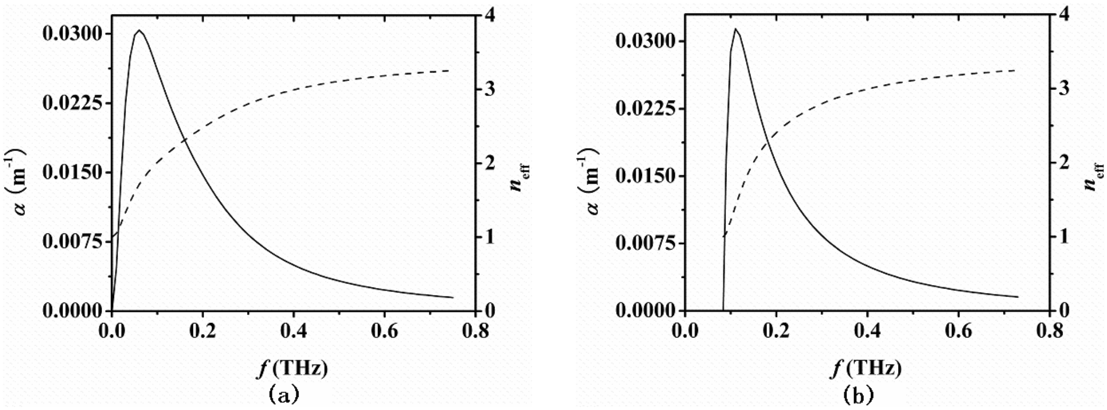

Fig. 4. The dependences of both the amplitude loss coefficients (solid line) and effective refractive indices (dashed line) of the even mode (a) and odd mode (b) on the THz wave frequency

3.4 Mode field distributions of the double-dielectric-slab waveguide

When the slab thickness is t = 0.15 mm, the space between the two slabs is d = 0.3 mm, the THz wave frequency is f = 0.15 THz, and the plasma oscillation frequency of silicon is f = 0.15 THz, the propagation constants of the even mode and odd mode are

$\beta = 7126.93 - i0.0196$ and $\beta = 6288.93 - i0.0245$, respectively. Based on the propagation constants, we obtain the transverse electric field amplitudes of the even mode and odd mode by using Eqs. (1) and (2), respectively, as shown in Fig. 6. A remarkable difference between the two modes is that, at $x = 0$, the even mode amplitude does not equal to zero but the odd mode amplitude equals to zero. On the two sides of $x = 0$, the vibration directions of the electric field are the same for the even mode, but opposite for the odd mode. For the given waveguide structure, the beam widths of the even mode and odd mode are both very small. As shown in Fig. 6, the full width at half maximum (FWHM) of the even mode is 0.74 mm, and the FWHM for one peak in the odd mode is 0.28 mm. Therefore, one can guide the THz wave with low propagation loss and simultaneously small beam width (compared with the wavelength of the THz wave $\lambda = 2$ mm) by using the double-dielectric-slab waveguide.

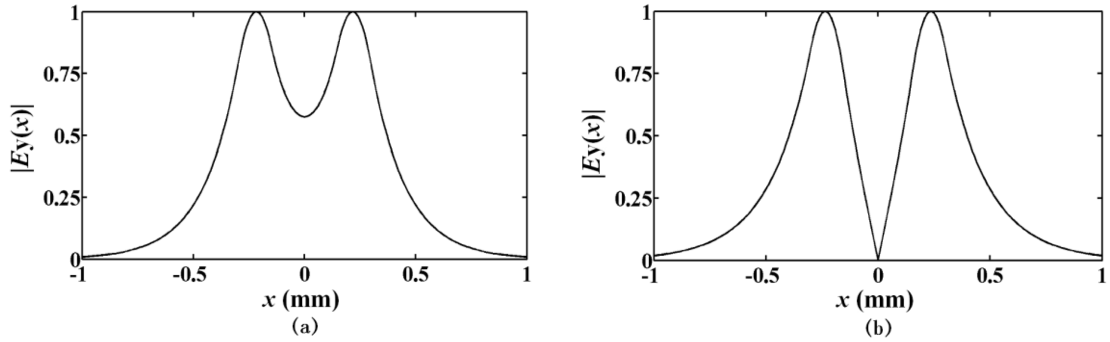

Fig. 5. The normalized amplitudes of the transverse electric fields of the even mode (a) and odd mode (b)

4. Conclusion

The double-dielectric-slab waveguide is presented for guiding the broadband THz wave. By using the dispersion equations of the even mode and odd mode, we study the relationships between the propagating characteristics and the waveguide structure, as well as the THz wave frequency. And then the mode field distribution characteristics are discussed. The results obtained show that the broadband THz wave can be guided with much lower propagation loss than the similar structure in reference [21] although the beam width is a little wider. The combination of the low propagation loss and the small beam width makes the double-dielectric-slab waveguide very useful in many THz application fields, including communication, sensing, and detection.

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