Terahertz energy confinement in finite-width parallel-plate waveguides

Hui Zhan, Rajind Mendis, and Daniel M. Mittleman*
Rice University, Department of Electrical and Computer Engineering, MS-366
6100 Main Street, Houston, TX 77005, USA

Abstract: We experimentally investigate the terahertz energy confinement in finite-width parallel-plate waveguides. Although there is some apparent energy confinement parallel to the plates due to the narrowing of the width, this does not result in actual energy conservation, when the plate separation is as large as 1 cm. However, these findings indicate that by reducing the plate separation, it may be possible to achieve real energy confinement along with energy conservation in these waveguides.

Keywords: Terahertz, waveguides

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The parallel-plate waveguide (PPWG) has proven to be a powerful platform for terahertz (THz) research, enabling THz interconnects [1, 2], THz generation [3], THz spectroscopy [4-6], THz sensing [7], THz imaging [8], THz signal processing [9], via the excitation of the single TEM mode of the waveguide. This mode exhibits no low-frequency cutoff and is therefore dispersionless [1], making it an obvious choice for the propagation of broadband THz pulses. It is generally considered that the one-dimensional nature of confinement of the PPWG, where there is no physical boundary to confine energy parallel to the plates, can result in energy leakage, and therefore additional diffraction losses, when realizing long propagation path lengths [2].

However, since the recent presentation of the so called metallic-slit-waveguide [10], which is essentially a finite-width PPWG, it has been somewhat of a controversy as to how THz radiation is being guided with the associated claim of high confinement. The numerical simulations in the above work showed that by limiting the width of the plates, one could actually achieve complete two-dimensional confinement, where the energy is additionally laterally confined parallel to the plates. To better understand this behavior, a more direct experimental investigation into this apparent energy confinement is necessary.

Towards this goal, we investigate the energy-confinement behavior of finite-width PPWGs via the propagation of broadband THz pulses along relatively long propagation paths. We compare the behavior of finite-width PPWGs with their conventional counterparts having much wider widths, using a relatively large plate separation of 1*cm*. Our experiments showed that the lateral THz beam profile measured at the output face of a narrow-width PPWG has a smaller size, along with relatively smaller signal amplitude, than that from a wide-width PPWG. These results indicate that there is some energy confinement due to the narrower width, but with no apparent energy “conservation”. The fact that the measured propagation loss for the narrow-width PPWG is higher than that for the wide-width PPWG is consistent with this observation.

A fiber-coupled THz-time-domain-spectroscopy system was used for the THz generation and detection. The THz transmitter and the receiver are both photoconductive antennas with attached silicon lenses providing a~6 *mm* diameter aperture for the emission/detection beams. The waveguides were fabricated using aluminum plates, where the inside surfaces are well polished to minimize any scattering losses due to roughness. As shown in the inset of Fig.1, two different PPWG geometries were used, both having a plate separation of b=1*cm* and a propagation length of L=25*cm*. The wide PPWG has a width of w =10*cm* (representing an ideal PPWG in this work), and the narrow one has a width of w=2*cm*. The reshaped THz beam was coupled into the waveguides with a 1/e beam waist diameter of ≈2*cm*, centered in both the x and y directions as shown in inset of Fig. 1. In our experiments, the input THz beam was polarized in the y direction, perpendicular to the plates, to excite the fundamental TEM mode [1, 2].

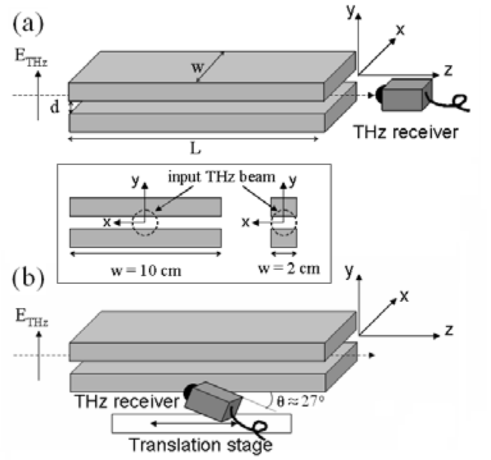

Fig. 1 Setup schemes with the THz receiver scanning (a) the output face of the PPWG, and (b) the side of the PPWG. The inset shows the input coupling surface for the two PPWG geometries.

Fig. 2 shows the mode profiles of the THz signals at the output face of the two waveguides, with the receiver scanning in the x direction, approximately 2 *mm* from the output face, as shown in Fig. 1(a). The THz signals (not shown) from the 10cm-wide PPWG are slightly stronger than the ones from the 2*cm*-wide PPWG. We note that the mode profile of the 2*cm*-wide PPWG is narrower than that of the 10*cm*-wide one, which indicates an apparent energy confinement as presented in Ref.[10]. These two facts do however, indicate that compared to the 10*cm*-wide PPWG, there is less total energy propagating along the 2*cm*-wide PPWG, meaning there is no apparent energy conservation.

To understand the narrowing of the beam profile, we also studied the THz leakage from the sides of the waveguides, with the receiver rotated around the y axis so that the line-of-sight was ~ 27 from the input beam axis [shown in Fig.1(b)], in order to obtain a reasonable signal-to-noise ratio. The receiver was situated 7.5*cm* away from the input beam axis, same for both the wide and narrow waveguides. The receiver was mounted on a translation stage, and scanned along the z direction parallel to the input beam axis. We observed that the leakage curves for the 10 *cm*-wide and 2*cm*-wide PPWGs exhibited the same trend as the curve without any waveguide (when the beam was freely propagating in space), besides some experimental artifacts. This fact indicates that the leakage mechanism for the three cases is the same, and that the finite width of the PPWG does not cause any real energy conservation in the direction parallel to the plates.

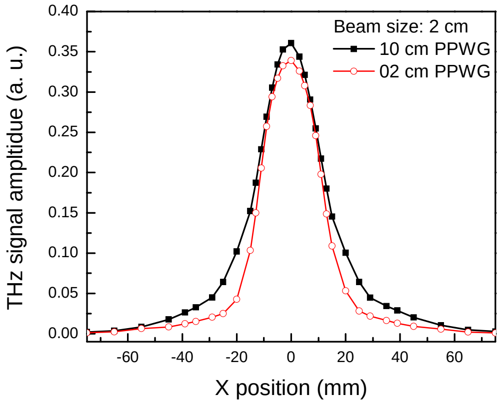

Fig. 2 The mode profiles of the propagated THz signals in the *x* direction at the output of both the 10*cm*-wide and 2*cm*-wide PPWGs.

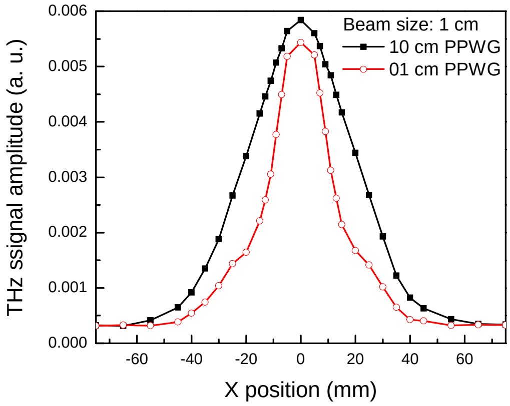

Fig. 3 The mode profiles of the propagated THz signals in the *x* direction at the output of both the 10*cm*-wide and 1*cm*-wide PPWGs, while a 1*mm*-diameter aperture is applied to the attached silicon lens of the receiver.

To further study the effects of this apparent energy confinement due to the finite width, we performed a similar experiment on another pair of PPWGs, where the narrow one is now 1 *cm* wide, and the other with the same 10 *cm* width as before. The plate separation and the propagation length were also kept the same. The input THz beam size was reshaped to a 1 *cm* beam-waist diameter, with the same coupling polarization. The mode profiles of the detected THz signals are compared in Fig. 3. Similar to the previous case, we observe the same narrowing of the beam profile here. The 1 *cm*-wide PPWG clearly shows some confinement, although at the expense of reduced overall energy as seen by the reduced THz signal levels.

Based on the above experiment results, we believe that the energy confinement associated with narrow-width PPWGs results in a higher propagation loss compared to their wide-width counterparts. To clarify this loss behavior, we measured the guided THz signals from a long-path PPWG (L=25 *cm*) and a short-path PPWG (L=2.54 *cm*), and obtained the total propagation loss (α_T) for the PPWGs, which includes both the diffraction loss (α_D) and the ohmic loss (α_R), as shown in the appendix. Our experimental α_T showed that the total propagation loss for the narrow-width PPWG is higher than the wide-width PPWG through the usable bandwidth of our system. This higher loss is consistent with the narrowing of the beam due to energy leakage in the finite-width PPWG having a relatively large plate separation (b=1*cm*). Furthermore, considering an ideal (wide width) PPWG, theoretically, it is possible to show that the diffraction loss is more dominant than the ohmic loss, and as such plays a major role in the total propagation loss, which is also consistent with the above experimental observations.

This study shows that, as far as the mode profile is concerned, a PPWG with a finite width exhibits an apparent narrowing or confining, consistent with ref. [10].With a relatively large plate separation (b=1 *cm*), this narrowing of the profile does not lead to better energy conservation, compared to an idealized (wide width) PPWG. Instead, the total propagation loss of the finite-width waveguide is higher than that of the idealized PPWG. However, we expect that decreasing the plate separation could eventually result in much better energy confinement as well as energy conservation in finite-width PPWGs.

APPDENDIX: LOSS CALCULATION

Starting from the fundamental frequency-domain, input-output expression for the single-mode waveguide

$$E_o = E_i T C_y^2 C_x e^{-j\beta L} e^{-\alpha L} \tag{1}$$

where E_o and E_i are the complex spectral components, T is the total transmission coefficient that takes into account the impedance mismatch at both the input and output, C_y is the coupling coefficient for the y direction (perpendicular to the plates). C_x is the coupling coefficient for the x direction (parallel to the plates). The coupling coefficients are analyzed using the standard overlap-integral method [2], where C_y takes into account the similarity of the input/output Gaussian beam to the guided-mode in the y direction, while C_x takes into account the spreading of the beam in the x direction due to diffraction. L is the propagation length, β is the phase constant, and α_R gives the ohmic loss.

Applying Eq.(1) to the short and long path-lengths separately, taking the complex ratio, and extracting the amplitude information, we can write

$$\left|\frac{E_{o2}}{E_{o1}}\right| = \frac{C_{x2}}{C_{x1}} e^{-\alpha_R (L_2 - L_1)} = e^{-\alpha_T (L_2 - L_1)} \tag{2}$$

Where the subscripts ‘1’ and ‘2’ stand for the short and long waveguides, and α_T is “artificially” defined to give the total loss accounting for both the diffraction loss and the ohmic loss. Re-arranging Eq. (2), we can derive an expression for α_T as

$$\alpha_T = \alpha_R + \frac{1}{(L_1 - L_2)} \ln\left[\frac{C_{x2}}{C_{x1}}\right] = \alpha_R + \alpha_D \, , \tag{3}$$

Where $\alpha_D = 1/(L_1 - L_2)\ln[C_{x2}/C_{x1}]$ accounts for the diffraction loss. Note that all losses are for an air-filled PPWG.

It should be emphasized that in the case of an ideal PPWG (with wide plates), although α_R depends only on the waveguide configuration (the plate separation d and metallic conductivity σ), α_D on the other-hand is unique to the experimental configuration, depending on the input-beam size, path-length of the waveguides, and the collecting-beam aperture size, and does not depend on d.

Acknowledgement

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