Investigation of the lowest-order TE mode of the parallel-plate metal waveguide for terahertz pulses

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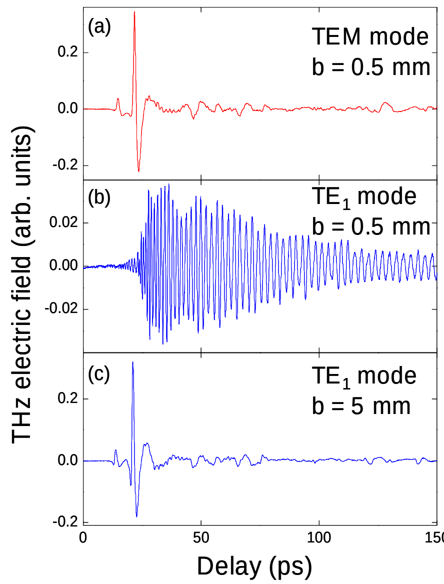
***Abstract*— We describe an experimental and theoretical study of the lowest-order transverse-electric (TE_1) mode of the parallel-plate waveguide for the propagation of broadband THz pulses, and demonstrate undistorted THz pulse propagation via the TE_1 mode. This demonstration overcomes two fundamental problems associated with the low-frequency cutoff of this mode, the group velocity dispersion and the spectral filtering, which have prevented the use of this mode for THz wave guiding in the past. We also observe a remarkable counter-intuitive property of the TE_1 mode: its attenuation decreases with increasing frequency. This phenomenon has not been observed with any other THz waveguide to date, and can enable extremely low-loss propagation. In addition, we find that it is possible to achieve almost 100% coupling to the TE_1 mode from an input Gaussian beam. These results favor the use of the TE_1 mode for the efficient guiding of THz pulses.**

I. Introduction And Background

In recent years, numerous wave-guiding techniques have been investigated for the propagation of broadband THz pulses, using hollow metallic structures[1], dielectric fibers[2], dielectric slabs[3], parallel-plate structures[4,5], photonic crystal fibers[6], coaxial lines[7], metal wires[8,9], and metallic slits.[10] However, despite their potential for applications such as high-speed interconnects, spectroscopy, sensing, imaging, and microscopy, none of these approaches is feasible for long distance (~10 m or more) THz pulse propagation. The techniques with the lowest loss involve the use of the dominant transverse-magnetic mode of a dielectric slab waveguide, or the Sommerfeld mode of a cylindrical metal wire. However, the former suffers from severe group velocity dispersion (GVD)[3], while the latter is prone to radiation losses and suffers from poor coupling.[9,11]

The lowest-order transverse-electric (TE_1) mode of the parallel-plate waveguide (PPWG) has been proposed for extremely low-loss, single-frequency wave-guiding in the mid-infrared[12,13], with losses in the dB/km range. If this mode could be used for the guiding of THz pulses, and such low losses realized, then one could achieve very long propagation distances. However, the obvious difficulty has been the presence of a low-frequency cutoff at $f_c = c/(2b)$, where b is the plate separation. For broadband THz pulses having frequency components extending from almost DC up to several THz, this will cause both the loss of frequency components below cutoff, and high GVD for components near the cutoff. These two fundamental problems would result in severe distortion of the pulses, and have prevented the use of this mode for THz pulse transport. Here, we experimentally and theoretically investigate the use of the TE_1 mode, and describe a practical solution to both of these problems. We also remark on two extremely advantageous properties of the TE_1 mode: (1) the mode attenuation *decreases* with increasing frequency for all frequencies above f_c, and (2) the input coupling from a free-space Gaussian beam can be almost *perfect*. This collection of properties makes the TE_1 mode a strong candidate for the efficient guiding of THz pulses.



II. Results

For the experiment, we fabricate several PPWGs using highly polished aluminum plates, all having a transverse width larger than the ~ 10 mm input-beam diameter. In the first set of measurements, the plates are spaced by $b = 0.5$ mm. The THz pulses, generated and detected using a THz-TDS system, are coupled into and out of the PPWGs using two silicon plano-cylindrical lenses.[3,4] Fig. 1(a) shows the pulse after propagating through a 25.4 mm long PPWG with the input Gaussian beam polarized perpendicular to the plates to excite the TEM mode. As expected, we see little distortion in the propagated pulse compared to the reference (not shown), indicating single TEM mode propagation. This is further validated by its amplitude spectrum (derived by Fourier-transforming the truncated pulse), which shows no cutoff (see Fig. 2). Fig. 1(b) shows the pulse after propagating through the same PPWG, but with the input beam polarized *parallel* to the plates to excite the TE_1 mode. In contrast to the TEM case, the pulse is strongly reshaped and broadened, and exhibits a positive chirp. Its amplitude spectrum (dotted curve in Fig. 2) has a cutoff at $f_c = 0.3$ THz, as expected for the TE_1 mode with $b = 0.5$ mm. We conclude that the pulse propagates via the single TE_1 mode, as the next possible higher-order mode

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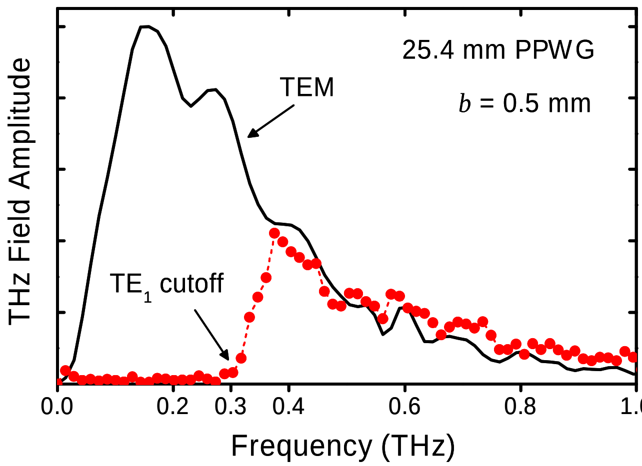
which can be excited by an input beam with even spatial symmetry[1,2,4], the TE_3 mode, has its cutoff at 0.9 THz, almost at the high end of the input spectrum.



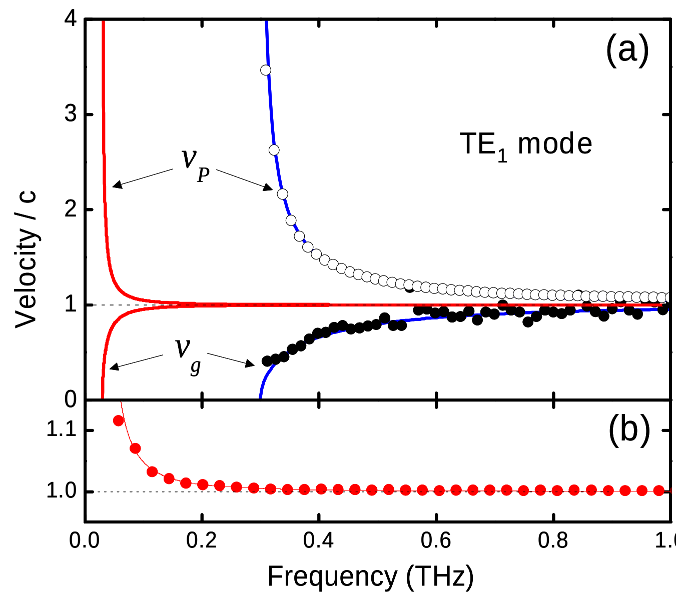
As in previous studies[4,5], by comparing the phase and amplitude spectra of the time pulses corresponding to multiple waveguide lengths, we can extract the experimental phase constant β and attenuation constant α for the propagating mode. The derived phase velocity v_p $(=\omega/\beta)$ and group velocity v_g $(=\partial\omega/\partial\beta)$ are plotted in Fig. 3(a) by the open circles and dots, respectively. These show excellent agreement with the theoretical (thick solid) curves calculated using classical guided-wave theory[14,15] for the TE_1 mode of the PPWG with $b = 0.5$ mm. The curves clearly demonstrate the highly dispersive nature of propagation due to the cutoff, where the high-frequency components travel faster, resulting in the observed positive chirp. The experimentally derived α is plotted in Fig. 4(a) by the dots, along with that of the TEM mode by the open circles. Also plotted are the corresponding theoretical (thick solid) curves, computed using the expressions[14,15] $\alpha_{TEM} = 2R_s/(Z_o b)$, and

$$\alpha_{TE} = \frac{4R_s\left(f_c/f\right)^2}{Z_o b\sqrt{1-\left(f_c/f\right)^2}}. \qquad (1)$$

Here, Z_o is the free-space impedance, R_s is the surface resistance given by $R_s = \sqrt{\pi f \mu/\sigma}$, μ is the permeability and σ is the DC conductivity. The experimental and theoretical curves agree reasonably well, and reveal a remarkable, counter-intuitive property of the TE_1 mode: the attenuation *decreases* with increasing frequency for all frequencies above cutoff.[12,13,16] This dependence is in direct contrast to the attenuation of the TEM mode that increases with frequency, and has not been observed with any other THz waveguide.

III. Discussion

We can gain some insight into this phenomenon by analyzing the TE_1-mode propagation in terms of a plane wave that travels down the guide, bouncing back and forth between the plates with *s*-polarized incidence (inset of Fig. 4). In fact, we need two plane waves to represent the mode field, but these two are mirror-symmetric about the center plane of the waveguide. As the frequency f decreases, the incidence angle θ decreases, and at cutoff, $\theta = 0°$, implying no power flow. At each bounce, there will be some power loss due to the finite conductivity of the metal, which to first-order can be assumed to be independent of θ due to the high conductivity. As f decreases, the number of bounces per unit length increases, increasing the overall loss, and leading to the observed frequency dependence. One can show that the attenuation derived from an analysis of this bouncing plane wave description is *identical* to that given by Eq. (1).



The significance of this frequency dependence is that it allows one to reduce the attenuation by moving the input spectrum to higher frequencies, or alternatively, by pushing the cutoff to lower frequencies. We can lower the cutoff frequency by increasing the plate separation. For example, when $b = 5$ mm, $f_c = 30$ GHz, which is at the low end of the input spectrum. The corresponding theoretical attenuation (thin solid curve) is also plotted in Fig. 4(a), with an enlarged view of the baseline shown in Fig. 4(b). This demonstrates an extraordinarily low attenuation, where the value at 1 THz is 2.6 dB/km. This is only an order of magnitude higher than the attenuation of telecommunications-grade optical fiber at 1550 nm. In addition, lowering the cutoff frequency has the advantage of reducing the dispersion to almost negligible values, as seen by the (thin solid) velocity curves plotted in Fig. 3(a) for $b = 5$ mm. Except for the very low end of the spectrum, the curves exhibit zero dispersion.

The idea of shifting the TE_1 cutoff to the low-frequency end by increasing the plate separation has the obvious disadvantage of permitting multi-mode propagation. Since the cutoff frequencies of many higher-order modes now fall within the input spectrum, multiple modes could be simultaneously excited, leading to excessive loss and dispersion. However, this problem can be overcome if the input coupling is optimized to selectively excite only the TE_1 mode via mode matching. In fact, the electric field of the TE_1 mode has a

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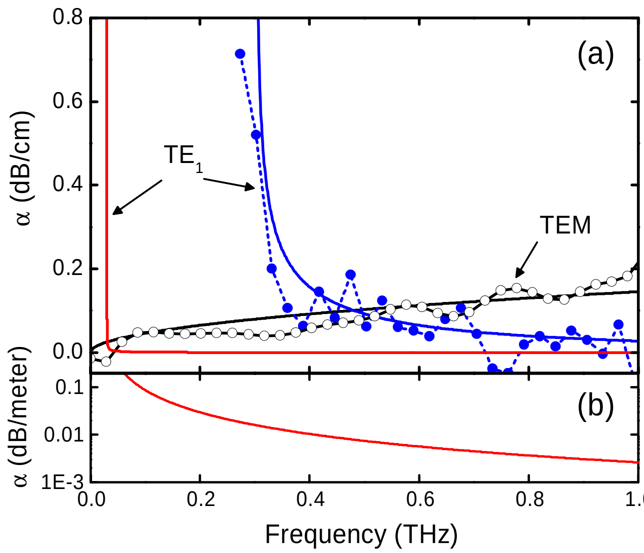
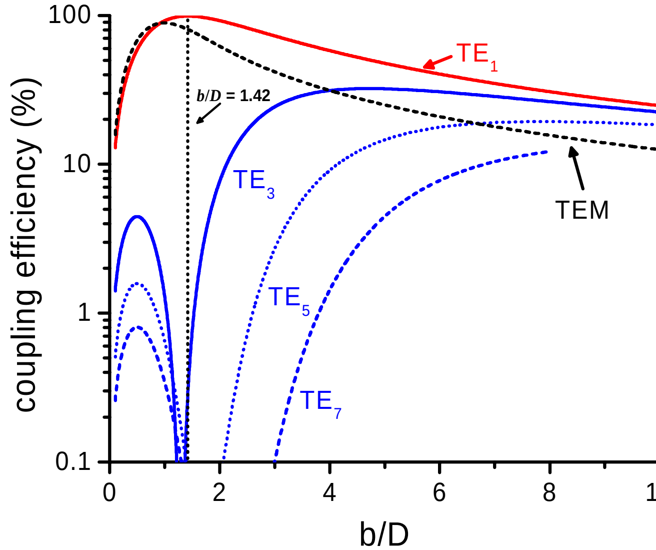
spatial dependence of $E(y) \sim \sin(\pi y/b)$, where y is the coordinate normal to the plates with the origin at the plate surface. This spatial profile is more closely matched to a Gaussian input beam than is the flat-top profile of the TEM mode, for example, and therefore enables better coupling. To quantify this, we calculate the power coupling efficiency (η) from an input Gaussian beam to the TEM mode and to several even-symmetric TE modes. This is computed as a function of b/D, where D is the $1/e$ beam size of the Gaussian input beam. This result, plotted in Fig. 5, shows that the *maximum possible* η to the TEM mode is 89% (for $b \approx D$), whereas it is over 99% to the TE_1 mode (for $b/D = 1.42$). In fact, $\eta > 90\ \%$ for $0.53 < b/D < 2.1$, implying that the excitation is almost purely TE_1 for a large range of b/D values. In other words, a frequency-independent input beam size is not strictly required to obtain nearly single-mode excitation over a broad bandwidth. Therefore, we have the freedom to select a practically feasible large value for b to achieve extremely low losses and negligible dispersion, while selecting a matching input beam size to couple all the available power to the single TE_1 mode - the ultimate combination for the efficient guiding of THz pulses.



In an attempt to test some of these capabilities, as a first demonstration, we use the same PPWGs as in our earlier measurement, but with a large plate separation of $b = 5$ mm. We directly excite the guided wave with a weakly focused THz input beam, without using cylindrical lenses. Fig. 1(c) shows the resulting pulse, where we observe only a mild reshaping of the pulse, in sharp contrast to the severe pulse distortion seen in Fig. 1(b). The experimentally derived phase velocity (dots) for this larger value of b, shown in Fig. 3(b), is in excellent agreement with the theoretical prediction (solid curve), indicating negligible dispersion. This clearly demonstrates that we have achieved single TE_1 mode propagation, implying the high selectivity of the input coupling, and moreover, demonstrates that we have successfully solved the GVD problem. Determining the experimental attenuation is not possible in these measurements due to the extremely low losses [Fig. 4(b)]. This would require much longer (e.g., meters) propagation distances than used here.



There is, however, one issue that needs to be resolved before we could actually implement long-distance propagation, i.e., the energy leakage in the unconfined (transverse) direction of the PPWG. In practice, there will be a loss associated with beam diffraction due to the partially open nature of the waveguide.[5] One way to suppress this would be to provide a slight curvature (a transverse concavity) to the plate surfaces[12,13] as shown in the inset of Fig. 5. This can be understood in terms of the "bouncing plane wave" description outlined above, where the wave is made to undergo some focusing at each bounce to precisely offset the diffraction. Theoretical studies based on this analytical description suggest that it is indeed possible to achieve complete confinement with slightly concave parallel plates. We conclude that the experimental and theoretical evidence strongly favors the utilization of the TE_1 mode of the PPWG for long distance THz pulse propagation.

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