AIP Applied Physics Letters

Comment on "The transition from a TEM-like mode to a plasmonic mode in parallel-plate waveguides" [Appl. Phys. Lett. 98, 231113 (2011)]

M. Navarro-Cía, R. Mueckstein, and O. Mitrofanov

Citation: Appl. Phys. Lett. **102**, 246103 (2013); doi: 10.1063/1.4811131
View online: http://dx.doi.org/10.1063/1.4811131
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v102/i24
Published by the AIP Publishing LLC.

Additional information on Appl. Phys. Lett.

Journal Homepage: http://apl.aip.org/
Journal Information: http://apl.aip.org/about/about_the_journal
Top downloads: http://apl.aip.org/features/most_downloaded
Information for Authors: http://apl.aip.org/authors

ADVERTISEMENT

TREK, INC. • 11601 Maple Ridge Road, Medina, NY 14103 USA • Toll Free in USA 1-800-FOR-TREK • (t)+1-585-798-3140 • (f)+1-585-798-3106 • sales@trekinc.com

Downloaded 18 Jun 2013 to 155.198.134.251. This article is copyrighted as indicated in the abstract. Reuse of AIP content is subject to the terms at: http://apl.aip.org/about/rights_and_permissions

APPLIED PHYSICS LETTERS **102**, 246103 (2013)

Comment on "The transition from a TEM-like mode to a plasmonic mode in parallel-plate waveguides" [Appl. Phys. Lett. 98, 231113 (2011)]

M. Navarro-Cía,[1,2,3,4,a)] R. Mueckstein,[1,b)] and O. Mitrofanov[1,c)]
[1]*Department of Electronic & Electrical Engineering, University College London, London, Torrington Place, WC1E 7JE, United Kingdom*
[2]*Optical and Semiconductor Devices Group, Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2BT, United Kingdom*
[3]*Centre for Plasmonics and Metamaterials, Imperial College London, London SW7 2AZ, United Kingdom*
[4]*Centre for Terahertz Science and Engineering, Imperial College London, London SW7 2AZ, United Kingdom*

(Received 21 February 2013; accepted 29 May 2013; published online 17 June 2013)

[http://dx.doi.org/10.1063/1.4811131]

In a recent letter, Liu *et al.*[1] describe the effect of dominant mode profile change in a parallel plate waveguide (PPWG) that the authors observed experimentally at THz frequencies. The energy distribution at the waveguide output showed a TEM-like mode at 0.1–0.2 THz and an edge plasmon-like mode with the energy concentrated at the edges of the PPWG above 0.3 THz. Formation of the edge-plasmon mode, as the fundamental mode for the waveguide at THz frequencies, invalidates the classical approximation for wave propagation as the TEM-like mode.

Here, we would like to point out that the effect of energy concentration near the edges of the PPWG can have another origin: it can be caused also by interference of waveguide modes, the TEM-like mode and a higher order mode, namely, the transverse electric TE_{20}-like mode. These two explanations are principally different. Although they lead to a similar result for the case considered by Liu *et al.*, their conclusions are drastically different for a general PPWG: the edge-plasmon mode maintains its profile after it is formed, whereas the mode interference results in recurring transitions between the two field profiles throughout the waveguide length.

To analyze the case considered by Liu *et al.*,[1] we model their experimental setup with CST Microwave Studio™. Following Ref. 1, the parallel plate waveguide has a length of 250 mm, plate width $w = 10$ mm, and distance between plates $b = 1$ mm (see Fig. 1(a)). We use here the perfect electric conductor approximation after checking that a real metal (aluminum) with conductivity $\sigma = 3.56 \times 10^7$ S/m leads to no significant difference in the results. The diameter of the incident Gaussian beam is 5 mm at the central frequency $f_0 = 0.4$ THz. The temporal Gaussian signal of the spatial Gaussian beam has a full-wave at half maximum (FWHM) of ∼2.9 ps, i.e., spectral components between 0.1 and 0.7 THz (see Fig. 1(a)) to match the experimental spectrum of Fig. 1 from Ref. 1. Without loss of generality, we place the parallel plate waveguide 3 mm from the source to avoid undesired coupling between the source and the structure. A cubic grid of 0.04 mm × 0.04 mm × 0.04 mm is used, leading to a total of 302 108 625 unit cells.

The spatial mode profile evolution along the length of the waveguide allows us to determine the effect origin. In the case of edge-plasmon mode, we expect to observe graduate mode formation along the waveguide, and for the case of mode interference, we expect to observe mode beating. In the former case, spectrum of the propagating pulse gradually loses its high frequency components in the central region of the waveguide, whereas it displays interference maxima and minima in the latter case.

The calculated spectrum of the pulse at different positions along the parallel plate waveguide is shown in Fig. 1(b). The spectrum displays a minimum moving from low frequencies to high frequencies as the pulse propagates. This behavior suggests mode beating. The shift of the minimum to high frequencies is consistent with the phase velocities of the TEM-like mode and a higher order mode, the TE_{20}-like mode as shown later. We note that the calculated spectrum at around $z = 185$ mm (blue line in Fig. 1(a)) resembles the spectrum shown by a blue line in the inset of Fig. 1 from Ref. 1. The exact z position where the minimum occurs is somewhat different in Ref. 1. The minimum is determined by the phase delay between the two modes and therefore, it depends on coupling at the waveguide input.

The cross-sectional electric field distribution (at $z = 185$ mm) is plotted as a function of frequency on the right-hand side of Fig. 1(b). The spectra are normalized to the input spectrum shown by the red curve in Fig. 1(a). The spatial profile shows the effect similar to the observations reported in Ref. 1, i.e., the energy is concentrated in the center of the waveguide for low frequencies (0.2–0.3 THz) and at the edges for higher frequencies (0.3–0.6 THz). At 0.7 THz, however, the distribution changes again: the energy moves back to the center of the waveguide. This behavior is characteristic of mode interference.

To test the mode interference hypothesis further, we also compute the spectrum at different z for the interference of the ideal TEM and transverse electric TE_{20} modes (Fig. 1(c)). This is calculated using an approximation $E(\omega, x = y = 0, z) = \sqrt{\frac{\pi}{a_0}} e^{-(\omega-\omega_0)^2/4a_0}\left(e^{i\beta_{TEM}(\omega)z} + e^{i\beta_{TE_{20}}(\omega)z}\right)$, where $a_0 = \frac{2\ln 2}{FWHM}$ and $\beta_{\mathrm{TEM}}(\omega)$ and $\beta_{\mathrm{TE20}}(\omega)$ are the wavenumbers of the bounded TEM and TE_{20} modes, respectively. Note that we assume both modes carry the same energy. We

---

[a)] Electronic mail: m.navarro@imperial.ac.uk
[b)] Electronic mail: r.mueckstein@ee.ucl.ac.uk
[c)] Electronic mail: o.mitrofanov@ucl.ac.uk

© 2013 AIP Publishing LLC

Downloaded 18 Jun 2013 to 155.198.134.251. This article is copyrighted as indicated in the abstract. Reuse of AIP content is subject to the terms at: http://apl.aip.org/about/rights_and_permissions

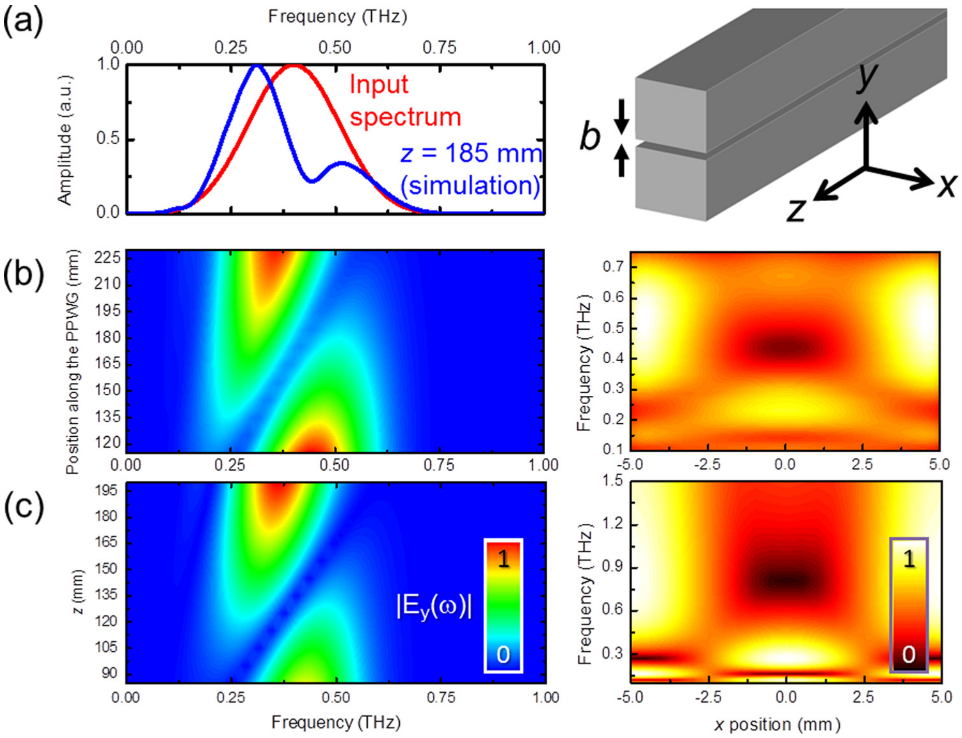

FIG. 1. (a) Spectrum of the incident pulse and the numerically computed one at $z = 185$ mm (left) and sketch of the geometry (right). (b) Numerically computed spectrum at the central position of the parallel plate waveguide for different z positions (left) and contour plot of the cross-sectional electric field distribution $E_y(\omega, x, y = 0,\ z = 185\,\text{mm})$ normalized to the input spectrum (right). (c) Analytical spectrum as a function of the z propagation distance for the multimode propagation of TEM and TE_{20} modes (left) and contour plot of the cross-sectional electric field $E_y(\omega, x, y = 0,\ z = 135\,\text{mm})$ normalized to the input spectrum (right).

choose to consider the TE_{20} mode based on our observations in a tapered plate waveguide.[2] Unlike the bounded TEM mode, the bounded TE_{20} mode has a cutoff frequency f_c, $\text{TE}_{20} = c/w$, where c is the free-space velocity. For the dimensions of the considered PPWG, $f_c = 30$ GHz, and thus, the bounded TE_{20} mode is a propagating mode for the whole frequency range of interest. The analytical spectra along the waveguide axis show the same behavior as the numerically computed spectra in Fig. 1(b) indicating that the analytical model of mode interference describes the effect. Likewise, the analytically computed cross-sectional electric field at $z = 135\,\text{mm}$, $E(\omega, x, y = 0,\ \ z = 135\,\text{mm}) = \sqrt{\frac{\pi}{a_0}}\, e^{-(\omega-\omega_0)^2/4a_0}\left(e^{i\beta_{TEM}(\omega)z} + ie^{i\beta_{TE_{20}}(\omega)z}\cos\left(\frac{2\pi x}{w}\right)\right)$, resembles our numerical results, and those, reported in Ref. 1.

We note that the interference maxima and minima have slightly different frequencies in the model and the simulations. This discrepancy is attributed to the simplicity of our analytical approximation, which does not take into account the open boundaries of the parallel plate waveguide. The purpose of the analytical model here, however, is only to determine the effect origin.

In conclusion, we have considered the effect of mode profile transition in the parallel plate waveguide, in which the propagating energy is shifted to the edges of the waveguide. We find that in addition to the explanation discussed in Ref. 1, the effect can be caused by the interference of two waveguide modes. The two explanations are principally different and they lead to distinctly different behavior of THz wave propagation in practical parallel plate waveguides of finite width. As a result, choosing the appropriate model is essential for accurate description of effects observed THz parallel plate waveguides, such as the effect of the mode profile change discussed above[1] and as well as the effect of dispersive THz pulse propagation.[2]

This work was supported by the Engineering and Physical Sciences Research Council [Grant No. EP/G033870/1]. M.N.-C. is supported by the Imperial College Junior Research Fellowship.

[1] J. Liu, R. Mendis, and D. M. Mittleman, Appl. Phys. Lett. **98**, 231113 (2011).
[2] R. Mueckstein, M. Navarro-Cía, and O. Mitrofanov, Appl. Phys. Lett. **102**, 141103 (2013).

Downloaded 18 Jun 2013 to 155.198.134.251. This article is copyrighted as indicated in the abstract. Reuse of AIP content is subject to the terms at: http://apl.aip.org/about/rights_and_permissions