

Quasi-TEM mode propagation in twin-wire THz waveguides

(Invited Paper)

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Received June 20, 2011; accepted August 3, 2011; posted online September 30, 2011

We numerically investigate the trade-offs between the dispersion properties, coupling efficiency, and geometrical constraints in dual-wire (twin-lead) terahertz (THz) waveguides. In particular, we show that their inherent linearly polarized quasi-transverse electromagnetic (TEM) modes exist for waveguide transverse dimensions comparable with the wavelength, enabling significant end-fire coupling ($>10\%$) for numerical-aperture limited Gaussian beams while supporting a relatively low-dispersion propagation of below $0.5 \text{ ps}^2/\text{m}$, as desired for short-pulse time-domain spectroscopy applications. Starting from the dual-wire structure, we also demonstrate that low-dispersion tapers can be designed to improve coupling efficiency.

OCIS codes: 230.0230, 230.7370.

doi: 10.3788/COL201109.110013.

Terahertz (THz) bandwidth has been attracting much interest in material characterization, owing to its demonstrated advantages in probing and recognizing different materials, for various potential applications in fields spanning from biology to security. These applications rely on the free space propagation of broadband single-cycle THz pulses, which enables time-domain spectroscopy (TDS), capable of retrieving the amplitude and phase information of the spectral signature of various compounds^[1]. One of the recent challenges on the topic is the development of practical waveguides that are capable of transporting this signal to arbitrary locations.

Many studies highlight that the most confining structures do not exhibit the wide bandwidth required by typical pulses used in THz-TDS. The strong dispersion scrambles the phase-time information and renders the extraction of the complex spectrum rather difficult. Most studies have been based either on conventional metallic guiding structures such as hollow circular waveguides^[2] and hollow rectangular waveguides^[3]; or dielectric waveguides such as sapphire fibers^[4], plastic ribbon waveguides^[5], plastic photonic crystal fibers^[6], and parallel-plate photonic waveguides^[7]; or dielectric waveguides coated with metal sheets^[8].

Some structures, such as metallic parallel-plate waveguides^[9–11], are known to support the propagation of almost dispersiveless transverse electromagnetic (TEM) or quasi-TEM modes at the expense of providing confinement in only one dimension, which largely limits their practical impact.

Other structures, such as coaxial^[12] and metal wire waveguides^[13], better known as Sommerfeld rods^[14], exhibit ring-shaped coaxial modes with a radial polarization distribution; hence, they have poor end-fire coupling efficiency when used with conventional THz sources, that generally output linearly polarized quasi-Gaussian beams.

Recent studies report low loss propagation in THz two-wire waveguides^[15] with a wire separation of 4.7 mm ^[16]. However, mode analysis (Fig. 1) confirms that when

the conductors' separation exceeds three to four times the wavelength, the propagation mode no longer exists between the two wires; instead, there are individual Sommerfeld modes around each wire, resulting in negligible coupling with bell-shaped THz beams^[14]. Conversely, the original design of the twin-lead structure relies on sub-wavelength wire radii and separation, and supports the low loss propagation of TEM dispersionless modes^[17]

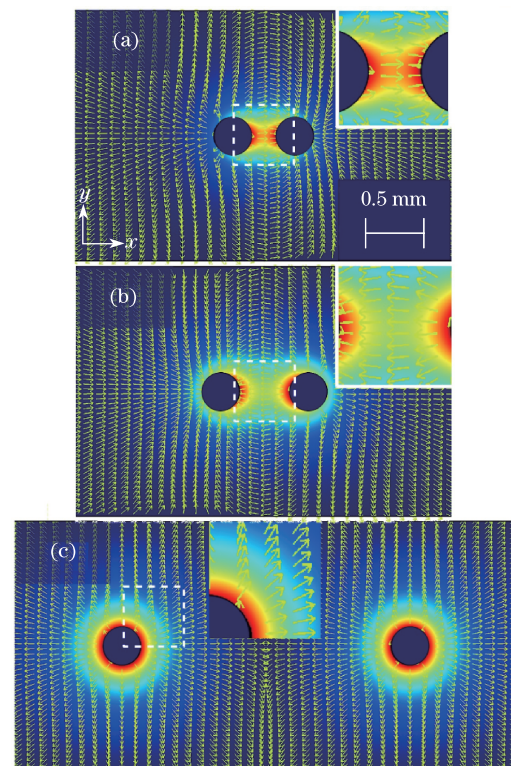


Fig. 1. Mode field distribution in the transverse plane between the two copper wires of radius $r = 150 \mu\text{m}$ at separations of (a) $200 \mu\text{m}$, (b) $400 \mu\text{m}$, and (c) 2 mm ; the arrows indicate the local field polarization direction.

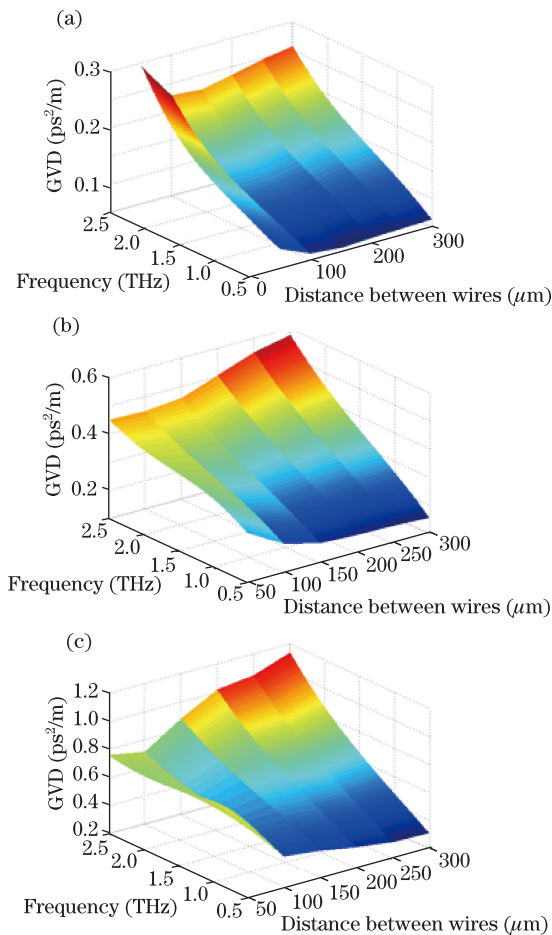


Fig. 2. GVD over a frequency range of 0.5–2.5 THz for wire radii of (a) 50, (b) 100, and (c) 150 μm .

in a bandwidth extending from the DC onwards. However, this sub-wavelength structure is not suitable for end-fire coupling due to the practical difficulty of focusing the input beam on such a small scale.

We investigate the influence of the waveguide's transverse size and wire radii on the dispersion and coupling efficiency of the typical THz bandwidth associated with standard TDS systems (0.5–2.5 THz). In particular, we target the identification of the regions of the parameters corresponding to significant coupling coefficients and low dispersions, supporting quasi-TEM mode propagation. In this letter, we demonstrate a twin-wire waveguide structure capable of simultaneously addressing these issues. In addition, starting from the dual-wire structure, we demonstrate that low-dispersion input couplers can be designed by simply joining multiple dual-wire waveguides using a Y-junction interconnection.

To properly characterize the dispersion and coupling efficiency, we start with Maxwell's equations. Full vectorial calculations were performed for the mode analysis of dual copper wire waveguides as their radii and separation were varied. Figure 1 shows the electric field in the plane perpendicular to the wires for a 1-THz ($\lambda = 0.3 \text{ mm}$) guided wave. As depicted in Figs. 1(a) and (b), when the wire separation is comparable to the wavelength, the fundamental mode essentially remains concentrated within the two wires and maintains a linear

polarization while still being parallel to the plane containing the axes of the two wires. However, as can be seen in Fig. 1(c), for a wire separation of about 7λ , the mode consists of two single-wire modes.

The results of the mode simulations provide an effective refractive index of the quasi-TEM mode, n_{eff} . Its group velocity dispersion (GVD) is calculated as

$$\beta_2 = \frac{\partial^2}{\partial \omega^2} \left[\frac{\omega}{c} \cdot n_{\text{eff}}(\omega) \right], \quad (1)$$

where ω is the angular frequency and c is the speed of light^[18].

Figure 2 shows the GVD for wire radii of 50, 100, and 150 μm over a frequency range of 0.5–2.5 THz as the wire separation is varied. As can be seen, the GVD increases with frequency and is minimized for wire separations of the same order as the wire radius.

The coupling efficiency, C_f , is calculated from the overlap between the electric Gaussian beam field at the input section of the waveguide and the actual mode of the structure using the following equation^[19]:

$$C_f = \left[\frac{4\beta_g\beta_m}{(\beta_m + \beta_g)^2} \right] \frac{\left(\iint \mathbf{E}_g \cdot \mathbf{E}_m dx dy \right)^2}{\iint \mathbf{E}_g \cdot \mathbf{E}_g dx dy \iint \mathbf{E}_m \cdot \mathbf{E}_m dx dy}, \quad (2)$$

where $\beta_g = \omega/c$ and $\beta_m = n_{\text{eff}}\omega/c$ are the propagation constants of the Gaussian beam and the mode, respectively; $\mathbf{E}_g = \exp[-(x^2 + y^2)/W_0]\mathbf{x}$ is the input field (where W_0 is the beam waist); x and y are the coordinate axes, as defined in Fig. 1(a); \mathbf{E}_m is the waveguide mode profile.

Figures 3 and 4 plot the coupling efficiency at 1 THz (the typical THz center bandwidth) and 2.5 THz (the band limit of standard TDS systems), respectively. The best coupling efficiency is generally obtained when the Gaussian beam waist is comparable to the wires' separation.

By comparing Fig. 3 or 4 with Fig. 2, we observe that a coupling efficiency exceeding 10% for a GVD of below 0.5 ps^2/m can be achieved. Notably, this GVD value is very low compared to the typical dispersion of conventional THz waveguides^[2]. As shown in Fig. 1, a linearly polarized mode centered between the two wires ceases to exist for separation greater than about two wavelengths; above this value, the coupling efficiency rapidly collapses to zero as Sommerfeld modes arise.

As seen in Fig. 1, two-wire inherent modes are associated with wire separations comparable to or smaller than the wavelength. Meanwhile, Fig. 3 indicates that the best coupling efficiency is achieved when the waist of the input Gaussian beam is comparable to the wire separation. Consequentially, this has detrimental effects on the achievable coupling efficiency if very low dispersions are desired because the input beam can hardly be focused down to such a small scale. In the microwave domain, waveguide couplers, such as antennas and horn reflectors, are used to achieve high coupling efficiencies. However, these structures can exhibit considerable dispersion, thus becoming unsuitable for the broadband single-cycle pulses used in typical THz-TDS systems.

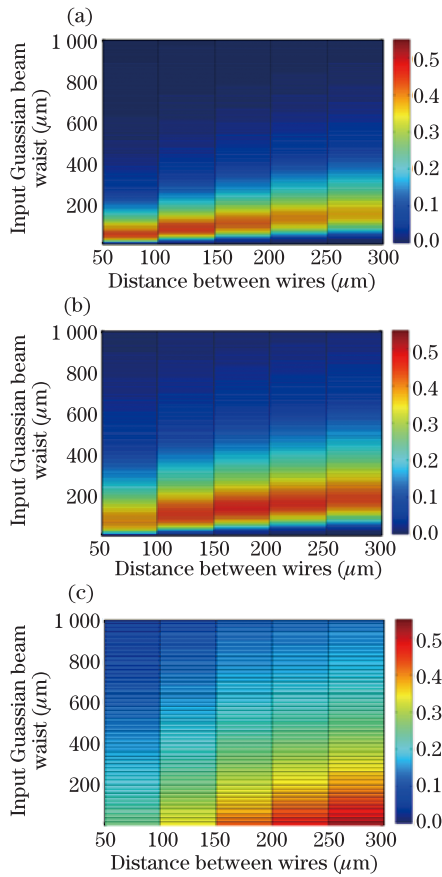


Fig. 3. Coupling efficiency at 1 THz for wire radii of (a) 50, (b) 100, and (c) 150 μm .

To improve the coupling efficiency, we designed a waveguide coupler, shown in Fig. 5(a), based on a pair of parallel Y-shaped wire structures. The dispersion and coupling efficiency are obtained by full vectorial finite-difference time-domain (FDTD) simulations.

The four wires (with radius of 100 μm each) at the input facet are separated along y by 200 μm and along x by 100 μm . The pairs are then coupled together using 700- μm -long Y-shaped structures that adiabatically merge the two waveguides. The simulations are performed considering the coupling of a single-cycle THz pulse centered at 2 THz having a 500- μm -waist Gaussian spatial field profile (with intensity full-width half-maximum FWHM = 590 μm). This spot size is used because it can be generated by the standard wide-band parabolic concentrators with numerical aperture $\text{NA} = \sin 45^\circ$ commonly used in the TDS system. By simply applying the diffraction limit, $\text{FWHM} = 1.22\lambda$, we found that the focusing condition can be maintained for a frequency of above 0.6 THz (which is consistent with the launched pulse). In this case, we estimated the coupling efficiency via the ratio between the spatio-temporal integration of the field's Poynting vector at the waveguide output and at the input coupler facet. Effective coupler dispersion and efficiency depend significantly on the merging angle between the two input waveguides. FDTD simulations are very demanding in terms of computer resources; hence, we could only calculate for a coupling stage shorter than 0.5 mm. However, we could verify that for a given input geometry, the

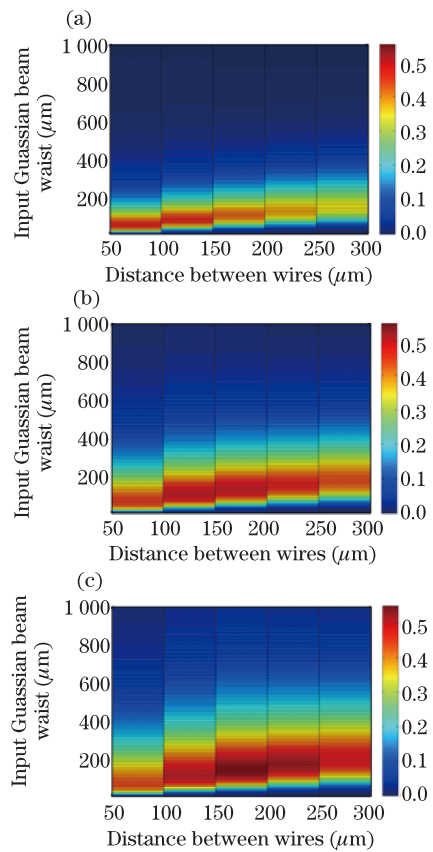


Fig. 4. Coupling efficiency at 2.5 THz for wire radii of (a) 50, (b) 100, and (c) 150 μm .

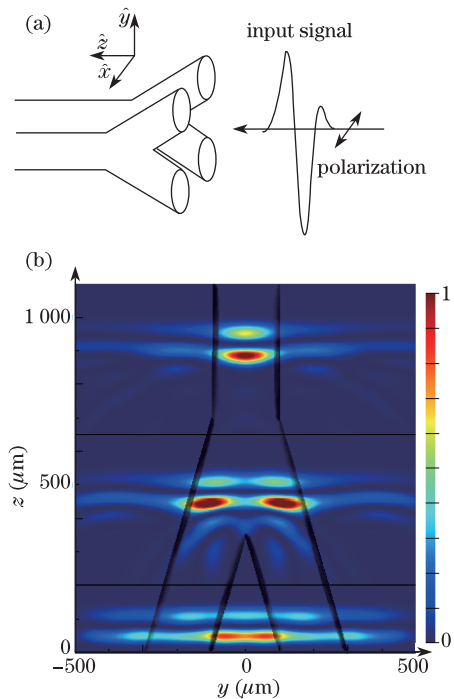


Fig. 5. (a) Sketch of the input coupler configuration; (b) field intensity distribution in the coupler mid-plane (y, z) in pseudo-color map at three different times during the simulation; a coupling efficiency exceeding 22% is demonstrated.

dispersion of the coupler starts to increase when the coupler length exceeds $350\ \mu\text{m}$, as depicted in this study. Nevertheless, for this short coupling stage (Fig. 5(b)), we demonstrated a coupling efficiency exceeding 22% (two to four times higher than the equivalent case without input coupler) with an accumulated pulse chirp of below $0.04\ \text{ps}^2$, which corresponded to the dispersion contribution induced by less than 8 cm of the dual-wire waveguide.

In conclusion, we address the trade-offs between the coupling efficiency, dispersion properties, and geometrical constraints in a quasi-TEM mode propagation in a twin-wire design. Significant coupling can be achieved with an overall dispersion that is lower than that of the equivalent solutions made using a closed metallic structure. In addition, an input coupler solution based on two parallel Y-shaped wire structures is investigated. This proved that the coupling efficiency of the twin-wire waveguide can be above 22% for sub-wavelength wire separations without significant impact on the overall guiding dispersion. Furthermore, owing to the low dispersion characteristics associated with a relatively tight confinement, the prospect of using this waveguide to enhance the THz field for the study of its nonlinear behavior is promising^[20]. This is because the dispersion mainly depends on the waveguide structure and not on the material where the propagation takes place. This opens a new realm of possibilities for nonlinear THz photonics.

This work was supported by the FQRNT (Le Fonds Québécois de la Recherche sur la Nature et les Technologies), the Natural Sciences and Engineering Research Council of Canada (NSERC), the NSERC Strategic Projects, and the INRS. M. P. wishes to acknowledge a Marie Curie Outgoing International Fellowship (No. PIOF-GA-2008-221262).

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