Undistorted guided-wave propagation of subpicosecond terahertz pulses

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We report efficient quasi-optic coupling of a freely propagating beam of terahertz (THz) pulses into a parallel-plate copper waveguide (with a plate separation of 108 μm) and subsequent low-loss, single-TEM-mode propagation with virtually no group-velocity dispersion. Undistorted, low-loss propagation of the incoming 0.3-ps FWHM THz pulses was observed within the bandwidth from 0.1 to 4 THz for a length of 24.4 mm. We compare experimentally derived values for the absorption and phase velocity with theory to show consistency. This demonstration is direct proof of the excellent performance of the parallel-plate waveguide as a wideband THz interconnect. © 2001 Optical Society of America

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Recently, efficient broadband coupling of freely propagating pulses of terahertz (THz) electromagnetic radiation into circular and rectangular metal waveguides,[1,2] single-crystal sapphire fibers,[3] and plastic ribbon planar waveguides[4] was demonstrated. Single-mode coupling and propagation were achieved for all the waveguides mentioned above, even though for the metal waveguides the spectral bandwidth overlapped as many as 25 additional modes. Such waveguide propagation has already demonstrated much larger bandwidths, with approximately 1/10 the loss of lithographically defined coplanar transmission lines.[5] Although these waveguides are quite useful for narrow-band or THz time-domain spectroscopy applications, they all have very high group-velocity dispersion (GVD), which renders them incapable of subpicosecond (subps) pulse propagation.

For metal waveguides, the excessive broadening of subps THz pulses is caused by extreme GVD near the cutoff frequency. GVD of dielectric guides is caused by the frequency dependence of the modal field pattern, where the extent of the fringing fields increases with wavelength. Since GVD of planar plastic waveguides can be the opposite of that of metal-tube and fiber waveguides, dispersion compensation or mutual pulse compression between the two types of waveguide should be possible.

Excessive pulse broadening owing to GVD will not occur for the TEM mode of a two-wire coplanar line, a coaxial line, or a parallel-plate metal waveguide that does not have a cutoff frequency. The group and phase velocities of such a TEM mode are determined solely by the surrounding dielectric. Unfortunately, quasi-optic coupling techniques would not be effective for the complex field patterns of the TEM mode of the two-wire coplanar line or the coaxial line. However, efficient coupling should be possible for the simple field pattern of the TEM mode of the parallel-plate metal waveguide.

Here we report efficient quasi-optic coupling of freely propagating subps pulses of THz radiation into a parallel-plate metal waveguide and subsequent low-loss, single-TEM-mode propagation that exhibits negligible GVD. Consequently, for what is to our knowledge the first time, we have realized the ideal THz interconnect,[5] capable of propagating subps pulses with minimal loss and no distortion.

The experimental setup is similar to that used to investigate THz propagation in plastic ribbon waveguides[4] and incorporates plano–cylindrical lenses to couple the energy into and out of the guide. As shown in the insets of Figs. 1(b) and 1(c) the lens at the input of the guide is used to focus the beam along only one dimension, producing an approximately Gaussian beam having an elliptical cross section with a frequency-independent $1/e$-amplitude minor axis of 200 μm at the waist, where the entrance face of the guide is located. An identical optical arrangement is used at the exit face.

We obtain the reference pulse shown in Fig. 1(a) by removing the waveguide and moving the lenses to their confocal position, as shown in the inset. The small secondary pulse is due to the reflections from the flat surfaces of the two lenses. Pulses propagated through a 12.6- and a 24.4-mm-long copper parallel-plate waveguide with a plate separation of 108 μm are shown in Figs. 1(b) and 1(c), respectively. The secondary pulses are due to the reflections at the input and output of the guides. Since there is no impedance mismatch between the freely propagating wave and the guided wave, we believe that the reflections at the input and output faces of the guide (in addition to the reflections from the flat surfaces of the lenses) are from the thick sidewalls of the copper plates.

The comparison of the propagated pulses and the reference pulse given in Fig. 2(a), plotted to the same time reference, clearly shows almost no dispersive pulse broadening and minimal absorption, unlike in any of the previous observations of THz waveguides.[1-4] The low-loss nature of the waveguide and the high coupling efficiency are also shown in Fig. 2(b), which gives the amplitude spectra of the isolated pulses. The figure shows a useful input spectrum extending from 0.1 to ~4.5 THz as well.

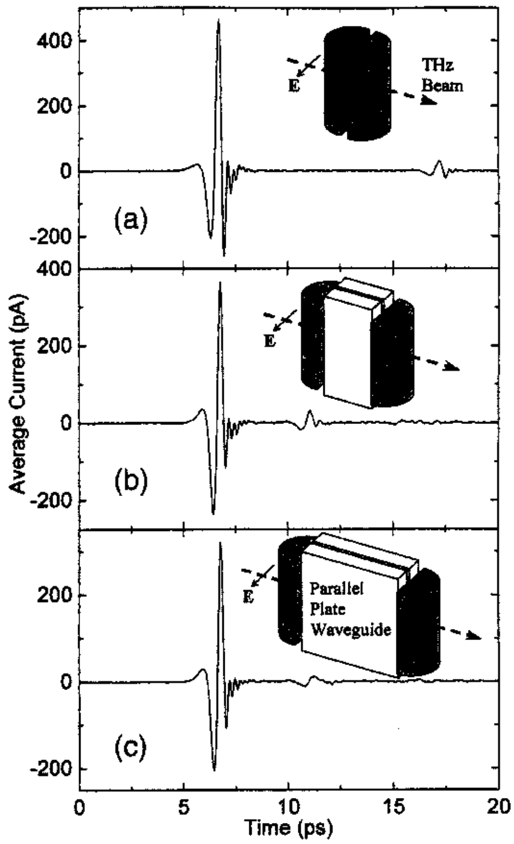

Fig. 1. (a) Scan of the reference pulse with the confocal lens system shown in the inset. (b), (c) Scans of the propagated pulse through the (b) short and (c) long waveguides with the lens–waveguide–lens systems shown in the insets. The zero reference time is the same for (a)–(c).

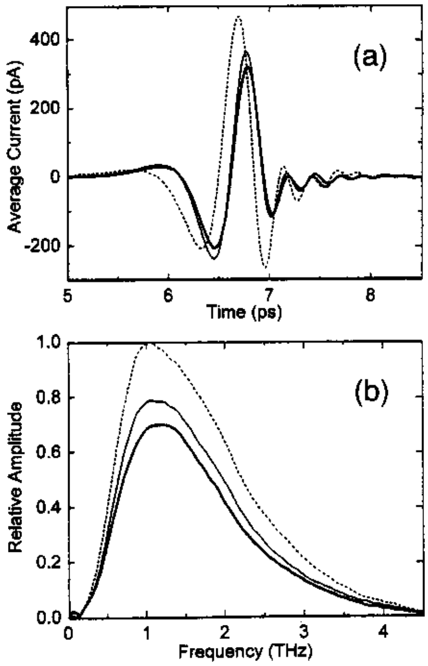

Fig. 2. Comparison of (a) the reference (dashed lines) and propagated pulses and (b) their amplitude spectra. The thin and thick solid curves correspond to the output of the short and long waveguides, respectively.

The relative smoothness of the output spectra, with no low-frequency cutoff or oscillations owing to multimode interference, confirms the single TEM mode behavior of the waveguide.[1,2] The slight reshaping observed between the two propagated pulses is due to the frequency-dependent absorption and to a small amount of dispersion inherent in any system with a frequency-dependent loss process, introduced by the finite conductivity of copper. The change in shape and the slight temporal shift between the reference pulse and the propagated pulses are mainly due to the phase and amplitude changes caused by the frequency-dependent nature of the coupling into and out of the guide.

The fundamental equation governing the input and output relationship of the system, assuming single-mode propagation, can be written in the frequency domain as

$$E_{\mathrm{out}}(\omega) = E_{\mathrm{ref}}(\omega) T C^2 \exp[-j(\beta_z - \beta_0)L] \exp(-\alpha L)\,, \tag{1}$$

where $E_{\mathrm{out}}(\omega)$ and $E_{\mathrm{ref}}(\omega)$ are the complex spectral components at angular frequency ω of the output and reference electric fields, respectively; T is the total transmission coefficient, which takes into account the reflections at the entrance and exit faces; and C is the amplitude coupling coefficient, the same for both the entrance and the exit faces, analyzed generally in terms of the standard overlap-integral method,[2] which takes into account the similarity of the excitation beam to the guided-mode profiles. L is the distance of propagation, α is the amplitude absorption constant, β_z is the phase constant, and $\beta_0 = 2\pi/\lambda_0$, where λ_0 is the free-space wavelength.

The phase term in Eq. (1) illustrates the experimental condition in which the spatial distance between the transmitter and receiver is fixed. Within this fixed distance, the cylindrical lenses are moved and the waveguides are inserted as shown in Fig. 1. Consequently, we have an absolute time reference and obtain no temporal effect as a result of the movement of the lenses. The only time shifts in Fig. 1 are due to the complex coupling coefficient and the difference between the propagation velocity and free-space velocity c.

Based on the well-known two-dimensional analysis,[6] for an input electric field that is linearly polarized in a direction normal to the plane of the plates, only TM modes can exist in the waveguide. For an air-filled guide, the cutoff frequency, $f_{cm} = mc/2b$, where $m = 0, 1, 2, \ldots$, and b is the plate separation. The lowest-order TM_0 (TEM) mode has no cutoff frequency and, for perfectly conducting plates, has no GVD; both the group velocity (v_g) and the phase velocity (v_p) are equal to c, and the wave impedance is equal to that of free space. The propagation losses that are due to the finite conductivity of the metal plates are given explicitly in Eq. (15c) of Ref. 6.

The theoretical loss curves[6] for the first three modes in a copper parallel-plate waveguide with a

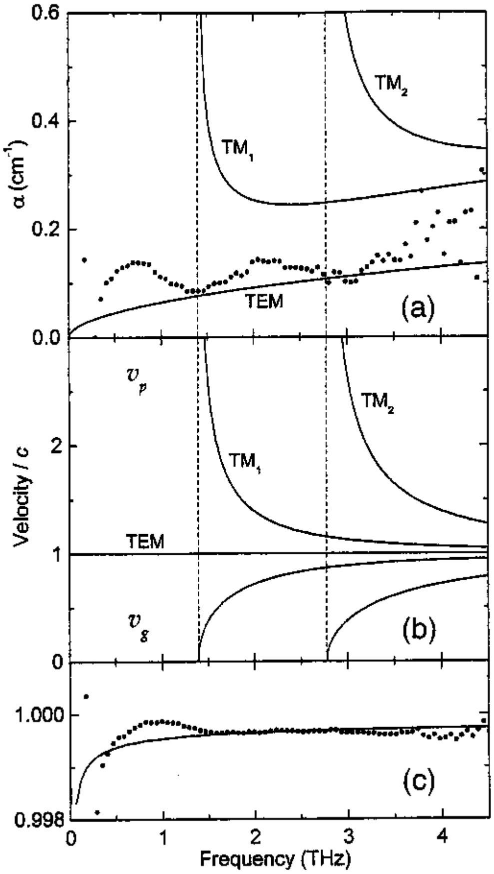

Fig. 3. (a) Amplitude absorption constant and (b) phase and group velocity for the first three modes. Cutoff conditions are shown by the dashed vertical lines. (c) Enlarged view of (b) in the vicinity of unity. Experimental values are shown by the filled circles.

plate separation of 108 μm are plotted in Fig. 3(a). By choosing a sufficiently small plate separation and an even incoming field pattern with the correct beam size, single-TEM-mode propagation is possible. The even incoming field pattern does not couple to the odd TM$_1$ mode. If some residual coupling to the TM$_2$ mode did occur, the higher absorption than that of the dominant TEM mode would more rapidly attenuate the TM$_2$ mode. Figure 3(b) gives the v_p and v_g curves (as a ratio with respect to c), which show the high GVD of the TM$_1$ and TM$_2$ modes compared with that of the TEM mode.

We can experimentally deduce α and β_z by applying Eq. (1) to the short and long waveguides separately, then taking the complex ratio to eliminate the product TC^2 (assumed to be identical for the two guides), and then separating the amplitude and phase information. The experimentally determined α plotted as in Fig. 3(a) is consistent with the predicted low absorption for the TEM mode.

For completeness we also compared the experimental and theoretical values of v_p, shown on an expanded scale in Fig. 3(c). The values were derived experimentally from β_z and alternatively derived theoretically by use of the nearly local approximation to the Kramers–Kronig relations,[7] starting from the frequency-dependent loss given by Ref. 6. Use of the local approximation is justified because of the smooth variation in the loss. The theoretical curve, which was fitted to the experimental values at 2 THz, together with the experimental values clearly exhibits virtually zero dispersion (with a velocity change of less than 0.1% within the relevant bandwidth), even under the influence of finite conductivity.

We have demonstrated the excellent performance of the parallel-plate waveguide as a wideband THz interconnect that is ideal for subps pulse propagation. These THz pulses propagating in the TEM mode open the door to many new research applications. For example, the metal plates could be coated with films of other metals and alloys, Langmuir–Blodgett films, or conducting polymers. These materials could then be characterized by waveguide THz time-domain spectroscopy. A unique application for high-power TEM THz pulses would be the study of nonlinear pulse propagation, demonstrating nonlinear coherent effects of samples that fill the space between the metal plates. Here, for what is believed to be the first time, we have shown that a THz pulse can maintain its spatial focus for arbitrarily long paths without temporal broadening, thereby enormously increasing the effects of nonlinear interactions. This situation is similar to the nonlinear enhancement obtained with optical fibers.

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