THz Interconnect With Low-Loss and Low-Group Velocity Dispersion

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***Abstract*—We report the demonstration of a physically flexible, practicable THz interconnect with minimal pulse distortion and loss. The interconnect is a parallel-plate waveguide with the TEM mode excited, constructed of two thin copper strips. The incoming 0.22 ps THz pulse broadens to 0.39 ps after propagating 250 mm in the waveguide and is also attenuated by a factor of ten. We show that this attenuation is mainly due to the finite conductivity of copper with some additional loss caused by the beam spread in the unguided dimension. The pulse broadening is due to the frequency-dependent loss since the group velocity dispersion is negligible.**

***Index Terms*—Parallel-plate waveguide, quasioptic coupling, subpicosecond pulse.**

I. INTRODUCTION

THE importance of undistorted propagation of ps or sub-ps electromagnetic pulses has forced the consideration of guided-wave propagation effects at the single electronic chip level. Phenomena previously considered only by the microwave community in the GHz frequency range are now becoming manifest in the ps time-scale at THz frequencies. A low-loss THz interconnect will soon be required by the insatiable demand for high speed devices and wideband communication. Such an interconnect will probably involve both optical and microwave concepts and techniques.

Recently, efficient quasioptic coupling and single-mode propagation of sub-ps THz pulses in circular and rectangular metal waveguides [1], sapphire fibers [2], and plastic ribbons [3] have been demonstrated with much larger bandwidths and approximately $1/10$ of the loss compared to lithographically defined coplanar transmission lines. Although these waveguides are quite useful for narrowband applications, they all have very high group velocity dispersion (GVD), which render them incapable of sub-ps pulse propagation.

The TEM mode of a parallel-plate metal waveguide does not have a cutoff frequency and consequently has a very low GVD with the group and phase velocities determined solely by the dielectric medium between the plates. A most recent study [4] has reported efficient coupling of freely propagating sub-ps pulses into a rigid 24 mm long parallel-plate copper waveguide and the subsequent low-loss, single TEM mode propagation exhibiting negligible GVD.

Here, we report the first demonstration of a physically flexible, practicable THz interconnect with minimal pulse distortion and loss. The waveguide is constructed using two 100 μm thick copper strips 35 mm wide and 250 mm (or 125 mm) long. They are joined together (electrically isolated) lengthwise by double-sided adhesive tape 10 mm wide and 90 μm thick, which provides an air-space having cross-sectional dimensions of 90 $\mu\text{m} \times 15$ mm between the plates. This is illustrated in Fig. 1(c), which shows the cross-section of the guide. TEM mode propagation is preserved as long as the axial changes in the waveguide (bends and twists) are spatially slow compared to the propagating wavelengths [5]. We demonstrate efficient quasioptic coupling into these waveguides and show that the observed attenuation is mainly due to the finite conductivity of copper with some loss due to beam spreading in the unguided dimension. The observed pulse broadening is due to the frequency dependent loss since the GVD is negligible.

II. EXPERIMENT

The experimental setup shown in Fig. 1(a) consists of an optoelectronic transmitter and receiver, along with THz beam shaping and steering optics. This is a slightly modified version of the standard THz-TDS (time domain spectroscopy) setup [6], for which the sample under investigation is placed at the confocal beam waist between the two parabolic mirrors. For the experiment presented here, a lens-waveguide-lens system is placed in this central position. Plano-cylindrical lenses (L_1 and L_2) made of high-resistivity silicon are used to convert the spherical geometry of the beam into a planar one, in order to accommodate the planar geometry of the waveguide. At L_1, the THz beam is linearly polarized in the y-direction.

Fig. 1(b) gives the plan view of the propagation paths for the 125 mm long ($r = 11.5$ mm) and 250 mm long ($r' = 27.5$ mm, $D = 54$ mm) waveguides. In actual operation, only one waveguide is in place. As shown in Fig. 1(a) and (b), the input lens L_1 is used to focus the beam only along the y-dimension producing a Gaussian beam having an elliptic cross section. The input face of the guide is located at the waist of this beam that has a frequency-independent minor axis (in the y-direction) and a linearly frequency-dependent major axis (in the x-direction) with $1/e$-amplitude sizes of approximately 200 μm and 8 mm (@1 THz), respectively. An identical optical arrangement is at the output face.

The reference pulse shown in Fig. 2(a) is obtained by moving the lenses L_1 and L_2 to their confocal position, with no waveguide in place as shown in Fig. 1(a). The small secondary pulse

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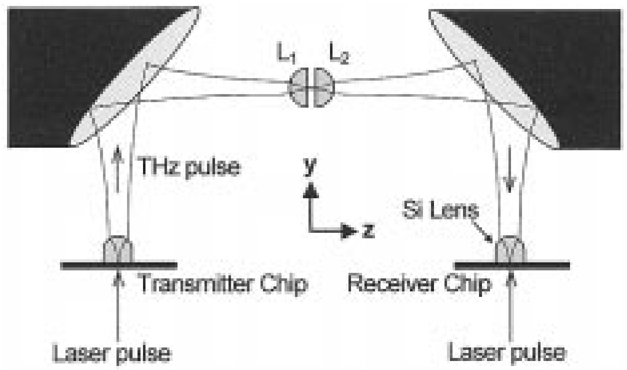
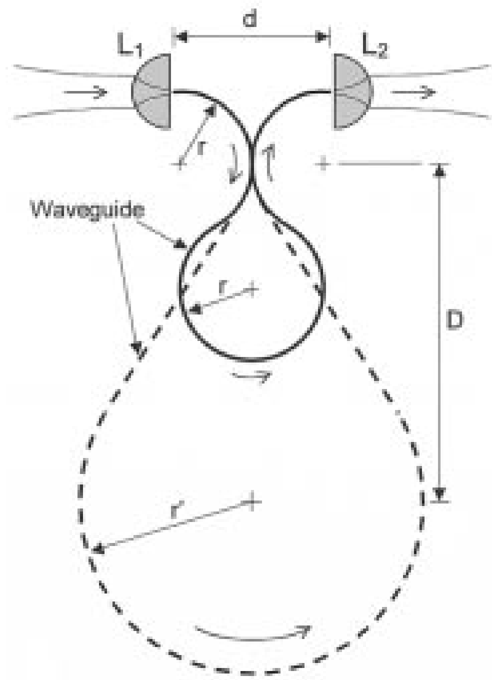


(a)



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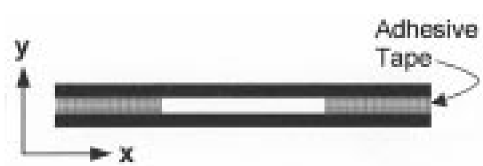
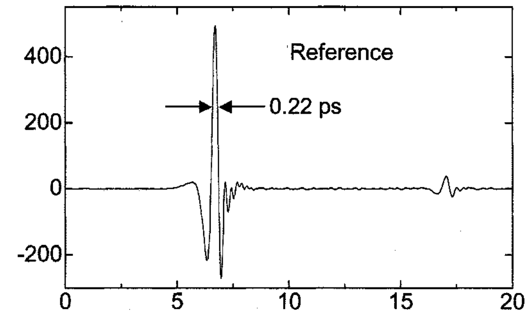
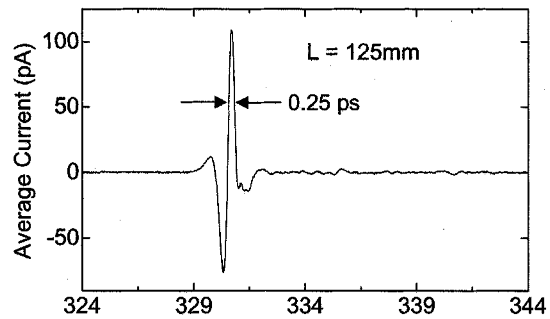


(c)

Fig. 1. (a) Optoelectronic THz-TDS system incorporating the cylindrical lenses L_1 and L_2. (b) Plan view of the propagation paths for the 125 mm long (solid line) and 250 mm long (dashed line) waveguides. The x-direction is normal to the plane of paper. (c) Cross-sectional view of the waveguide (not to scale).



(a)



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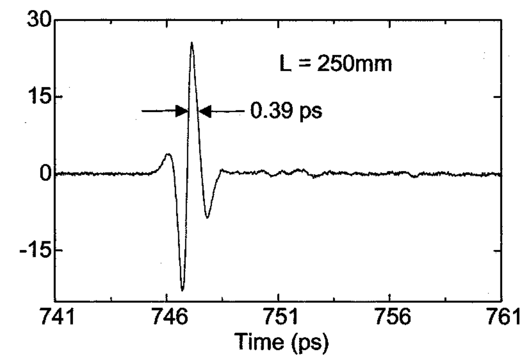

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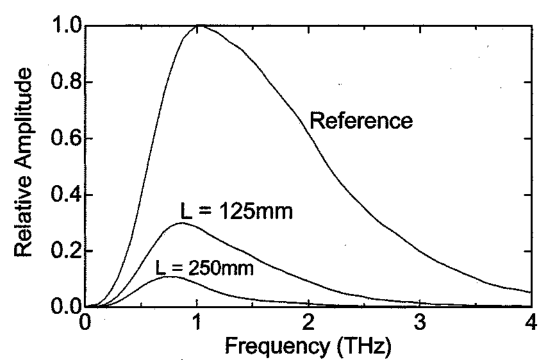

(d)

Fig. 2. (a) Reference pulse; propagated pulse through (b) the 125 mm long and (c) the 250 mm long waveguide; (d) amplitude spectra of the isolated pulses.

is due to the reflections from the flat surfaces of the two lenses. Propagated pulses through the 125 mm long and 250 mm long parallel-plate waveguides are shown in Fig. 2(b) and (c), respectively. Fig. 2(b) is the average of 2 scans, and Fig. 2(c) is the average of eight scans. The FWHM is 0.22 ps for the reference pulse, 0.25 ps for the $L = 125$ mm pulse, and 0.39 ps for the $L = 250$ mm pulse. Characteristic of TEM mode propagation, the propagated pulses clearly exhibit no dispersive pulse broadening [4]. The minimal broadening observed in the output pulses is due to the relative loss in the high frequency content as seen in Fig. 2(d), which gives the amplitude spectra of the isolated pulses. The FWHM of the amplitude spectra are 1.62 THz, 1.14 THz, and 0.74 THz for the reference, $L = 125$ mm, and $L = 250$ mm pulses, respectively. The smoothness of the output spectra revealing no low frequency cutoff confirms single TEM mode propagation [1].

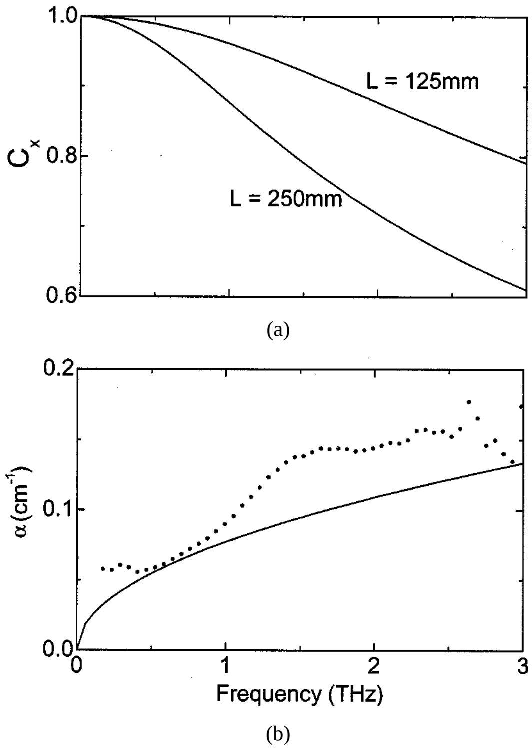

Fig. 3. (a) C_x for the two waveguides; (b) theoretical (solid line) and experimental values (dots) of the amplitude attenuation constant α.

III. THEORY & ANALYSIS

The input and output relationship of the single-mode waveguide system can be written in the frequency domain as

$$E_{\text{out}}(\omega) = E_{\text{ref}}(\omega) T C_y^2 C_x e^{-j(\beta_z L - \beta_o d)} e^{-\alpha L} \qquad (1)$$

where $E_{\text{out}}(\omega)$ and $E_{\text{ref}}(\omega)$ 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 input and output, C_y is the coupling coefficient for the y-direction (squared, since the same at the input and output), and C_x is the coupling coefficient for the x-direction (not squared, since 100% at the input). L is the distance of propagation, d is the direct free-space path length (along the optic axis) replaced by the guide, α is the amplitude attenuation constant, β_z is the phase constant, and $\beta_o = (2\pi/\lambda_o)$, where λ_o is the free-space wavelength. The phase term in Eq. (1) illustrates the experimental condition that the transmitter and receiver are fixed in space. Within the fixed spatial distance, the cylindrical lenses are moved apart and the waveguides are inserted as shown in Fig. 1(a) and (b).

The coupling coefficients are analyzed using the standard overlap-integral method [1], where C_y takes into account the similarity of the input Gaussian beam to the guided mode in the y-direction, and C_x takes into account the spreading of the beam in the x-direction due to diffraction, assumed to be the same as in free-space. Fig. 3(a) shows the frequency dependence of C_x calculated for the two guides. As the beam spreads in the x-direction, it may be incident at shallow angles upon the adhesive tape boundary. To avoid any significant effects (due to reflections) from this boundary, this tape would have to be either transparent or a good absorber. No such effects were observed in this experiment.

Applying (1) to the short and long waveguide data separately and taking the complex ratio, we can eliminate the product TC_y^2, and then after extracting the amplitude information, obtain an expression for the attenuation as

$$\alpha = \frac{1}{(L_1 - L_2)} \ln \left| \left[\frac{E_{\text{out2}}}{E_{\text{out1}}} \right] \left[\frac{C_{x1}}{C_{x2}} \right] \right| \qquad (2)$$

where subscripts 1 and 2 stand for the short and long waveguides, respectively.

Based on the well-known, two-dimensional analysis, for an input electric field linearly polarized 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 c is the free-space velocity, $m = 0, 1, 2, \ldots,$ and b is the plate separation. The lowest order dominant TM_0 (TEM) mode has no cutoff frequency, and, for perfectly conducting plates, has no GVD with both the group velocity and phase velocity equal to c and the wave impedance equal to that of free-space, η_o. The loss associated with the TEM mode, introduced by the finite conductivity σ of the metal plates, can be expressed as $\alpha = R/(\eta_o b)$ with $R = 10.88 \times 10^{-3} [10^7/(\sigma \lambda_o)]^{0.5}$ [7].

The experimentally determined α calculated using (2) and the theoretical value are compared in Fig. 3(b) and show consistency between experiment and theory. The observed excess loss can be attributed to dimensional variations of the waveguide, surface roughness and impurities of the copper strips, and undesirable effects due to bending such as mode conversions and reflections.

IV. CONCLUSION

We have demonstrated better performance than any other THz interconnect to date. This flexible metal ribbon waveguide with low-loss and negligible GVD, transmitted a subpicosecond THz pulse 250 mm, with an excellent output signal-to-noise ratio. This demonstration shows that chip-to-chip THz guided wave interconnections with data rates approaching Tb/s are feasible.

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