HTML ABSTRACT + LINKS

Parallel plate THz transmitter

S. Coleman and D. Grischkowsky[a)]
School of Electrical and Computer Engineering, Oklahoma State University, Stillwater, Oklahoma 74078

(Received 29 September 2003; accepted 2 December 2003)

A THz transmitter that directly excites the guided wave modes of a dielectric filled parallel plate waveguide is demonstrated. When coupled to free space, the transmitter yields a large peak time-domain THz signal. The device yields significant signal amplitudes with varying output spectra with and without a bias field applied. This transmitter provides powerful direct excitation of guided wave modes and is the next step toward an integrated guided wave transverse-electromagnetic mode THz bandwidth device. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1644923]

Terahertz waveguides have recently been demonstrated as an alternative to coplanar transmission lines for guiding THz bandwidth electrical pulses. In particular, the parallel plate waveguide has been demonstrated to yield single transverse-electromagnetic (TEM)-mode propagation with low, frequency-dependent losses limited by the finite conductivity of the metals used to fabricate the guide.[1,2] Very recently, quasioptical components have been demonstrated within these guides and have demonstrated a viable means of confocally coupling the TEM guided mode with minimal loss and dispersion for arbitrarily long path lengths.[3] The so-called two-dimensional interconnect layer confines the beam to a plane and guides both dimensions orthogonal to the direction of propagation.[3] The remaining challenge to the realization of integrated guided wave TEM-mode THz bandwidth structures is the ability to generate and detect THz within the waveguide.

Direct guided wave excitation in parallel plate waveguides has been demonstrated quite recently by Cao *et al.*[4] In that effort, the guided mode was excited by optical rectification in a nonlinear optical polymer. In this work we describe a THz source called the parallel plate THz (PPT) transmitter. This transmitter directly excites a guided wave in a dielectric filled parallel plate waveguide via photoconductive switching together with optical rectification. The PPT transmitter is a simple device consisting of two metal plates between which lies a layer of semi-insulating (SI) gallium arsenide (GaAs). The metal plates form a parallel plate waveguide for the generated THz and provide a means of applying a bias voltage to the semiconductor.

For the purposes of this preliminary investigation the waveguide output of the PPT transmitter is coupled to free space and examined in a standard confocal THz time-domain spectroscopy (THz–TDS) arrangement.[5] Thereby, the transmitter is examined in a well-characterized optical arrangement for comparison to previously demonstrated transmitters. The spherical quasioptics used in this demonstration are not optimal for handling the complex output beam of the transmitter. However, the measured time-domain signals for the PPT transmitter are in excess of the maximum signals obtained in our labs with other transmitters, albeit with reduced bandwidths and reduced detection efficiency.

The PPT transmitters were constructed from 10 mm×20 mm pieces of a ⟨100⟩ oriented SI-GaAs wafer thinned to a thickness of 120 μm. One side was polished by hand while the remaining side was left with an as received polish. The hand polished side was used as the device cathode. The thinned GaAs was cleaned, the oxide removed, and the wafer piece was metallized on both sides with 100 nm/450 nm Ti/Al metal layers using a thermal evaporator. No lithography was performed so a cleanroom was not required for device fabrication. Individual transmitter chips were diced from the 10 mm×20 mm metallized SI-GaAs piece using a dicing saw, yielding a final chip geometry of 120 μm×860 μm×5 mm.

For mounting purposes, each chip was sandwiched between two machined aluminum electrodes, which served as mechanical support and a heat sink. These electrodes were aligned on an optical flat to the diced output face and were machined to within 10 μm of the chip excitation face. Figure 1 schematically illustrates the mounted PPT chip. A high-resistivity Si collimating lens was butted against the electrodes and output face of the waveguide structure. A 2.5 μm thick Mylar layer was used to separate the lens and electrodes to prevent the lens from electrically shorting the assembly. In later experiments the Mylar layer was replaced by thermally growing a 1 μm thick layer of SiO_2 directly on the lens surface. Figure 1 also illustrates a mounted PPT transmitter with the Si lens attached and the entire assembly installed in a standard THz-TDS system.

The PPT transmitter is effectively an 860 μm long dielectric filled parallel plate waveguide. This transmitter is inherently astigmatic with a focus in the xz plane at the excitation face, corresponding to the excitation spot focus. A second focus lies in the yz plane at the output face and corresponds to the planar wave front that exits the guide parallel to the xy plane. Therefore, the peak time-domain signal and spectra were examined for various focal positions of the spherical collimating lens. With the focus of the lens in an intermediate position between the excitation and output faces, a maximum peak signal was achieved. However, with the lens focused on the output face, the smoothest output spectrum was achieved. Throughout this work, the focus of the lens lay at the output face of the PPT transmitter chip, which reduced the maximum available signal by only 10%.

The receiver consisted of a 30 μm dipole with a 5 μm

[a)]Electronic mail: grischd@ceat.okstate.edu

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 139.78.28.91 On: Tue, 21 Jul 2015 21:56:44

 © 2004 American Institute of Physics

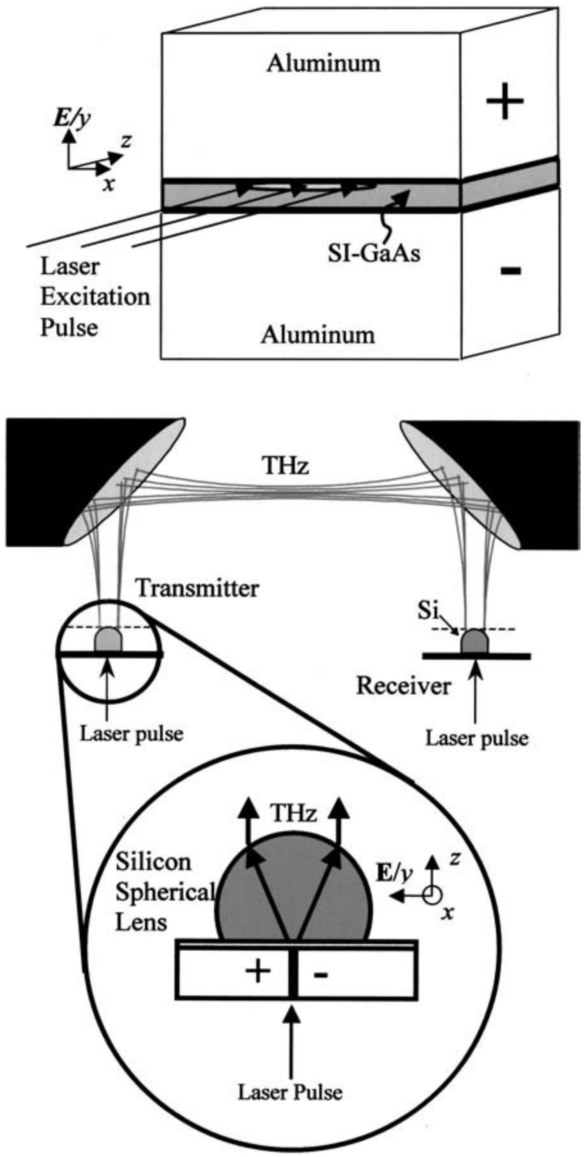

FIG. 1. Mounted PPT transmitter and mounted transmitter installed in the standard THz-TDS configuration (not to scale).

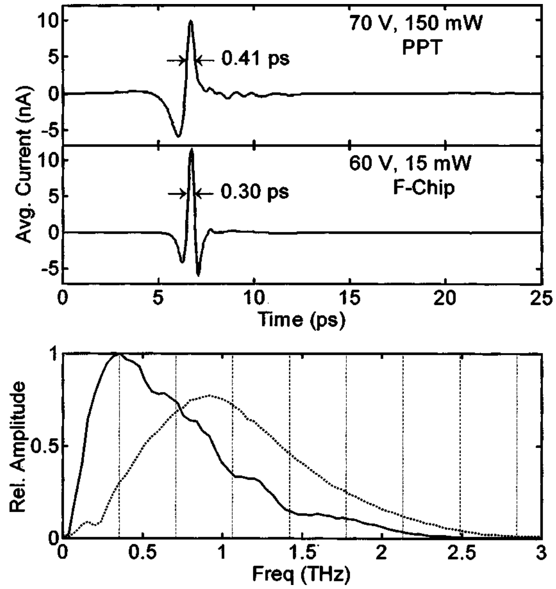

FIG. 2. Measured time-domain THz signals and amplitude spectra for the PPT transmitter (upper solid line) and the F-chip transmitter (lower dotted line). The bias voltage and laser excitation power are listed in each frame. The broken vertical lines correspond to the first eight even and odd TM mode cutoff frequencies for the PPT device.

gap at the center situated between the lines of a coplanar transmission line structure with 10 μm linewidth and 30 μm line spacing. The receiver was fabricated on low temperature grown GaAs, and was excited with 15 mW average laser power. The Ti:sapphire excitation laser operated at a center wavelength of 810 nm with a repetition rate of 90 MHz. The 2.5 mm diam, 150 mW average power laser beam was focused on the excitation face using a 300 mm focal length plano-convex cylindrical lens in concert with an 8 mm focal length plano-convex spherical lens. At the focal plane of this lens system the laser pulses were focused to an elliptical spot with a major axis length of approximately 230 μm and a minor axis length of 15 μm. The laser polarization was parallel to the minor axis of the excitation spot and simultaneously parallel to the bias field of the transmitter.

The PPT transmitter was compared to the ''F-chip'' type transmitter typically used by our group. The F-chip was fabricated on SI-GaAs with 20 μm wide coplanar Ti/Al lines separated by 80 μm. A Si spherical lens was attached to the back side of the F-chip to collimate radiated THz. The focus of this lens lay in the excitation plane. While biased with 60 V, the F-chip was excited with 15 mW average laser power focused to a circular spot with an approximate diameter of 15 μm near the device anode, but was otherwise examined in the same experimental setup with the same receiver as the PPT transmitter.

Figure 2 shows the THz wave forms detected and spectra from the PPT transmitter and the F-chip transmitter. Compared to the results in Fig. 2, the maximum peak receiver currents documented in our labs are 50 nA for the PPT transmitter and 20 nA for the F-chip. As observed, the PPT transmitter generates a signal with a narrower spectrum and a lower center frequency. It should be noted that the conversion efficiency from optical to THz radiation is higher for the F-chip than for the PPT transmitter. However, the PPT transmitter can safely be pumped with much more optical power than the F-chip. It can therefore generate THz power equal to or exceeding that of the F-chip. In general, alternate excitation beam focal patterns and increased excitation power can be used to double the F-chip output signal.

Both transmitters also produce a THz signal with no bias voltage applied via optical rectification, as shown in Fig. 3. The spectrum of the F-chip is the average of nine scans with the entire spectrum multiplied by a factor of 20. For the PPT transmitter, recall that the illuminated face of the GaAs was diced from a ⟨100⟩ oriented wafer. The dicing process therefore reveals a surface normal to the (100) plane. In general, this surface is of an electro-optic material that lacks inversion symmetry and should therefore be expected to produce a THz signal via optical rectification.[6] In fact, if the wafer is diced (or cleaved) along the proper axis one may reveal the (110) plane, which has been previously exploited for THz generation via optical rectification.[7,8]

The spectra in Fig. 3 show that both the PPT and F-chip transmitters are capable of producing similar bandwidth signals at zero bias. Two-dimensional (2D) scanning measurements of the phase fronts generated with the spherical lens

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 139.78.28.91 On: Tue, 21 Jul 2015 21:56:44

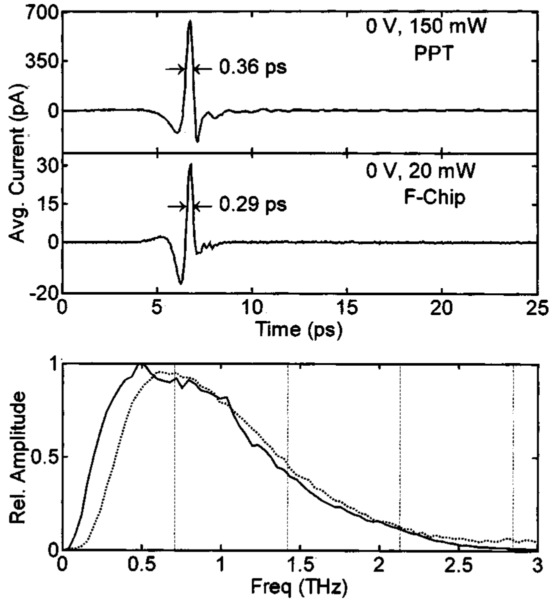

FIG. 3. Measured time-domain THz signals and amplitude spectra for the PPT transmitter (solid line) and the F-chip transmitter (dotted line; the spectrum is average of nine scans and multiplied by 20). The bias voltage and laser excitation power are listed in each frame. Broken vertical lines indicate the first four even mode cutoffs.

installed show that the output beam exhibits an elliptical phase front, as expected due to the PPT asymmetry. However, the spectra in Fig. 3 imply that over the bandwidth of interest, which is limited by the receiver, this ellipticity does not significantly affect the coupled THz up to approximately 2 THz. The ellipticity of the phase front was expected to affect the coupled bandwidth at higher frequencies. To confirm this, a smaller receiver (5 μm lines with a 10 μm dipole/5 μm gap) was installed in the THz-TDS system in order to observe a larger bandwidth signal. Data taken with this receiver reveal that the effects of the astigmatism of the PPT transmitter become observable at frequencies higher than approximately 1.75 THz, thereby yielding a significantly narrower spectrum for the PPT than for the F-chip.

For a linearly polarized excitation field perpendicular to the plane of the waveguide plates, only the TM modes of the guide may be excited.[9] The lowest order of these modes, the TM_0 or TEM mode, has no cutoff frequency. While the PPT transmitter spectra exhibit a significant structure, there are no observed low frequency cutoffs, indicating that most of our detected signal travels in the TEM mode. For our transmitter geometry the first eight higher-order TM modes correspond to the broken vertical lines in Fig. 2. The first four even modes are likewise depicted in Fig. 3. For the biased PPT transmitter, it appears in Fig. 2 that some of the spectral features coincide with higher-order mode cutoff frequencies.

When biased, the PPT transmitter is excited near the anode, which maximizes the THz signal generated. This edge excitation allows both the odd and even modes of the parallel plate transmitter to be excited. Conversely, the THz signal obtained via optical rectification in the PPT transmitter exhibits a maximum when excitation occurs midway between the device electrodes. At this position, symmetry of the generated field allows only the even modes of the PPT transmitter to be excited. However, the receiver used is not sensitive to modes whose field integrated over the sampled spatial region is zero.[10] Therefore, the field detected is essentially the TEM mode of the guide. Thus, the location of the excitation spot relative to the device electrodes is an important parameter in determining the number and amplitude of guided modes of the transmitter that are excited, however the higher-order modes are not detected.

We have demonstrated a THz transmitter that directly excites the guided modes of a dielectric filled parallel plate waveguide. When coupled to free space this transmitter yields a large signal with a reduced spectrum compared to our standard coplanar photoconductive devices. Although several guided modes are likely excited, the primary mode detected by the transmitter is the TEM mode of the parallel plate guide for both the biased and unbiased cases. Excitation of specific guided modes can be tailored by a judicious choice of excitation spot position. The PPT transmitter provides a powerful and simple means by which to directly excite a parallel plate waveguide and is the next step in achieving an integrated guided wave TEM-mode THz bandwidth device.

The authors gratefully acknowledge the efforts of Jianming Dai, Christine Co, and those of Matthew Reiten and Alan Cheville for 2D beam profile measurements. This work was partially supported by the National Science Foundation, the U.S. Army Research Office, and the Semiconductor Research Corporation, Center for Advanced Interconnect Systems Technologies.

[1] R. Mendis and D. Grischkowsky, Opt. Lett. **26**, 846 (2001).
[2] R. Mendis and D. Grischkowsky, IEEE Microw. Wirel. Compon. Lett. **11**, 444 (2001).
[3] S. Coleman and D. Grischkowsky, Appl. Phys. Lett. **83**, 3656 (2003).
[4] H. Cao, R. A. Linke, and A. Nahata, *Proc. Conference on Lasers and Electro-Optics, OSA Technical Digest Series* (Optical Society of America, Washington DC, 2003), CMB1.
[5] M. van Exter and D. Grischkowsky, IEEE Trans. Microwave Theory Tech. **38**, 1684 (1990).
[6] D. H. Auston, K. P. Cheung, J. A. Valdamanis, and D. A. Kleinman, Phys. Rev. Lett. **53**, 1555 (1984).
[7] A. Rice, Y. Jin, X. F. Ma, X.-C. Zhang, D. Bliss, J. Larkin, and M. Alexander, Appl. Phys. Lett. **64**, 1324 (1994).
[8] H. Cao, T. F. Heinz, and A. Nahata, Opt. Lett. **27**, 775 (2002).
[9] N. Marcuvitz, *Waveguide Handbook* (Peregrinus, London, 1993).
[10] G. Gallot, S. P. Jamison, R. W. McGowan, and D. Grischkowsky, J. Opt. Soc. Am. B **17**, 851 (2000).

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 139.78.28.91 On: Tue, 21 Jul 2015 21:56:44