*Armenian Journal of Physics, 2009, vol. 2, issue 2, pp. 122-128*

# UNDISTORTED TERAHERTZ PULSE PROPAGATION IN SLIGHTLY CURVED PARALLEL PLATE WAVEGUIDE AND ITS USE IN TIME-DOMAIN SPECTROSCOPY

**Yu. H. Avetisyan[1], A. H. Makaryan[1], K. Khachatryan[1], and A. Hakhoumian[1,2]**

[1]Department of Radiophysics, Yerevan State University, Yerevan, 1 Alek Manoogian, Armenia
[2]Institute of Radiophysics and Electron. NAS Armenia, 1 Alikhanian Bros., Ashtarak, Armenia
*yuriav@ysu.am*

**Received 24 February, 2009**

***Abstract:*** A nearly undistorted THz pulse propagation through the 8-cm-long slightly curved parallel plate oversized waveguide has been demonstrated. The possibility of use of CPPOWG in waveguide time-domain spectroscopy is tested by measuring absorption lines of tiny amount of water vapor.

***Key Words:*** terahertz, waveguide, THz time-domain spectroscopy

PACS: 84.40.Az, 32.30.Bv, 78.47.jc

## 1. INTRODUCTION

The terahertz (0.1-10 THz) region of electromagnetic spectrum, located between millimeter wave and infrared frequencies, has found an increasing number of applications in security, biology, environment monitoring, sensing, and so on [1]. Among them is the study of the terahertz response of thin films which is of great importance in both fundamental and applied sciences since it could bring information on the physical, structural, and chemical properties of the films [2]. Many materials with a large dielectric constant (such as ferroelectrics or metals) have been investigated by use THz time-domain spectroscopy (TDS) [3]. It is based on recording the time dependence of the electric field of subpicosecond electromagnetic pulses transmitted through a sample [3]. The ratio of the Fourier transforms of the data recorded with and without the sample yields the complex transmission coefficient of the sample in the frequency domain. The broad spectral bandwidth (from 0.1 to ~ 3 THz) associated with these so-called THz-pulses, makes THz-TDS a unique technique to gather spectroscopic information in this otherwise hardly accessible frequency range. However, these systems are quite large thus not easy to integrate with optical and infrared techniques. Besides, characterizing thin films with a high precision is a difficult challenge because for common materials, the optical thickness (thickness × THz refractive index) is significantly smaller than the wavelength of THz radiation.

To overcome these problems a new technique, called waveguide THz-TDS has been recently developed [4]. It is based on preparation (or placing) of a thin film in single-mode parallel plate waveguide (PPWG) with followed its measurement by the standard THz-TDS. The THz wave confinement in PPWG leads to a strong interaction between the THz field and the thin film over a distance of centimeters. This increased interaction length results in a significantly enhancement of the sensitivity proportional to the ratio of the length of sample to the separation between the waveguide plates, $d$ [4]. The last is typically chosen as $d$ = 50 μm to obtain both the high sensitivity enhancement and undistorted THz pulse propagation at single TEM-mode in waveguide [4, 5]. However, the PPWG preparation with so small separation between plates over distance a few cm is difficult. Besides, the high-resistivity plano-cylindrical Si lenses have to be used for effectively coupling THz beam into and out of the PPWG. Thus it is interesting to apply waveguide which providing undistorted THz-pulse propagation would be deprived of the lacks inherent to PPWG. The narrow-band THz-wave propagation in many waveguides has been reported [6-9]. However, they all have very high group-velocity dispersion (GVD), which renders them incapable of subpicosecond THz pulse propagation.

Here we propose and demonstrate the use of slightly curved parallel plate oversized waveguide (CPPOWG) for low-loss undistorted propagation of the THz pulses. The prospect of its using in waveguide THz-TDS is tested by measuring an absorbance spectrum of tiny amount of the water vapor in waveguide.

In continuous waves regime the low-loss electromagnetic wave propagation in CPPOWG has been demonstrated for both $CO_2$ laser and sub-THz radiations [10, 11]. The main advantage of this waveguide is self-focusing feature caused by curvature of plates. The confinement of THz beam in waveguide's middle is favorable to enhance THz field interaction with matter. The relatively large cross-section of the proposed waveguide facilitates its manufacturing and gives opportunity for escaping of the use of THz lenses as input and output coupling units. The drastic disadvantage of CPPOWG (as any oversized waveguide) is possibility of the simultaneous multi-mode propagation. Generally it is possible to have lowest-order single-mode propagation if efficiency of input coupling for this mode is significantly larger than that of other modes. By using such approach, an undistorted $TE_1$-mode propagation of THz pulses in oversized PPWG has been recently demonstrated [12]. The separation between plates was $d$ = 5 mm and length of the waveguide $L$ = 2.54 cm. To be able operate with smaller distance $d$ (which is favorable for high concentration of field) and longer $L$ (which is necessary to increase interaction length with matter in waveguide) we shall focus on TEM-mode propagation in proposed CPPOWG. Obviously that THz pulse broadening owing to GVD will not occur for the TEM mode which does not have a cutoff frequency.

## 2. WAVEGUIDE DESIGN AND EXPERIMENTAL SETUP

The cross-section and 3D-picture of proposed waveguide is shown in Fig.1. It consists of two aluminum curved plates with identical dimensions of 10 mm (width) × 80 mm (length) × 1mm (thickness). The waveguide plates are fabricated using standard machine-shop tolerances and inner waveguide surfaces are polished to mirror finish. In order to insert the investigated materials in waveguide, narrow plated-through slits (30-mm-long and 0.15-mm-wide) are made in the middle of the plates.

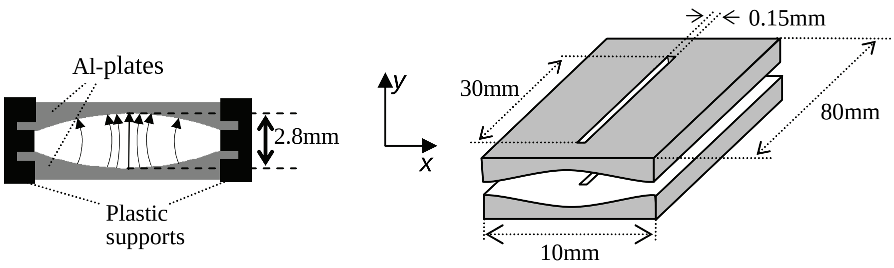


Fig.1. Cross-section and 3D-picture of waveguide

The $d$ = 2.8 mm separation between the curved plates (with curvature radius $R \approx 14$ mm) is maintained by two plastic slabs placed at the lateral edges of the waveguide. A standard THz-TDS setup was used to excite CPPOWG and to measure its response (Fig.2).

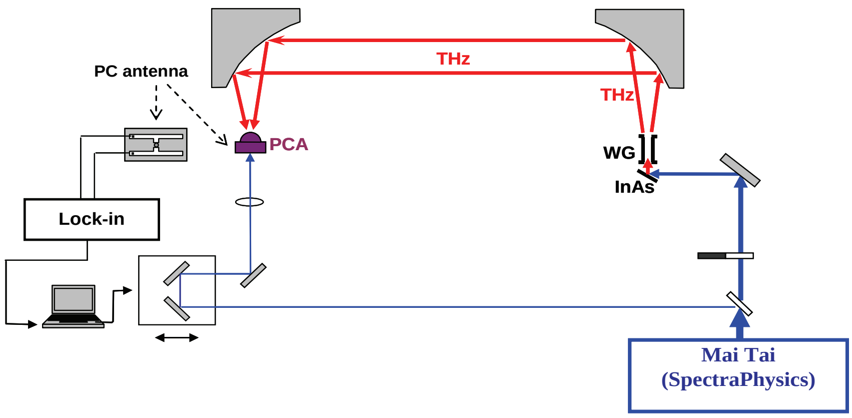


Fig.2. Experimental setup

THz-pulses were generated by illumination of [111] InAs emitter surface with fs-laser beam having waist diameter of $d_0 \approx 3$ mm. The laser pulses duration is typically ~80 fs, repetition frequency 80 MHz, and average power 1.85 W. The input flange of CPPOWG is placed close to THz surface emitter and its output edge is in focus of collecting off-axis parabolic mirror. THz beam size on the input waveguide is chosen slightly bigger than the separation between the plates. We consider that similar to case of the parallel plate waveguide, it is favorable for TEM-mode excitation. The dependence of coupling efficiency on ratio of waveguide’s plate separation and input Gaussian beam diameter $2w_0$ is illustrated in Fig. 3.

For acquiring THz-pulse waveform the traditional method based on a sampling technique is used. The delay of the gating pulse is swept relative to that of the other, and the average photocurrent generated in the photoconductive antenna (PCA) is measured as a function of delay time. To improve signal-noise ratio, PCA output photocurrent is registered by a lock-in amplifier.

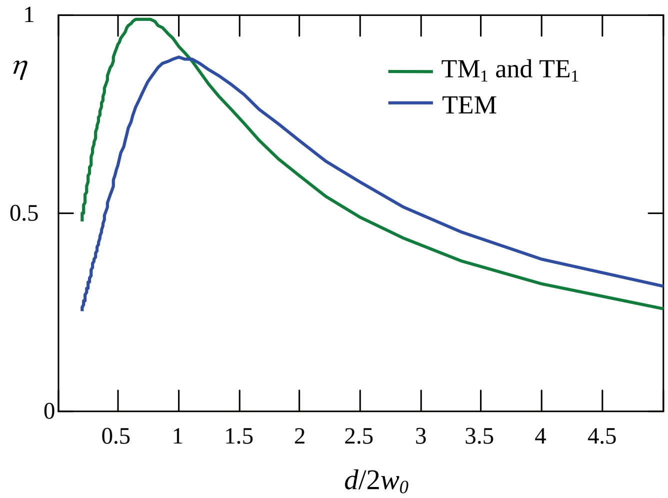


Fig. 3. Dependence of waveguide coupling efficiency with incident beam on ratio of plate’s separation and beam diameter $2w_0$

## 3. RESULTS AND DISCUSSION

The measured THz waveforms in free space and after propagating through CPPOWG for input THz beam polarized along the $y$-axis are presented in Fig. 4*a*. The comparison of the THz waveforms indicates a nearly undistorted THz pulse propagation in the waveguide at TEM mode. Generally $TE_m$-modes with odd number of $m$ may be excited, especially $TE_1$, whose efficiency of input coupling is close to that of TEM mode. However, even low dispersion of $TM_1$-mode in oversized waveguide is sufficient for distortion of THz-pulse after passage of 8 cm distance. We were convinced of it by measuring THz waveform for 90°-rotated waveguide. In this case $TE_1$-mode, having same dispersion as that of the $TM_1$-mode, is predominantly excited. As seen in Fig. 4*b*, THz waveform exhibits multi-cycle oscillations which evidently indicate on dispersion. The observed distorted THz-pulse propagation at $TE_1$-mode in oversized waveguide does not contradict the results of Ref. [12] because in our case the plate separation is nearly 2 times smaller and waveguide is over 3 times longer.

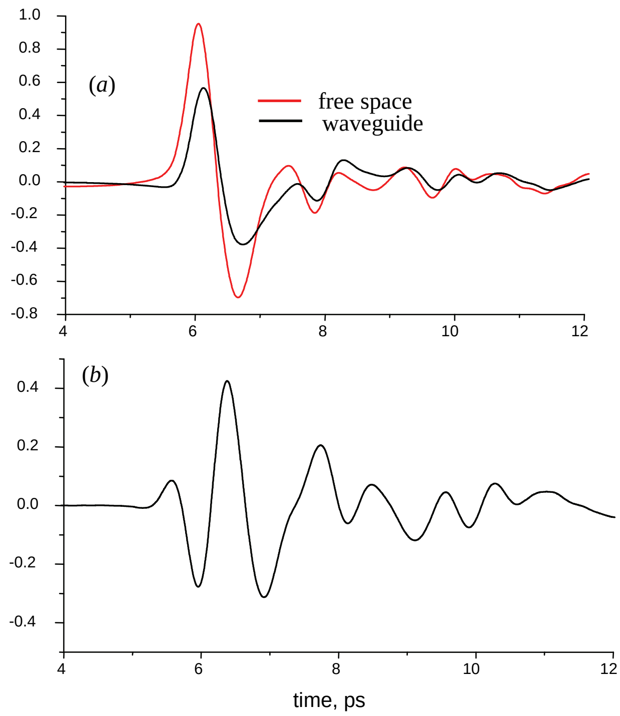


Fig.4. THz waveforms after passage through free space (red line) and waveguide (black lines) for cases when input THz beam is polarized: (*a*) along *y*-axis, (*b*) along *x*-axis.

To demonstrate possibility of using CPPOWG in waveguide THz-TDS we measure absorbance spectrum of water vapor. The waveguide was operated in dry air condition and then a very small drop of water was put onto the narrow slit made in Al-plate of the waveguide. The measurement of waveguide transmittance spectrum reveals the absorption lines of water vapor originated through evaporation. As seen in Fig.5, the characteristic absorption lines at 1.1 THz, 1.16 THz, 1.41 THz, and 1.67 THz can be easily identified.

We also measured THz transmittance spectrum when a 120-μm-thick and 25-mm-wide high-density polyethylene (HDPE) was placed into the waveguide through the narrow slits in both plates of waveguide. Nearly tenfold reduction of THz field was observed around 0.66 THz (Fig.6). It is probably related to geometrical resonance of the sample. Indeed, the peak of attenuation is shifted to 0.6 THz if HDPE film is rotated at angle of $\alpha \approx 28°$ (inset of Fig.6). The detailed experimental and theoretical researches are now under development.

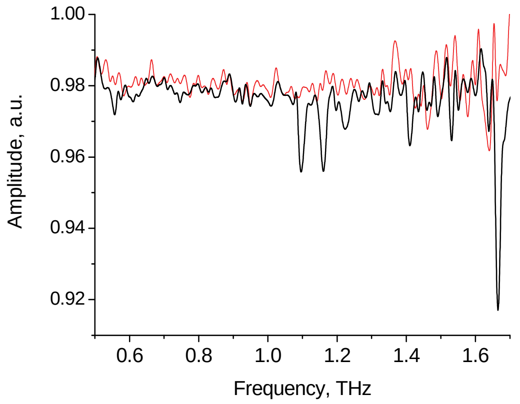


Fig.5. Transmittance spectra of waveguide filled by dry air (red line) and tiny amount of water vapor (black line).

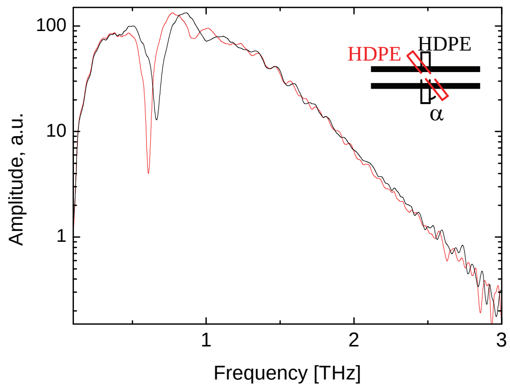


Fig.6. Transmittances of waveguide filled by perpendicularly (black line) and tilted (red line) oriented HDPE film.

## 4. CONCLUSION

In conclusion a nearly undistorted THz pulse propagation through the 8-cm-long slightly curved parallel plate oversized waveguide has been shown. The possibility of CPPOWG using in waveguide TDS is demonstrated by measuring absorption lines of tiny amount of water vapor.

## ACKNOWLEDGMENTS

The authors wish to thank to Prof. R. M. Martirosyan for fruitful discussions. We acknowledge the support of the Ministry of Science and Education of Armenia and ANSEF Grant EN-1521.

## REFERENCES


1. M.Tonouchi, Nature Photon. **1**, 97 (2007).
2. Z. P. Jiang, M. Li, and X. C. Zhang, Appl. Phys. Lett. **76**, 3221 (2000).
3. M. Hangyo, M. Tani, and T. Nagashima, Int. J. Infrared and MM waves, **26,** 1661 (2005).
4. J. Zhang and D. Grischkowsky, Opt. Lett. **29**, 1617 (2004).
5. R. Mendis and D. Grischkowsky, Opt. Lett. **26**, 846 (2001).
6. C. S. Ponseca et al. Opt. Lett. **33**, 902 (2008).

7. G. Gallot, S. P. Jamison, R. McGowan, and D. Grischkowsky, J. Opt. Soc. Am. B **17**, 851 (2000).
8. J. A. Harrington, R. George, P. Pedersen, and E. Mueller, Opt. Express **12**, 5263 (2004).
9. Li Cheng et al. Appl. Phys. Lett. **92**, 181104 (2008).
10. H. Nishihara, T. Inoe, and T. Koyama, Appl. Phys. Lett. **25,** 391-393 (1974).
11. K. Agababyan, R. Avakian, A. Hakhoumian, R. Martirossian, and N. Pogosyan, Tech. Dig. 27th Conf. on Infrared and MM Waves, 2002, p. 347-348.
12. R. Mendis and D.M. Mittleman, Tech. Dig. CLEO/QELS – 2008 post deadline papers, CPDA5.