Adiabatic Coupling into Terahertz Parallel-Plate Waveguides

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Abstract

We report on the coupling process of broadband terahertz radiation into metal parallel-plate waveguides with sub-wavelength gaps. Starting from well known quasi-optic coupling using silicon lenses, we developed a coupling scheme based on adiabatic coupling using metal flares. The metal surfaces change their shape slowly and smoothly with respect to the wavelength of terahertz radiation (300 µm). The undistorted pulse shape and dispersion-free propagation is maintained in the TEM geometry. The obtained coupling efficiencies for different waveguide geometries exceed previous values. For an optimized layout, also spectroscopic results of polycrystalline molecular samples are presented revealing high resolution absorption lines.

1. Introduction

The terahertz (THz) frequency band, located between the microwaves and the infrared, covers frequencies between 100 GHz and 10 THz. This low energetic radiation in the far-infrared is particularly interesting for various spectroscopic investigations as phonon modes of molecular solids are located here. To probe those transitions, typically a transmission measurement is carried out using THz time-domain spectroscopy (THz-TDS) [1]. This technique allows detecting a broadband frequency range between 100 GHz and 5 THz in one single scan. The layout of a THz-TDS system is displayed in Fig. 1. It shows the THz beam path without the peripheral laser components. Femtosecond laser pulses gate the transmitter (Tx) and the receiver (Rx). By varying the time delay between these two pulses, the THz electric field can be sampled in the time domain. A photoconductive antenna generates the THz radiation. The emerging beam is shaped by a silicon lens and a parabolic mirror. A wavelength dependent beam waist is formed in between an optically complementary detection scheme. The object (here a vacuum chamber incorporating a waveguide) is placed in the center of symmetry.

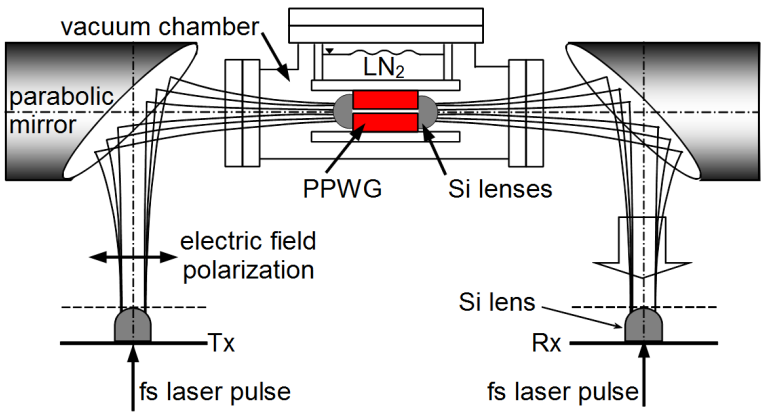

Fig. 1: THz beam path of the time-domain spectroscopy (THz-TDS) system. In the waist of the collimated beam, the objects are measured between two parabolic mirrors. Here a parallel-plate waveguide with Si lens coupling is shown.

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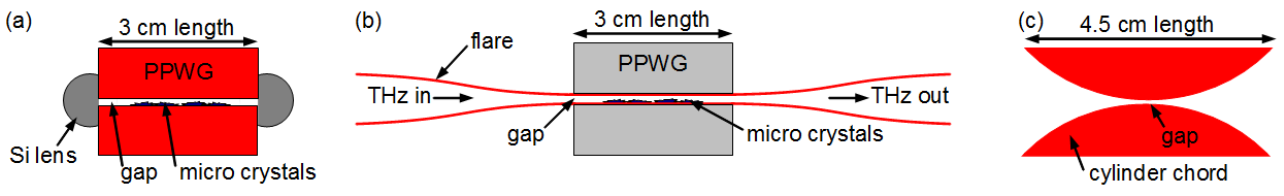

Fig. 2: Cross-sections of (a) standard parallel-plate waveguide (PPWG) with plano-cylindrical silicon lenses for coupling; (b) flare coupled PPWG; (c) 2-cylinder waveguide coupler with adiabatic wave compression.

2. Flare Coupled Parallel-Plate Waveguides

Different techniques are used to measure solid samples. The simplest approach is to measure a diluted pressed pellet. Then all crystal orientations are present broadening the absorption signatures. As a powerful alternative, we will concentrate on THz parallel-plate waveguides (PPWG) [2]. Their advantage is the high spatial confinement of the THz wave and the possibility to investigate a small volume of sample between the metallic plates [3]. The transversal modal profile in the PPWG for a particular gap width d is given by the number of propagating modes (m-th order mode cut-off frequency $f = mc/2d$). With respect to the incoming THz polarization, transverse electric (TE) and transverse magnetic (TM) modes can be excited. For spectroscopy, we are only interested in single-mode propagation. So we are working with a TM polarization (TM0 corresponds to TEM), as the waveguide (WG) remains single-mode in the frequency window up to 4 THz for a plate separation of less than 75 µm.

The standard and well-elaborated approach uses quasi-optic coupling to the parallel plates. The free-space THz beam is focused down to a line focus of roughly 150 µm width by a pair of plano-cylindrical silicon lenses. Due to the high index of refraction of silicon in the THz range (n=3.41) and the proper layout of the lenses (height 6.56 mm at a radius of 5 mm) the coupling remains good even for sub-wavelength gaps. Typical coupling efficiencies, defined by the transmitted amplitude divided by the reference amplitude of dry air, are better than 20% for a gap width of 50 µm. Due to Fresnel losses, beam truncation at the faces, modal mismatch and ohmic losses, the optimal coupling efficiency is 32% [4].

Based on the results reported by Zhang and Grischkowsky [5], a new type of coupling imitating the microwave approach is presented. It is known that the plate separation at the center of a PPWG can be compressed without significantly reducing the transmission. The reason is that the lateral compression is introduced adiabatically, which means slowly with respect to the wavelength. For an adiabatic coupling process the beam shape adapts itself to the new conditions without major losses or reflections [6]. This fact is used to design a coupling scheme without transmission optics, which would eliminate the 50% amplitude loss at the two silicon lenses, increase the flexibility and reduce the cost. The new coupler is shown in Fig. 2(b). It consists of two metal flares made out of commercial 100 µm thick copper shim. The standard surface quality and roughness of the raw shim is already sufficient for THz optics. Two 12 cm long strips were cut and mounted in between two 3 cm long metal plates. The entrance and exit flares have a full-opening of roughly 5 mm. The measured coupling ratio of the flare coupled WG was 32% at 1 THz, compared to 22% for Si lens coupled PPWG. The frequency dependent coupling ratio for both approaches can be seen in Fig. 3. To demonstrate the good performance of the flare coupled WG (high coupling ratio, no echoes, dispersion-free, high thermal conductivity of mount), spectroscopic scans of various molecular samples were taken.

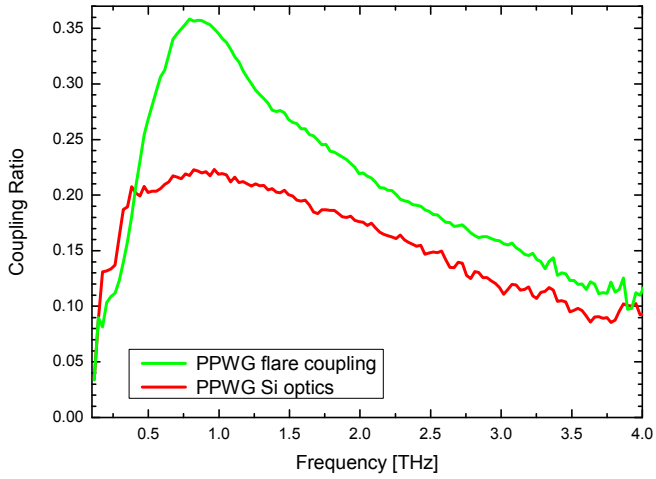

Fig. 3: Coupling ratios of identical PPWGs obtained with flare coupling compared to Si lens optics.

3. Two-Cylinder Waveguide Coupler

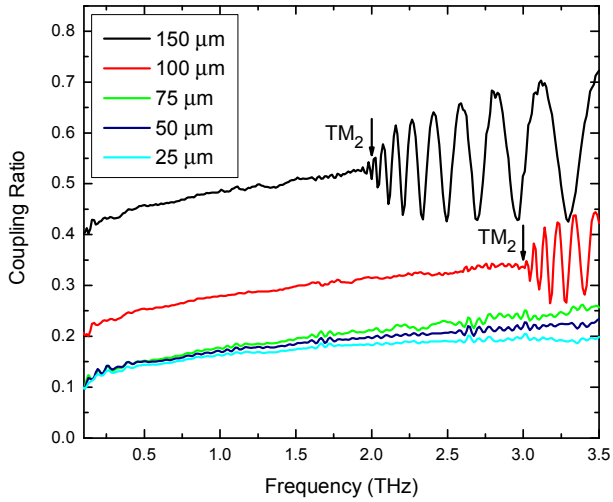

Fig. 4: Coupling ratio of the 2-cylinder coupler with TM polarization for different gap widths. For clarity, the curves with higher order modes have been lifted (100 µm curve +0.1, and 150 µm curve +0.3). For small gaps single-mode TEM propagation is observed.

Even if the long and flexible metal shims couple very efficiently due to the extended compression, for opto-mechanical ease, a solid coupler would be preferable. One possibility is to machine the shape of the flares into a bulk piece of aluminum [7]. This keeps the coupling ratio high, but also requires a precise mechanical accuracy and results in a bulky device. Another possibility is to use cylinder pieces. This approach unifies a good coupling ratio with the flexibility of commercial standard components. A sketch of such a coupler is shown in Fig. 1(c). It was made by cutting a chord from a full aluminum cylinder with a diameter of 64 mm. The height of the cylinder pieces was 9.5 mm, giving a chord of 45 mm length. The two facing cylinder pieces were attached together having spacers in between, so different gap width can be set. The coupling ratio for different gap widths is shown in Fig. 4. For all measured gaps (25 µm and larger) the coupling ratio is 0.15 without disturbing modulations. The overall coupling ratio is smaller than for the shim flares. This is expected as the cylindrical shape is less adiabatic due to the fast compression. For gaps larger than 100 µm, higher order modes can be observed. Interestingly, the coupling remains roughly constant even for very small gap widths. For spectroscopic applications, this means that especially for narrow gaps, the cylinders have a significant advantage compared to the Si lens optics.

4. Spectroscopic Results

To show the spectroscopic capabilities of the flare coupled sensor (see Fig. 1(b)), different solids were investigated [8]. The dissolved samples were drop cast on the metal shim recrystallizing to a micro-crystalline film of high crystal quality (inset Fig. 5). The copper shim (sample mount) is directly used as one half-side of the PPWG. Due to the confinement of the field and the high filling factor this technique allows for the investigation of tiny amounts of sample. A mass of 100 µg is already sufficient to obtain strong absorption lines.

The curvature of the flare was formed manually out of the flat shim. It is screwed together keeping a 50 µm gap. The measurement is carried out either at room temperature (295 K) or in the He cryostat (11 K). Exemplarily, the results for 1,2-dicyanobenzene (1,2-DCB) are given (Fig. 5). Out of the spectrum of the transmitted THz amplitude, absorption lines are cut out. At room temperature, wide signatures are observed while for cooling the sample, narrow absorption lines emerge. The determined line center frequencies and line widths are identical to those measured with the Si lens coupled PPWG.

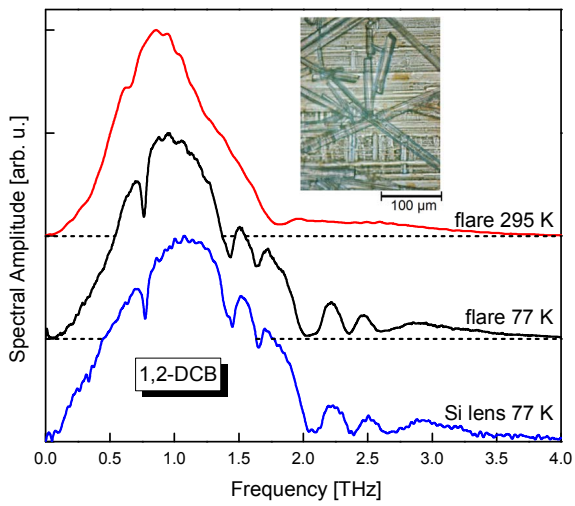

Fig. 5: Spectral amplitudes for a drop cast sample of 1,2-dicyanobenzene (1,2-DCB) in the PPWG. The results of the flare coupled waveguide at temperatures of at 295 K and 77 K compared to the results for the Si lens coupling. Inset: Microscope image of the sample revealing individual micro-crystals on the copper shim.

5. Conclusion and Outlook

We have shown that adiabatically shaped metal surfaces can be used to couple THz radiation into parallel-plate waveguides without transmission optics. Flexible couplers based on metal shim are presented, showing a high coupling ratio. Also rigid components made out of standard cylinders can be used, efficient even down to sub-wavelength gaps. Spectroscopic results indicate that also this type of coupling has the capability to do high resolution spectroscopy with easy-to-use components and a simple alignment. Maybe this low-cost alternative will bring an advantage for the industrial application of this technology.

6. Acknowledgments

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