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THz-TDS using a photoconductive free-space linear tapered slot antenna transmitter

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Abstract: A near-field edge-coupled photoconductive free-space linear tapered slot antenna has been constructed as a planar alternative to the standard photoconductive switch coupled to a silicon substrate lens. The temporal response along the optical axis is investigated to ensure the structure itself does not introduce pulse distortion which would fundamentally limit the usefulness of the structure. Experimental results show that a 1.6 THz bandwidth with a ≈50dB dynamic range is achievable with the new structure which is comparable to our reference experiment with a standard silicon substrate lens. The investigated structure has the added benefit of a potential substantial physical size reduction and can also be used to excite waveguides in the near-field.

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1. Introduction

Terahertz photoconductive (PC) switches have existed for a number of years and were investigated as early as 1984 [1]. In [1] two PC switches were placed on opposing sides of the same substrate and did not include free-space propagation. Subsequently, extensive research was pursued in free-space antenna design and optimization. At this point two approaches appeared for collimating the generated THz field: guided-wave electronic antennas [2–6] and optical lensing from a point source [7, 8].

The work completed by [2–4] uses substrate slotline and coplanar strip antennas. These antennas function admirably but distort the temporal response due to reflections and the refractive index mismatch on the guiding interface. The induced pulse distortion limits the ability for these antennas to function as a broadband THz time-domain spectrometer (THz-TDS) source. In [5, 6] the undesired effects associated with the substrate are mitigated by using a slotline antenna on a thin dielectric membrane. This method functions well but has several issues: the resulting antenna is delicate, manufacturing requires harsh etchants, and the conductor loss is relatively high. The issues associated with guided-wave antennas are mostly overcome by optical lensing [7, 8] which therefore became the dominate method for guiding the electromagnetic field generated by a photoconductive switch. The main issues associated with substrate lenses are: pulse attenuation and dispersion, lens manufacturing, alignment, physical size, and cost.

In this paper we investigate a hybrid photoconductive structure which is edge-coupled in the near-field region to a guided-wave metallic-slit antenna termed a photoconductive free-space linear tapered slot antenna (PC-FS-LTSA). Near-field coupling methods have existed for a number of years, although they are commonly found in the form of near-field probes for surface characterization [9–11]. The PC-FS-LTSA overcomes many of the issues associated with substrates lens and guided-wave antennas. The PC-FS-LTSA can be small (2mm × 2mm × 5mm), inexpensive (eg. fabrication using precision stamping), and easily assembled using a top-down alignment. Providing that the pulse shape remains undistorted at the output of the antenna, the PC-FS-LTSA could be a viable alternative to a substrate lens. Thus the pulse distortion along the optical axis of a prototype PC-FS-LTSA is investigated in this paper.

The novelty of the PC-FS-LTSA presented here arises from its simplicity and performance as a THz-TDS transmitter in the absence of refractive THz optical components. The same near-field edge-coupled source can be used as an alternative method (to [12–14]) for exciting waveguides without THz optics.

2. Design

Standard photoconductive antennas (PCAs) are commonly coupled to a high-resistivity float-zone (HRFZ) silicon lens to overcome the total internal reflection (TIR) of substrate back-face and direct the THz field [15]. It is desirable to eliminate the need for a HRFZ-Si lens because they are costly, lossy, and introduce dispersion thus limiting the transmitted power and bandwidth. Here we focus on the design of a PC-FS-LTSA for near-field edge-coupled THz antenna excitation as
an alternative to the standard HRFZ-Si lens.

Figure 1 illustrates the PC-FS-LTSA which consists of a photoconductive active-area on Si-GaAs which is edge coupled to a metallic-slit based antenna [16–21] (i.e. the FS-LTSA). The photoconductive active-area was patterned using standard UV-lithography and the metalization (15nm Ti, 150nm Au) was fabricated using E-beam deposition and lift-off. A Si-GaAs substrate was selected for its low-cost, high DC resistivity and high responsivity to 785nm [22].

The metalization pattern was selected to bias the active-area and guide the generated THz field into the FS-LTSA. It was found through simulation that the geometry illustrated in Fig. 1(b) was able to couple to the FS-LTSA without significant pulse distortion.

The FS-LTSA should be relatively thin ($T \approx 50\mu m$) to reduce the Fabry-Pérot resonances (see Appendix A) yet maintain mechanical rigidity and minimize conductor loss. In this work the FS-LTSA is constructed out of a relatively long ($L \approx 15\text{mm}$) and thick ($T \approx 127\mu m$) copper sheet because hand-polishing a short ($L < 5\text{mm}$) and thin ($T \approx 50\mu m$) copper sheet was found to be difficult. For this proof-of-concept experiment a FS-LTSA was selected (instead of, for example, a broadband Vivaldi taper [23]) for the manufacturing convenience. The FS-LTSA can be easily constructed by-hand whereas a Vivaldi taper requires precision machining.

Fig. 1. Design of the PC-FS-LTSA. a) Overall structure b) Active-area to FS-LTSA c) Image of experimental structure where $T \approx 127\mu m$, $S \approx 45\mu m$, $D \approx 85\mu m$, $L \approx 15\text{mm}$, and $\theta \approx 28^\circ$

A key difference between this work and past work [2–4] is the usage of a metallic-slit based free-space LTSA. A free-space antenna has a number of advantages over planar substrate based antennas. In particular, after the field is coupled to the FS-LTSA, the effect of substrate radiation, surface-waves, and dispersion are mostly eliminated. This goal has been mostly achieved by [5] where substrate etching was used to create an antenna on a thin ($<2\mu m$) SiO$_2$/Si$_3$N$_4$ membrane. The antenna presented here has some distinct advantages over thin membrane antennas: the metallic-slit based antenna has lower conductor loss due to increased conductor surface area,
it is less delicate due to the material and thickness, and the manufacturing process doesn’t require harsh etchants (EDP, HF, etc). Other substrate-based antennas [2–4] which closely model coplanar strip/slotline configurations can have a total loss of ≈17 dB/mm at 1 THz [24], whereas the free-space metallic-slit geometry has a loss of <1 dB/mm at 1 THz [16]. To note, these numbers are not representative of all designs, but they illustrate the possible large difference between the expected losses.

The loss of a metallic slit waveguide is dependent on the conductor material, separation, and thickness. For the copper FS-LTSA used in this experiment a FEM simulation was used to estimate the loss. Given the FS-LTSA dimensions at the entrance to the antenna (T = 127 µm, S = 45 µm, f = 1 THz), the loss is 0.11 dB/mm. As the FS-LTSA expands (S increases) the field localization on the conductors reduces resulting in a lower loss. The antenna presented here provides an excellent alternative to membrane-based antennas and illustrates that a guided-wave antenna can be used as a THz-TDS transmitter.

3. Simulation

The design of the PC-FS-LTSA was aided by simulations performed using the Ansys HFSS transient solver which utilizes the Discontinuous Galerkin Time Domain (DGTD) method. Key observations that resulted from the simulations were: the existence of a transverse Fabry-Pérot resonance in the FS-LTSA which will disperse the THz pulse (cavity length = T), a resonance between the PC active-area and the FS-LTSA edge (cavity length = D), combination of both cavities (cavity length = D + T). To summarize, the thickness of the FS-LTSA should be selected to minimize the Fabry-Pérot resonances while maintaining some thickness to reduce conductor loss. Also the active-area should be close to the substrate edge.

Figure 2 illustrates the simulated E-field of the PC-FS-LTSA after transient excitation. Figure 3(b) plots the simulated pulse shape at the output of the PC-FS-LTSA. The active-area in the simulation is modeled by a current pulse with a rise time of 800 fs. The simulation illustrates that relatively few resonances are introduced by the waveguide and metalization geometries.

![Fig. 2. Transient simulation with Ansys HFSS which illustrates the E-field](image)

Note that the length, L, of the simulated structure is 2.25 mm, whereas the experimental structure has a length of 15 mm. The shorter length in the simulation was required to solve the simulation with an acceptable resolution. This is not expected to have a large effect on THz pulse because as the conductors separation increases the field confinement on the conductors reduces
resulting in a radiated wave [23].

The discrepancy between the experimental and simulated length may cause concern thus further elaboration is warranted. To reiterate, the manufactured PC-FS-LTSA length was selected purely based on manufacturing convenience. Given that this paper is an investigation of the temporal response along the optical axis, then the main requirement is that the conductor separation at the end of the FS-LTSA is much greater than the free-space pulse length. The conductor separation at the end of the experimental PC-FS-LTSA is ≈7.5mm and ≈1.1mm for simulated structure, both of which are multiple times greater than the free-space pulse length (≈0.3mm). The effects associated with the different lengths will appear in the off-axis field components which are not investigated in this paper. Appendix B illustrates the simulated results for a number of LTSA lengths and concludes that when the length of the LTSA is longer than 2.1mm the temporal and spectral responses are relatively unaffected.

4. Experiment

We used a standard THz-TDS arrangement [Fig. 3(a)] to investigate the PC-FS-LTSA’s performance. A 1570nm fiber laser with a 100mW average power producing 100fs pulses at 38MHz was used. The 1570nm beam is frequency doubled using a periodically-poled lithium niobate (PPLN) crystal resulting in ≈20mW at 785nm to excite the photoconductors. Then the optical beam is split into two paths to excite the transmitter and gate the receiver.

The transmitter optical beam path length can be varied using a mechanical delay line which is used to obtain the temporal response of THz field. The optical beam passes through an optical chopper, then afterwards the optical beam is focused onto the active-area to generate a THz field which is coupled to the FS-LTSA then radiated. Then the THz beam is passed through an iris to block or scatter off-axis wavefront components. This increases the detectable bandwidth but reduces the detectable power. A portion of the THz beam reaches and biases the commercial LT-GaAs PCA receiver [25] and the detected current is read by a lock-in amplifier. An identical experiment was performed with a PCA transmitter (identical to receiver) in-place of the PC-FS-LTSA to provide a comparison. The results of this experiment are plotted in Fig. 3(b).
5. Discussion

The temporal response [Fig. 3(b)] of the PC-FS-LTSA resembles that of a standard PCA which is desirable. The bandwidth of the PC-FS-LTSA reaches around 1.6THz which is admirable considering the simplicity of the design. It is also expected that the PC-FS-LTSA should become lossy at higher frequencies due to excitation of transverse Fabry-Pérot modes (see Appendix A). This effect is most clearly observed by comparing the experimental PC-FS-LTSA and standard PCA spectral responses.

A notable feature in Fig. 3(b) is the presence of the water vapor absorption lines which are observable around 1.26THz. Presence of these absorption lines indicate that the PC-FS-LTSA is capable of functioning as a THz-TDS source. These lines do not originate from the previously stated Fabry-Pérot resonance because the “cavity” has a relatively low Q.

When comparing the simulated and experimental results [Fig. 3(b)] an obvious discrepancy is observed. For the simulated results the pulse has a strong negative portion whereas for the experiment this is minor. This is expected since the simulation defines the source as an impulse, whereas a SI-GaAs transmitter has a slow carrier decay (step-like response) resulting in a small negative peak [22]. Also note that the simulation peak at ≈0.255THz originates from a cavity (length=D+T, ne ≈ √((12.9 + 1)/2) = 2.64) which is stronger for the simulated structure due to ideal edges.

Referring to Fig. 3(b), a common trait of a LTSA is observed. After the initial transient, a small “double hump” occurs which is characteristic of the LTSA [2]. The double hump is undesirable because it broadens the pulse thus limiting the bandwidth. The simple method to eliminate this feature is to use a Vivaldi taper instead of a linear taper. A small hump also appears for the standard PCA before and after the main pulse. This typically arises from imperfect substrate lens alignment.

The bandwidth of the PC-FS-LTSA could be increased by correcting non-idealities with the following adjustments: utilize a thinner FS-LTSA (T≈50µm), reduce the distance between the active-area and the FS-LTSA (D≈10µm), and use a Vivaldi taper.

Regarding the physical size of the PC-FS-LTSA simulation shows that the length could be reduced to, for example, the simulated size (L=2.25mm) without causing pulse distortion. Therefore the total structure could quite likely fit into a volume ≈5mm × 2mm × 2mm = 20mm³ which is significantly less than the volume of a typical PCA coupled to a silicon lens ≈10mm × 10mm × 5mm = 500mm³.

6. Conclusion

If the thickness of the FS-LTSA is adequately selected for the anticipated system bandwidth then the generated THz pulse should not exhibit signs of pulse distortion, thus illustrating that the PC-FS-LTSA could be a useful alternative to a substrate lens. Experimental results have shown that a ≈1.6THz bandwidth with a ≈50dB dynamic range can be achieved. Water vapor absorption lines can be resolved which confirms that the PC-FS-LTSA is a functional THz-TDS transmitter.

The PC-FS-LTSA allows for a planar THz setup which could be used for imaging or spectroscopy in a less bulky arrangement than current implementations which utilize PCAs coupled to a HRFZ-Si lenses.

Appendix A - Fabry-Pérot Resonance

The Fabry-Pérot modes can be excited when a thick (with respect to wavelength) metallic slit waveguide is used. Figures 4(a) and 4(b) illustrates the results of a time-domain simulation that shows the Fabry-Pérot resonance when the metallic slit is thick. The start and stop frequency of the excitation pulse are 0.3 and 3THz respectively. Figures 4(c) and 4(d) illustrates the removal of the resonance by reducing the thickness of the metallic slit waveguide. Figure 4(d) illustrates
the desired undistorted response.

Fig. 4. Transient E-field plot illustrating the Fabry-Pérot resonance. a) Thick waveguide, field profile around the source location just after excitation ($t=1\text{ps}$) b) Thick waveguide, field profile of guided-wave after 6ps, note that the field profile is dispersed by reflections. c) Thin waveguide, field profile around the source location just after excitation ($t=1\text{ps}$) d) Thin waveguide, field profile of guided-wave after 6ps, note that the field profile is relatively undispersed and confined to the waveguide.

Appendix B - FS-LTSA length

Figure 5 plots the temporal response for various FS-LTSA lengths. When the length of the FS-LTSA exceeds 2.1mm there is little change in the radiated temporal response. To note, the simulated structure in Fig. 5 does not include the substrate/FS-LTSA interaction (as found in Figs. 2 and 3(b)). The substrate was negated because the high dielectric constant of the substrate demands a finer mesh (more computational resources) which would limit our simulation structure size to less than 3.3mm. Also, the structure was excited by a current sheet (closely matched to fundamental mode) instead of a current line to minimize the Fabry-Pérot resonance as discussed in Appendix A. The noise floor of the various lengths are different due to nonidentical meshes at convergence and does not contribute much insight to the comparison as it models an extremely small portion of the injected energy.
Fig. 5. The radiated temporal response sampled along the optical axis for a selection of LTSA lengths and the associated spectral response.

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