Total Internal Reflection THz Devices for High Speed Imaging

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***Abstract*—Electron-hole pair photoexcitation switches a semiconductor's response from dielectric to conducting. We show that this process is most efficient in a total internal reflection (TIR) geometry allowing the use of cheaper, less powerful light sources. Further, by employing a digital micromirror device to spatially pattern the photoexcitation area, we perform imaging with single-element detector and present solutions to the optical problems of imaging in this geometry. We finally show that by taking into account the carrier lifetimes in the signal processing one can improve the acquisition rate by a factor 5.**

INTRODUCTION

THz technology still lacks efficient, quick and cheap modulators, which prevents the circulation of THz devices within the commercial world. For example, whilst the non-ionizing energies are of great interest for bio-medical imaging [1], the requirement of measuring a broadband spectrum at each image pixel results in the use of mechanical raster scanning stages as the most used imaging modality. However, the mechanical raster scanning results in an inherently slow image acquisition preventing applicability in hospitals. Further, the current cost of THz systems means hospitals will prefer to buy other diagnosis tools.

The recent advent of spatial light modulation techniques has opened the door to alternative imaging modalities. Namely, by using a single-element detector and by spatially encoding a beam of radiation, one can use a set of measurements for different spatial encoding patterns in order to reconstruct an image [2]. In the THz regime, it is most common to use a digital micromirror device to spatially pattern the photoexcitation area of a semiconductor, and then to pass the THz beam through the patterned photoexcited area [2]. The photoexcited regions are opaque due to the increased conductivity within those regions. However, in a transmission geometry to achieve high modulation efficiency one needs to use very high pump powers [3], a problem further exacerbated by photo-carrier saturation mechanisms. By performing the modulation in a TIR geometry, much lower pumping fluences are needed to achieve large modulation efficiencies [3].

THIS CONTRIBUTION

In this contribution we combine the high photo-modulation efficiency of the TIR geometry with optical spatial modulation techniques to perform THz imaging. Our setup is illustrated in figure 1**a**, a pulsed THz beam passes through an object and then using a lens an image of the object is projected onto the top-surface of a silicon prism whilst at the same time the top-surface of the Silicon prism is photoexcited with a spatially patterned optical beam. The THz beam is finally detected with normal photoconductive antenna. Our setup allows high modulation over larger areas with a cheap pumping light source (<50USD), however this is an unconventional imaging geometry as shown in figure 1**b**. Most notably, the image plane and the silicon surface are not parallel resulting in image blurring at the edges. We discuss possible solutions to this problem, namely a custom-made lens and a calibration technique (measuring the imaging impulse response) allowing post-processing removal of this issue. Furthermore, the carrier lifetimes of the photomodulator set the fundamental switch-rate limit. However, since the carrier lifetimes can be measured, one can fit the relevant mathematical model and obtain greatly enhanced images. In this scenario, it is not necessary to wait for the measurement to reach an equilibrium state thereby improving the acquisition rate.

Additionally, since we use spatial modulation techniques for imaging, our technique is compatible with compressive imaging modalities and therefore we further demonstrate under-sampling. However, image retrieval with compressed sensing requires complicated minimization algorithms and storage all the spatial encoding patterns in memory. For this reason, we explore other image under-sampling algorithms: adaptive-sampling based on the Haar-wavelet transform [4] and sparse-sampling via finite rate of innovations [5]. We conclude by demonstrating how these image under-sampling ideas perform in a standard THz spectrometer.

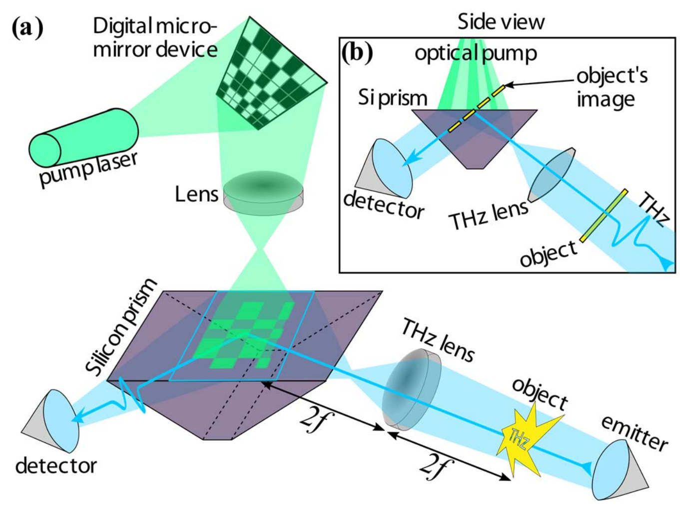

Figure 1: The imaging Scheme; A THz pulse is passed through an object and using a lens an image of the object is projected on the top-surface of a silicon prism. At the same time, an optical pump beam is spatially modulated and used to photoexcite the top-side of a silicon prism, which transfers the spatial encoding mask onto the THz pulse. Finally, the THz travels to a single-element detector. Knowledge of the patterns and of the corresponding detector signal are combined to give an image of the object. **(a)** 3D view, **(b)** 2D side view.

RESULTS

In regards to designing a custom lens to account for the unparallel imaging and silicon-surface planes, it can be mathematically shown that by considering the relevant Fourier optics model one can only minimize this effect with a custom-

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made lens and never completely eradicate it. Furthermore, there is little improvement when one considers the diffraction THz radiation. In a simple $2f$-$2f$ imaging system, with f=10*cm*, one can expect a resolving capacity of around 0.5*cm* at 0.7*THz.* Such heavy diffraction effects overpower the effect of having unparallel imaging and silicon-surface planes.

Measuring THz with a photoconductive antenna one almost always uses a Lock-In amplifier to filter out electrical noise, however filters reduce the acquisition speed and require external modulation to switch the THz on and off many times to measure a only single value. Therefore, to achieve the quickest acquisition rate we bypass the Lock-In amplifier and look at the raw currents. For imaging using a single-element detector and a spatial light modulator one needs to project a set of spatial encoding patterns, then by measuring the signals for each mask one can recover an image [2]. Since our masks are created via modulation of the silicon conductivity via photoexcitation using a CW source, one needs to wait until the photo-carriers reach an equilibrium state. Choosing a wafer with short carrier lifetimes gives higher switch rates, however this also reduces the equilibrium state photoconductivity thus reducing the modulation depth thus necessitating a tradeoff. Since the photoexcitation of silicon has been greatly studied, one can mathematically describe this process thereby allowing modelization of the raw signals. The raw and fitted currents from the photoconductive detector are shown in figure 2**a**. When a new mask is projected, the signal from the previous one will leak into the current mask signal until equilibrium is reached. As the leakage of signals is due to the photoexcitation of charge carriers in silicon, one can use an exponential fitting function to estimate the value when the carrier generation and recombination rates are at equilibrium.

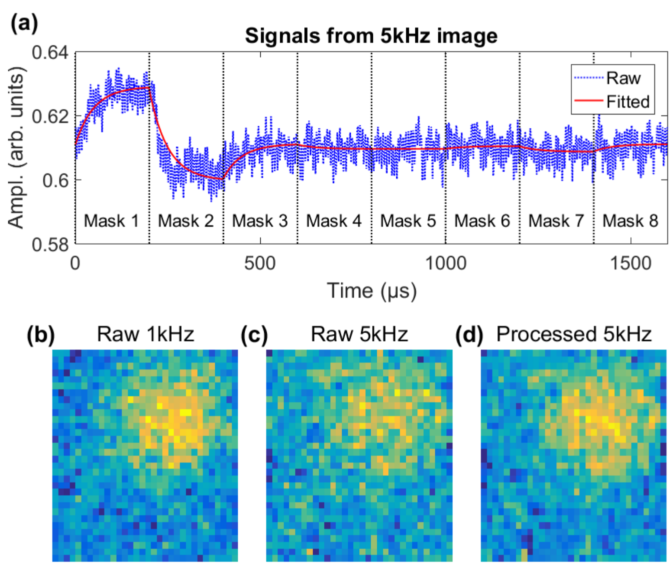

Figure 2: Measurement and images; (a) Raw (fitted) current measured from the photoconductive THz detector in dotted-blue (solid-red) line. Each imaging mask is projected for 200μs giving a switch rate of 5*kHz*. Only the signals for first 8 masks is shown. **(b-d)** 32x32 THz images (field of view 4x4*cm*) of a simple gaussian beam, where the pattern projection rate is 1, 5, *5kHz* respectively. Further, **(b)** and **(c)** use the average current value for each mask in the image reconstruction, whereas **(d)** takes into account the carrier lifetime in the silicon photomodulator (red line in part **a**).

In figures 2**b-d** we show THz images of a simple gaussian THz beam where the image data was obtained when the digital micromirror switch rate was at 1, 5, 5*kHz* respectively. Parts **b** and **c** use the average current value for each mask in their image reconstruction, and part **d** uses the estimated equilibrium value from the exponential fitting result (red curve in part **a**). Note that this is the measured value at the peak of the THz pulse. All the images show noisy images of the gaussian THz beam, with the worst being part **c** and parts **a** and **d** being of equal quality. This is because the silicon modulator used was measured to have a carrier lifetime of ~60.3μs requiring around 0.5*ms* to reach equilibrium, whereas the masks in part **c** are projected for a total of 0.2*ms*. In short, we did not wait long enough, however since we know the carrier lifetime we can estimate the final value obtaining a greatly improved image in part **d**. In fact, this improved image is of comparable quality to projecting each mask for 1*ms* as can be seen when comparing parts **b** and **d**.

Conclusion

We show that with post-processing to account for the carrier generation and recombination rates, one can improve the image acquisition rate by a factor 5 without sacrificing image quality. Whilst this work uses a photoconductive antenna to measure THz pulses, its results are also applicable to other types of THz detectors that work in continuous wave modalities. Future work will include improving the electronics to reduce electrical noise and investigation into image under-sampling techniques to optimize the software side of this THz imaging technique.

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