High-speed hyperspectral and phase-contrast THz imaging using differential chirped pulse down conversion

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Abstract: We demonstrate a THz imaging system using chirped pulses to acquire amplitude and phase information of various samples, enabling hyperspectral imaging and axial optical path delay determination approximately 50x better than the diffraction limited lateral resolution. © 2023 The Author(s) Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.

1. Introduction

With the increased research and development in the terahertz (THz) region, higher power sources and more sensitive detectors have driven investigations into THz radiation applications [1,2]. Due to its unique location in the spectrum, from 100 GHz to 10 THz, spanning the range between electronic and photonic frequencies, THz radiation has unique properties such as being transparent to non-conducting materials such as clothing, paper, and plastics. This enables non-destructive imaging of objects encased or hidden under traditionally opaque materials. Further, with coherent THz technologies, more techniques can be applied to extract the complex response function from the sample for material characterization [3].

In this work, we present a THz imaging system that acquires the magnitude and phase information over a 72 GHz region centered at 570 GHz using a differential chirped pulse down conversion scheme. We use amplifier multiplier chains (AMC) for THz generation and coherent detection that provides high power and high-speed readout [4]. We apply this imaging system to a variety of samples including reflective metals, test phantoms, and semiconductor chips.

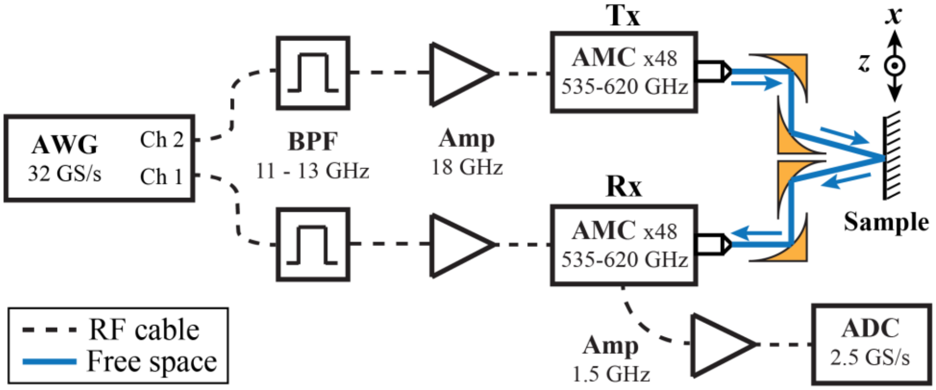

Figure 1: Schematic of the THz imaging system based on AMC THz generation in reflection mode.

2. Experiment

The imaging system is configured in reflection mode as shown in Fig. 1, using gold coated parabolic mirrors to focus the light on the sample and detector. The electronic components consist of an arbitrary waveform generator (AWG), the AMC transmitter (Tx) and receiver (Rx), and various microwave band pass filters (BPF) and amplifiers (AMP). The AMCs are driven by chirped microwave (MW) waveforms (WF) defined by the AWG which multiplies the MW frequencies by x48 from the 11.15 GHz to 12.65 GHz electrical signal region into the 535 GHz to 607 GHz optical region. The chirps are defined as follows for the Tx and Rx arms,

$$WF_i^{Tx}(t) = sin\left(2\pi f_{Tx_{start}} t + \frac{2\pi(f_{Tx_{stop}} - f_{Tx_{start}})}{2\tau_{CP}} t^2\right) \tag{1}$$

$$WF_i^{Rx}(t) = sin\left(2\pi f_{Rx_{start}} t + \frac{2\pi(f_{Rx_{stop}} - f_{Rx_{start}})}{2\tau_{CP}} t^2 - \frac{2\pi}{N_{chirps}}\left(\frac{t}{\tau_{CP}} + i\right)\right) \tag{2}$$

$$i = 1 \dots N_{chirps}, \;\; t = 0 \dots \tau_{CP}$$

where τ_{CP} is the duration of the chirp pulse that defines the RF comb resolution (100 kHz), and N_{chirps} defines the total interferogram length of 100 μs [5]. Each series of interferograms is Fourier transformed to form a comb spectrum that carries the complex response from the sample. The comb lines are sampled, inverse Fourier transformed, and normalized to recover the time domain magnitude and phase information for each pixel in the image. The optical path delay due to the propagation through or reflection from the sample results in a linear phase term in the down converted RF interferogram. Over the 72 GHz chirp, we can extract depth information with a resolution of 20 μm free space optical path length. This is approximately 50x better than the ≈1 mm lateral resolution defined by the diffraction limited spot size at these THz frequencies.

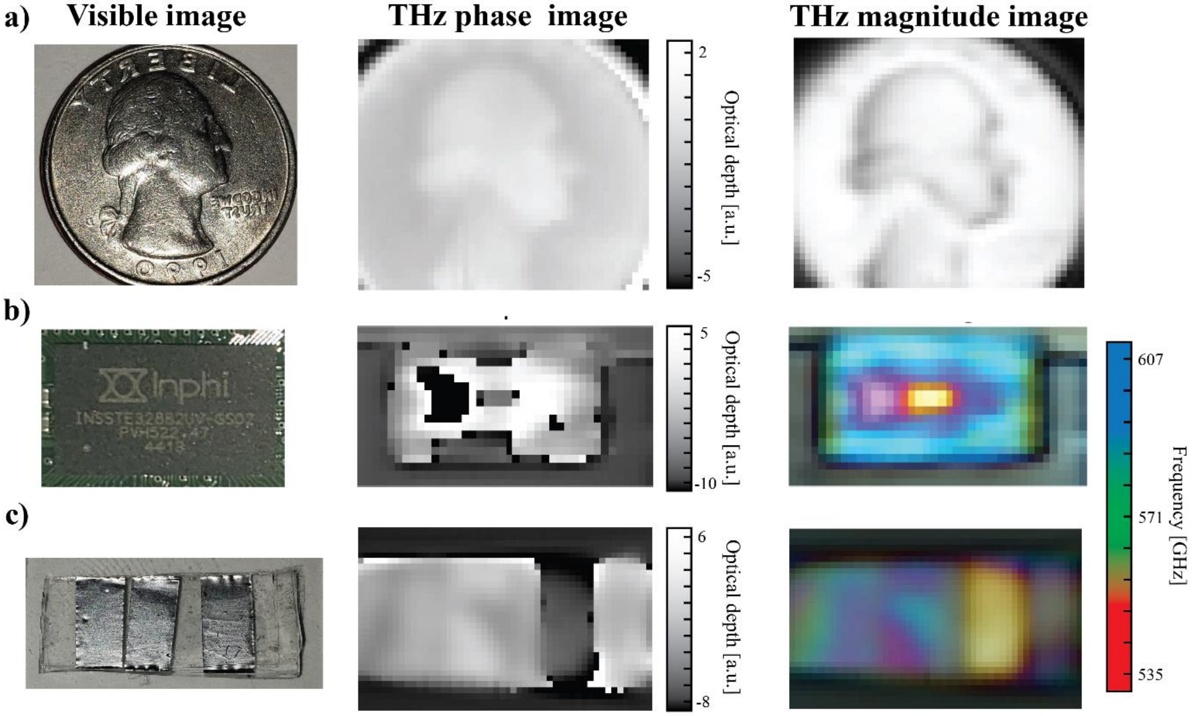

Figure 2: Visible and THz images of a) a quarter dollar coin, b) a RAM chip, and c) a PDMS and aluminum foil samples.

3. Results

The imaging system was applied to a quarter US dollar coin, random access memory (RAM) card chip, and Polydimethylsiloxane (PDMS) with embedded aluminum foil samples in reflection mode. Each pixel consists of a 100 μs interferogram, allowing for imaging at 10 kHz rate per pixel. Figure 2a shows a photograph of a quarter dollar coin in the visible wavelength and phase and magnitude images in the THz. The 50x43 pixel, 400 μm pitch, phase image shows the depth profile of the quarter, where the intensity is mapped to the linear phase term that is defined by the optical path delay and corresponds to the extrusion of the bust. The magnitude image is an intensity image due to the THz reflection from the metal surface, with slight power reduction around edges, angled surfaces, and background mirror due to the focus at the Rx detector. Figure 2b is a 40x20 pixel image, 500 μm pitch, of a RAM chip, revealing an interesting spectral signature in both the optical path delay and false color RGB magnitude images. This demonstrates a unique property of THz radiation and enables the hyperspectral imaging of a RAM chip through the plastic casing. Figure 2c shows a 50x30 pixel image, 400 μm pitch, of thin PDMS layers with strips of aluminum foil inserted at different depths to imitate a more complex layered sample. The phase image shows the reflection at the right-side foil strip reduces the phase delay, making it darker. The hyperspectral false color RGB image shows the complex interference due to reflections through the variable thickness of the PDMS structure.

In this paper, we demonstrate a high-speed THz system capable of imaging through plastics and determining optical path delays far below the diffraction limited lateral resolution. The high power and small footprint of the AMC based system make it adaptable for in-line applications or structured illumination techniques that would eliminate the need of intrinsically slow raster scanning for 2D hyperspectral data acquisition.

4. References

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