Quadrature & Frequency Diverse Terahertz Imaging with Metamaterials

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***Abstract*—Compressive sensing is an exciting approach to imaging and promises to make significant advance in the terahertz regime. However, compressive imaging is commonly implemented is such that acquisition proceeds in a serial manner, thus leading to unrealistic frame rates. We propose and demonstrate a new approach to terahertz single pixel imaging using all-electronic metamaterial spatial light modulators. Our technique is deterministic and permits parallel acquisition, resulting in a significant advance in image fidelity and frame rates compared to alternative approaches.**

I. INTRODUCTION

THE terahertz (THz) portion of the electromagnetic spectrum is a notoriously difficult regime in which to perform imaging. A lack of pixel sensitivity requires active illumination with a high power source, or long imaging times to increase signal to noise via averaging. Often raster scan imaging is employed, where an object is simply moved through the object plane and an image is built up from the measurements. Terahertz spectrometers—such as time domain spectrometers—realize high signal to noise, and with such a system it is possible for raster scan acquisition to produce high fidelity images. However, the imaging process in this case remains inherently serial, meaning it remains burdened with long acquisition times. A more critical limitation is that image resolution is set by the beam aperture size. There is thus a fundamental trade-off between image resolution and photon throughput, i.e., signal to noise.

We propose and demonstrate an alternative approach to imaging, using an all-electronic metamaterial spatial light modulator (SLM). The SLM is placed in a conjugate image plane and is used to multiplex the image. The multiplexed image is sent to a single pixel detector and a value is recorded. The SLM is dynamically reconfigured and detector values are recorded for each configuration of the mask. In single pixel imaging, the number of values recorded is equal to the desired resolution of the image, and we utilize masks derived from a number of different matrices, including Hadamard, S-matrix and random.

We describe our imaging process mathematically with a model based on matrix inversion. A column vector **X** represents the pixelated information of the scene, while the SLM masks are given by the rows of the measurement matrix **Φ**. Here we utilize the n=64 order Hadamard matrix as our measurement matrix[20], i.e. $\mathbf{\Phi}=H_{64}$. Through the imaging process we obtain Hadamard coefficients, represented with a vector

$$\mathbf{Y} = \mathbf{\Phi X}. \qquad (1)$$

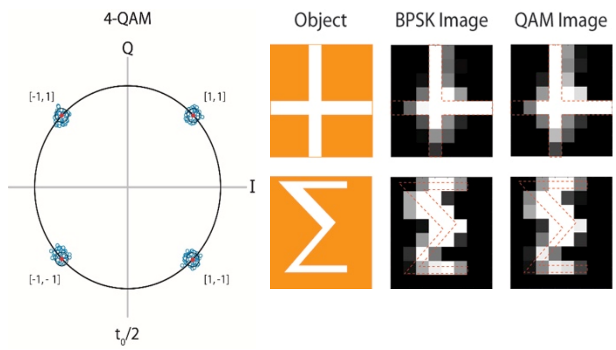

Fig. 1. (Left) Constellation diagram for quadrature amplitude modulation (QAM) obtained with the metamaterial spatial light modulator in a terahertz imaging system. (Right) Center gold images represent apertures used in a back illuminated terahertz single pixel imaging system. To the right are terahertz images obtained via binary phase shift keying (BPSK) and QAM modulation.

We then reconstruct the original image **X** *via* computational matrix multiplication with the inverse measurement matrix[21]

$$\mathbf{X}= \mathbf{\Phi}^{-1}\mathbf{Y}. \qquad (2)$$

Physically, the SLM consists of metamaterial absorbers fashioned with a doped Schottky epilayer. [1] The metamaterial geometry provides a relatively narrowband high absorption in the terahertz frequency regime. Metamaterials are multi-functional however, and thus we also use the metamaterial to provide reverse bias to the Schottky structure, depleting carriers. The effect on the electromagnetic response is that the narrowband absorption peak shifts to lower frequencies, and thus our metamaterial absorber acts as a frequency modulator. Our metamaterial device is separated into an 8x8 spatial light modulator, from which individual oscillating signals are multiplexed into a lock-in detector. Here we detail two separate technological demonstrations of single pixel terahertz imaging. [2]

II. RESULTS AND DISCUSSION

In Fig. 1 we show results of our metamaterial spatial light modulator. The left portion of the figure shows a so-called constellation diagram, which is a polar plot showing the amplitude and phase of our metamaterial SLM. In particular, we choose a set of radius-phase pairs known collectively as quadrature phase shift keying (QPSK), or quadrature amplitude modulation (QAM). The metamaterial SLM may thus simultaneously realize two separate masks, one encoded in-phase and the other encoded in quadrature. Consequently, imaging time is halved when using QPSK modulation in metamaterials. The right portion of the figure shows THz images obtained with binary phase shift keying (BPSK) and quadrature phase shift keying. As can be observed, there is no difference in image fidelity in the two types of images, indicating the advantage of imaging in quadrature. As a modulation scheme, QAM is in general extendable via further division of the phase space and the inclusion of multiple radial values in the constellation, but in a multiplexed system such as ours this is infeasible.

In pursuit of a more scalable method, we also perform frequency diverse imaging by encoding masks with different modulation frequencies. In this manner we increase spectral efficiency by a factor proportional to the number of frequencies employed. Fig. 2 shows QAM constellation diagrams realized simultaneously at four different modulation frequencies: f_1 = 204 Hz, f_2 = 208 Hz, f_3 = 213 Hz, f_4 = 216 Hz. These frequencies are orthogonal as seen in classic communications OFDM systems, that is:

$$\int_0^\tau g_1(t) g_2(t)\, dt = 0, \quad (3)$$

where τ is the integration time of the detector, called the symbol duration, and $g(t)$ gives the waveform of the carrier, in our case a square wave. As this inner product represents the crosstalk between two subcarriers, frequencies orthogonal in this sense may overlap in the frequency domain, allowing for

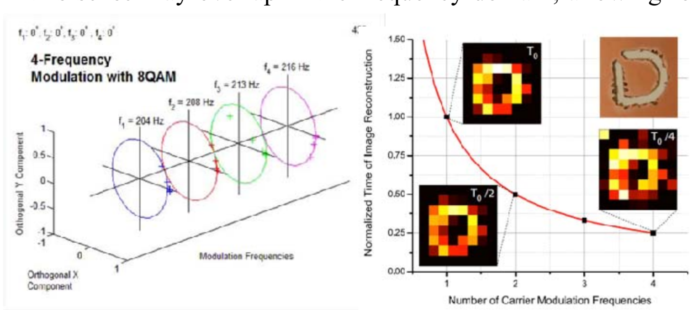

Fig. 2. (Left) QAM constellation diagrams for each frequency in the OFDM-based scheme. (Right) Imaging results for an increasing number of orthogonal carrier frequencies, using a BPSK modulation scheme. Image fidelity is maintained as the number of carriers increases.

more efficient use of system bandwidth. In addition, Fig. 2 depicts the imaging results of our frequency diverse THz system, acquired with greater and greater efficiency as the number of subcarriers increases. It is important to note that frequency diversity is not only efficient in its choice of subcarrier frequencies, but also highly scalable, i.e., more subcarriers can be introduced only at the cost of more effective bandwidth.

We emphasize that the techniques presented here do not sacrifice any of the information gained in image acquisition, fully preserving image fidelity. The QAM and frequency diverse images in Figures 1 and 2 appear visually similar to their conventional, non-parallel counterparts, but we can also perform an L_2 difference analysis on the acquired images to investigate quantitatively the effect of our methods. Fig. 3 shows the results of our analysis for both QAM and OFDM systems. Plotted as a percentage of maximum reconstructed value, differences between the images are relatively small. In principle, neither QAM schemes nor frequency diverse subcarriers result in the loss of the information, and we attribute the differences in the acquired images to noise.

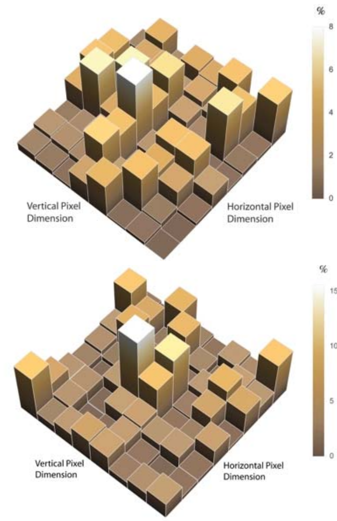

Fig. 3. (Left) Plots of the L_2 difference between the QAM and BPSK images shown in Figure 1 for a) cross object and b) the sigma object (Right) Plots of the L_2 difference between the D object imaged at for various numbers of orthogonal carrier frequencies, using a BPSK modulation scheme.

III. Summary

The methods we have detailed here are ultimately limited by the Shannon capacity of the channel on which they are implemented. However, as we have shown, for reasonable bandwidth and noise levels they are indeed capable of realizing significant gains in the spectral efficiency of single pixel systems. QAM and OFDM are in general compatible techniques, and as we have demonstrated here, they remain so in the context of single-pixel THz imaging. The techniques we have demonstrated are enabled by the development of efficient metamaterial SLMs, whose speed and efficiency far surpass alternatives such as digital micromirror or liquid crystal devices. Indeed, we have directly demonstrated metamaterial SLMs to be capable of far more than previously shown. The communications paradigm from which QAM and OFDM derive represent a new avenue for approaching single-pixel imaging, one with the potential for great impact in THz photonics.

References

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