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Metasurface Enabled THz Multi-User Communications

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***Abstract*—We report THz multi-user communication enabled with an electrically-controlled metasurface. By applying different voltage profiles on the metasurface, we show that we can achieve simultaneous 2-user communication with QPSK symbols.**

I. INTRODUCTION

MULT-USER (MU) communication is a crucial technique to increase wireless networks capacity by simultaneously transmitting multiple data streams to multiple users. This technique has been widely adopted by various wireless standards such as 802.11ac [1] operating at sub-6GHz and 802.11ay at 60 GHz [2]. In order to support multiple independent data streams, MU communication typically requires a large set of antenna arrays and baseband RF chains. However, at THz frequencies, the adoption of large antenna arrays is still a challenging and cost-prohibitive task. Therefore, alternative solutions are being developed to enable the implementation of MU communication at THz frequencies.

In this work we propose and experimentally demonstrate a metasurface-enabled, RF-chain-free transmitter architecture, capable of transmitting independent information symbols towards multiple users located at different directions from the metasurface. Specifically, the proposed metasurface has a direction-dependent response in which it modulates both the phase and amplitude of a THz wave in different ways across different directions. i.e., the same metasurface configuration can be used at a given frequency to transmit different symbols to different users. As can be seen in Fig. 1a, by carefully designing a set of different configurations, a transmitter equipped with our metasurface is capable of transmitting multiple independent QPSK information symbols to different users located at different angular locations from the transmitter.

II. RESULTS

1. Fabrication and characterization of the metasurface

The metamaterial device has a similar design to the one we described in Refs. [3,4]. In brief, it consists of an array of square-shaped split-ring resonators fabricated on a 2-µm thick *n*-doped GaAs epilayer grown on an intrinsic GaAs substrate (see inset of Fig. 1a). Six columns of these resonators are electrically connected to a common contact pad for external electrical control, resulting in a geometry consisting of 7 channels each with a 0.63 mm channel width. These channels are individually addressed with an analog output acquisition card with a 16-bit output voltage resolution.

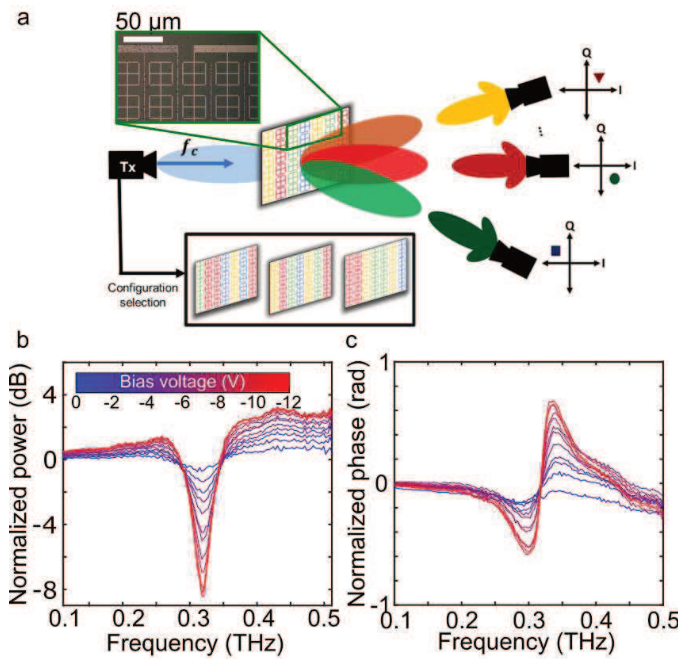

Fig. 1 (a) Schematic displaying multi-user enabled communications with a metasurface. A THz wave is incident on a metasurface, which has a given voltage configuration that allows to simultaneously transmit a symbol to user 1 and another symbol to user 2, given that users 1 and 2 are angularly separated. Inset shows a microscope image of the fabricated metasurface. (b) Normalized power and (c) phase response of the metasurface when uniform voltages across all channels are applied. Blue curves correspond to a voltage of -1 V, while red curved correspond to a maximal voltage of -12 V. The curves are normalized to a voltage value of 0 V.

We first use THz time-domain spectroscopy (THz-TDS) to characterize the resonance response of the metasurface at normal incidence, in transmission. As shown in Fig. 1b, when applying a uniform voltage of -12 V across the 7 channels, a resonance dip of depth ~8 dB appears at 324 GHz. This is accompanied by a phase change of up to ~0.7 rad in the vicinity of the resonance frequency. Importantly, the amplitude and phase changes occur over a broad spectral band, allowing us to choose the frequency for which the sets of amplitude and phase values exhibit the highest diversity.

2. **Multi-user communications**

We now explore the use of the metasurface for multi-user communications. In particular, we target the generation of quadrature phase shift keying (QPSK) symbols towards two users located at angles 45° and 55°. Instead of applying a uniform voltage to all channels, we use an analog output acquisition card to generate different voltages in each channel.

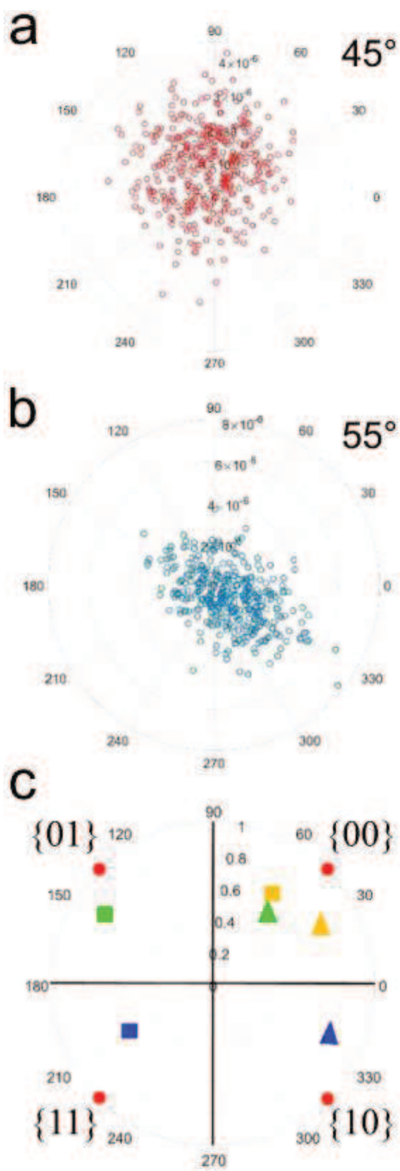

Fig. 2 (a) Complex values obtained at a frequency of 390 GHz with the set of 360 configurations for 45° and (b) 55°. These are plotted in polar coordinates, in which each dot represent a particular voltage configuration where the amplitude corresponds to the power and the angle to the phase. (c) Example of three configurations (in different colors) that allow multi-user communications at user 1 at 45° (triangle) and at user 2 at 55° (square). The red circles correspond to ideal QPSK symbols. Yellow corresponds to the case when both users receive the symbol {00}. Blue corresponds to the case when user 1 receives symbol {10} and user 2 receives symbol {11}. Green corresponds to the case when user 1 receives symbol {00} and user 2 receives symbol {01}.

For QPSK, the transmitter needs a set of 16 configurations that can satisfy all the possible symbol combinations, e.g., {01} to user 1 and {11} to user 2. We search among a set of 360 different configurations, each with a different voltage distribution across the 7 channels. These configurations are derived from a uniform distribution of the possible voltages i.e., -12V to 0V with a resolution of 0.01 V. Each configuration results in phase and amplitude change of the incident wave at 390 GHz, with a frequency and angular dependence. Fig 2a and Fig. 2b show the distribution of phase and amplitude measured at 45° and 55° degrees respectively. As can be seen at both directions, the tested configurations provide a set of symbol options that cover the IQ space. Specifically, phase shift coverage of $0-2\pi$ range is achievable by the metasurface at the two locations, allowing the transmitter multiple options to transmit QPSK symbols towards the two directions.

Next, in order to find the required 16 combinations for the two users simultaneously, we run an optimization problem that searches the available configurations to find the best set of configurations that is required. Specifically, for each of the 4 QPSK symbols we solve the following optimization problem:

$$\min \sum_{i=1}^{I} |E^{m}_{\text{desired}}(\theta_i) - E^{m}_{\text{measured}}(\theta_i)|^2 \; ,\forall m, \qquad (1)$$

where, $I = 2$ is the number of users, and the superscript m represents the QPSK symbol. The optimization problem result in the required set of configurations to be used by the metasurface.

Fig. 2c illustrates 3 of the 16 possible pairs of symbols. The 3 pairs of symbols are represented with different colors, while the triangle and square represent the symbols at 45° (user 1) and 55° (user 2) respectively. For example, the blue triangle corresponds to user 1 receiving the symbol {01}, while the blue square corresponds to user 2 simultaneously receiving the symbol {11}. These two symbols (the same color) are generated with the same set of control voltages applied to the metasurface, such that an incident wave at 390 GHz simultaneously generates these two symbols at the respective locations. Another voltage configuration (in yellow) allows users 1 and 2 to receive the same symbol {00}. We emphasize that, within our small search set (360 voltage configurations), we were able to find all the 16 required combinations for the 2-user QPSK case. This illustrates the large diversity in IQ values generated by the metasurface across angles in a diffracted beam, which can enable multi-user data streams in a low-power and simple device.

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