Manipulating Terahertz Waves Using Spatially-Resolved Optical Modulation

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***Abstract*—Tunable and reconfigurable devices for efficiently manipulating THz waves in advanced sensing, imaging and communication are challenging to realize. An alternative promising approach for developing the above THz devices based on spatially-resolved optical modulation (SROM) will be introduced followed by prototype demonstrations. Enhanced SROM using mesa-array structures for more advanced tunable/reconfigurable THz devices will be presented. High-performance optically-controlled THz switches enabling next generation adaptive integrated THz circuits/systems will then be discussed. Finally, in addition to magnitude modulation, a unique approach for achieving high-performance THz phase shifting will be proposed, making the SROM a more complete, systematic and versatile/powerful technology for manipulating THz waves.**

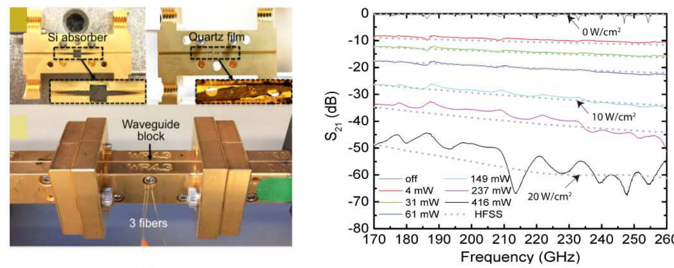
I. Introduction

In the last two decades, much effort had been devoted to developing THz sources and detectors, which has enabled a variety of promising applications. However, the research into active control and manipulation of THz wave propagation is still in its infancy. Such control in an effective way will lead to the development of a variety of tunable and reconfigurable circuits that are required in advanced THz sensing, imaging and communication. Although approaches such as thermal-tuning, use of liquid-crystals, semiconductor-device-based reconfiguring (e.g., HEMTs, diodes, PIN, etc.), metamaterial-based actuation, as well as employment of graphene modulator arrays have been reported, most of these approaches rely on complex tuning devices, prepatterned metal electrodes and cumbersome biasing lines to produce circuits or arrays, which greatly limits the achievable tunability and versatility.

An alternative, elegant and powerful approach for realizing such tunable and reconfigurable THz circuits is based on spatially-resolved optical modulation (SROM) using photo-induced free carriers in semiconductors [1]. This approach takes advantage of the fact that when light illuminates a semiconductor material, free carriers are generated if the photon energy of the light exceeds the bandgap energy of the semiconductor. As a result, the free carrier density, and hence the complex dielectric constant as well as photoconductivity of the material can be effectively and locally controlled by changing the incident light intensity patterns. For a THz wave incident onto the semiconductor, the wave transmittance, absorbance and reflectance can therefore be spatially controlled, leading to the potential for optically-controlled modulation.

II. Results

On the basis of the above SROM approach, a wide range of tunable/reconfigurable THz components such as tunable modulators, coded-aperture imaging masks, and beam-steering/forming Fresnel antennas have been successfully demonstrated [2-4]. In addition to modulating THz waves in free space, the SROM approach has also been adopted in rectangular waveguide configurations for achieving high-performance THz variable attenuators as shown in Fig. 1. Excellent performance was achieved, with a measured insertion loss of <0.7 dB, return loss better than 15 dB, and an average of 60 dB continuous attenuation range over the entire band [5].

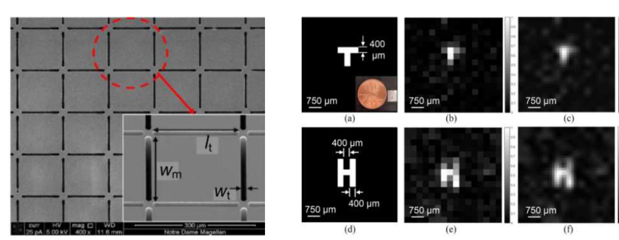


(a) (b)

Fig. 1. (a) Photographs of a WR-4.3 optically-controlled variable attenuator with Si absorber and three optical fibers for modulation. (b) Measured and simulated S-parameters of the variable attenuator as a function of frequency and incident optical power per fiber [5].

In order to further enhance the SROM performance, mesa-array structures consisting of isolated semiconductor islands as seen in Fig. 2(a) have been proposed and investigated. This improves both the achievable modulation depth and spatial resolution, while maintaining relatively high modulation speed [6]. Using a Si mesa array with a 100 μm × 100 μm mesa size, subwavelength THz coded-aperture imaging at 740 GHz has been experimentally demonstrated showing a wavelength-scale imaging resolution of ~400 μm as seen in Fig. 2(b). A subwavelength imaging resolution as small as ~250 μm can be potentially achieved. Using the mesa array structure as a technology platform, more tunable and reconfigurable THz circuits such as optically-controlled electromagnetic bandgap (EBG) filters, photo-induced SIWs can be realized,

To facilitate the adoption and seamless integration of SROM



(a) (b)

Fig. 2. (a) Scanning electron microscopy image of the fabricated Si mesa array, and the inset shows a zoomed-in image of a single unit (~100μm×100μm). (b) Photo-induced coded-aperture imaging at 740 GHz shows the imaging results for T- and H-shaped stencils with subwavelength features. A subwavelength imaging resolution of ~400 μm has been achieved [6].

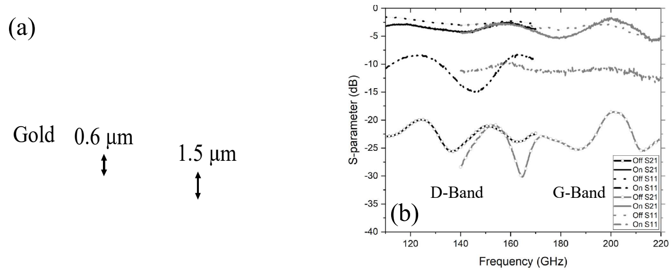


Fig. 3. (a) SEM image of the optically-controlled THz switch fabricated using a thin film friendly process on a silicon-on-sapphire substrate. (b) Measured S-parameters of the fabricated switch in both the D-band and G-band (combined) using on-wafer probe testing [7].

technology in next generation THz adaptive integrated circuits and systems, optically-controlled THz switches based on photoconductivity modulation have been investigated and experimentally demonstrated as shown in Fig. 3 [7]. Owing to the facts that both low on-state resistance and off-state capacitance being achieved in a non-contact architecture, as well as bias-free configuration for reduced parasitics, optically-controlled THz switches with extremely low insertion loss, superior isolation, record-high FOMs (Figure of Merit), and broadband operation can be achieved. Fig. 3(a) shows the first monolithically-integrated optically-controlled THz switch in a series coplanar waveguide (CPW) configuration based on silicon-on-sapphire (SoS) substrates. The SoS substrate employed not only enables wafer-scale switch fabrication/integration, but also facilitates potential integration with transfer-printed micro-LEDs for through-substrate illumination. On wafer measurements from 110-220 GHz (both D- and G-bands) of the fabricated switch prototypes have shown promising performance (Fig. 3(b)), with significant potential for optimization. Such THz switches using bias-free and optical modulation will enable the development of tunable and reconfigurable THz adaptive circuits such as filters and low loss feeding networks (for THz beam steering/forming).

Despite the above successful demonstrations of tunable and reconfigurable devices for THz wave manipulation, it is observed that all these devices have been based on magnitude modulation. THz phase modulation using the SROM approach/concept directly has never been proposed and explored. For the first time, we developed and demonstrated a unique and novel approach as shown in Fig. 4 for achieving high-performance THz phase shifting [8]. For a prototype demonstration, the device is designed based on a WR-5.1 waveguide configuration with an ITO layer on top of a quartz substrate as the ground plane at the waveguide end for low loss THz reflection. The core and active element of the device is a Ge mesa-array (12×6) on thin quartz substrate with a distance of *d* from the ITO layer. A closely coupled micro-LED array is then employed for illuminating the Ge mesa-array through the ITO for SROM. By changing the illumination area on the Ge mesa-array, the effective reflection plane can be adjusted, resulting in extremely low loss (< 1 dB), low IL variation, nearly continuous and broadband phase shifting as shown in Fig. 4 (b). By using only the light patterns with different combinations of vertical "strips" as shown in Fig. 4(a), 2^{11} = 2048 phase shifting states between 0º and 180º (360º achievable by changing distance *d* between the Ge layer and ITO) can be achieved with a phase tuning step as small as ~0.1º. This level of phase modulation capability has not been previously reported, and is prohibitively difficult to achieve using other technologies. This approach will enable the development of large-scale THz phased-arrays, reflectarrays and metasurfaces.

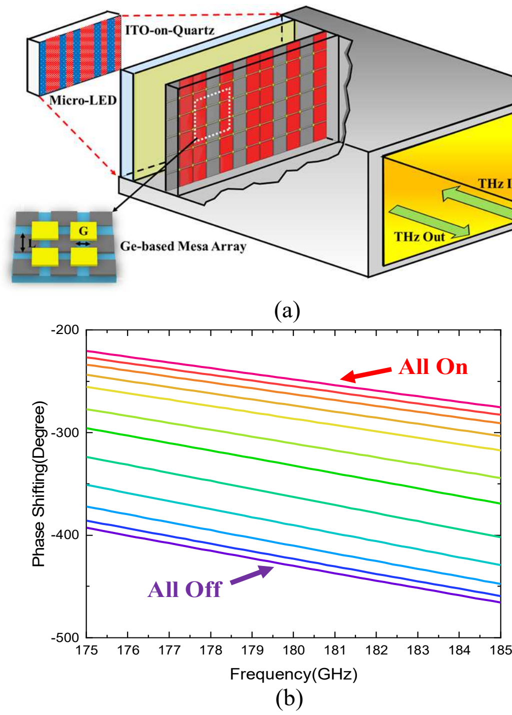


Fig. 4. Proposed high-performance THz phase shifting using spatially-resolved optical modulation. (a) A prototype demonstration using Ge mesa-array structure in a WR-5.1 waveguide with an ITO as the ground plane for low loss reflection. By illuminating the Ge mesa-array with different light patterns using a closely coupled micro-LED array, the effective reflection plane for the incident wave can be tuned, leading to variable phase shifting. (b) Full-wave simulated phase shifting showing high performance [8].

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