Ultrafast Tunable Metasurface with Transparent Conducting Oxide Antenna Array

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Abstract: We demonstrate large reflection and transmission modulation and femtosecond relaxation times in undoped zinc oxide films. Using these experimental results, we designed an optically tunable, terahertz-speed metasurface with a 17.4dB extinction ratio at 1.30 µm.
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1. Introduction

All-optical nanophotonic switches have the potential to push semiconductor data-processing speeds beyond the limits of Moore's Law because they are not limited by the electronic bandwidth [1]. This has, in part, lead to the investigation of light-matter interactions in nanostructured material in several all-optical data processing applications, encompassing fields of ultrafast switching and high-density data-storage [2]. Recently, ultrafast modulation of reflection has been demonstrated employing the inter-band excitation of electrons in direct bandgap semiconductors [3], and femtosecond optical polarization switching has been realized via sub-bandgap optical pumping in high-mobility semiconductors [4]. In order to have practical applications, it is of utmost importance to demonstrate ultrafast switching on a CMOS compatible material platform using geometries than can be easy to replicate on optical circuits. Furthermore, it is important to demonstrate switching in the telecom frequency range.

TiN has gained a lot of attention from the scientific community as a CMOS compatible plasmonic material with high thermal and chemical stability, biocompatibility, and optical properties comparable to gold [5]. Waveguides using TiN strips have been demonstrated which have performance close to that of gold waveguides in terms of mode confinement and propagation loss [6]. In the field of transparent conducting oxides, zinc oxide (ZnO) thin films have been studied as a promising alternative to other commonly used TCOs such as ITO. ZnO films are cheaper, non-toxic, and highly durable against hydrogen plasma compared to ITO, and their optical properties can be altered using a wide variety of dopants [7], making it the material of our choice.

As a step towards realizing fully CMOS compatible all-optical switches, we have designed a dielectric-loaded disk resonator array metasurface. It comprises disks of zinc oxide residing on an optically thick layer of titanium nitride. The performance of the metasurface has been investigated through numerical studies. An on-off ratio of 17.4 dB has been observed in simulation.

The findings of this research work will pave the pathway to the design of ultra-compact and ultrafast optical circuits employing dielectric-loaded waveguides and resonator arrays, and ultrafast, dynamically tunable metasurfaces.

2. Theory and Implementation

Using pump-probe spectroscopy, we have investigated the modulation performance of ZnO thin films deposited on glass substrates using pulsed laser deposition (PLD). We observe changes in reflection ($\Delta R/R$) up to 35% and changes in transmission ($\Delta T/T$) up to 45% when pumped by a 200 fs, 325 nm pulse, and probed by a 1300 nm pulse with the same pulse width (Fig 1 (a)). The photoexcited electrons change the permittivity of the ZnO through Drude dispersion, which, in turn, results in the change in reflection and transmission. The photoexcited carriers then recombine, returning the permittivity of the material to its steady-state values. The relaxation time for this change is 316 fs, which enables the design of terahertz speed all-optical switches with the material. The generated free carrier concentration that caused the transmission modulation at the lowest pump intensity was extracted from the pump-probe data to be 1.77×10^{20} cm^{-3}, which corresponds to a change in the relative permittivity of the ZnO film by -0.86 + 0.246i.

Next, we designed a metasurface to demonstrate ultrafast, all-optical switching. Focusing on CMOS compatibility, TiN deposited on MgO was chosen as the metal layer. Fig 1(b) shows the optical properties of the TiN film grown by DC magnetron sputtering at elevated temperatures on MgO. Fig 1(c) shows the optical properties of the ZnO film, grown by PLD on the TiN substrate. The unit cell for our metasurface comprises a zinc oxide disk on a metal reflector (Fig 1(d)). The steady-state resonance of the structure can be changed by changing the diameter (d) and the height (h) of the antenna. Simulations were done using the commercial software COMSOL Multiphysics. Using the relative permittivities of as-grown ZnO and TiN, we found that a disk height of 220 nm and a diameter of 600 nm resulted in a resonance at 1300 nm, where the reflectance is 1%, as shown in the red curve in Fig 1(e). For simulation purposes, we assume a steady-state continuous wavelength pump of the lowest intensity as shown in Fig 1(a). Using the change in the relative permittivities of the ZnO film as stated earlier, we found that the resonance of our metasurface blue-shifts by 100 nm (Fig 1(e)), causing the reflectance to rise from 1% to 54.9% at 1300 nm. This corresponds to a large on-off ratio of 17.4 dB. Fig 1(f) shows the electric field map of the resonator at 1300 nm without the pump.

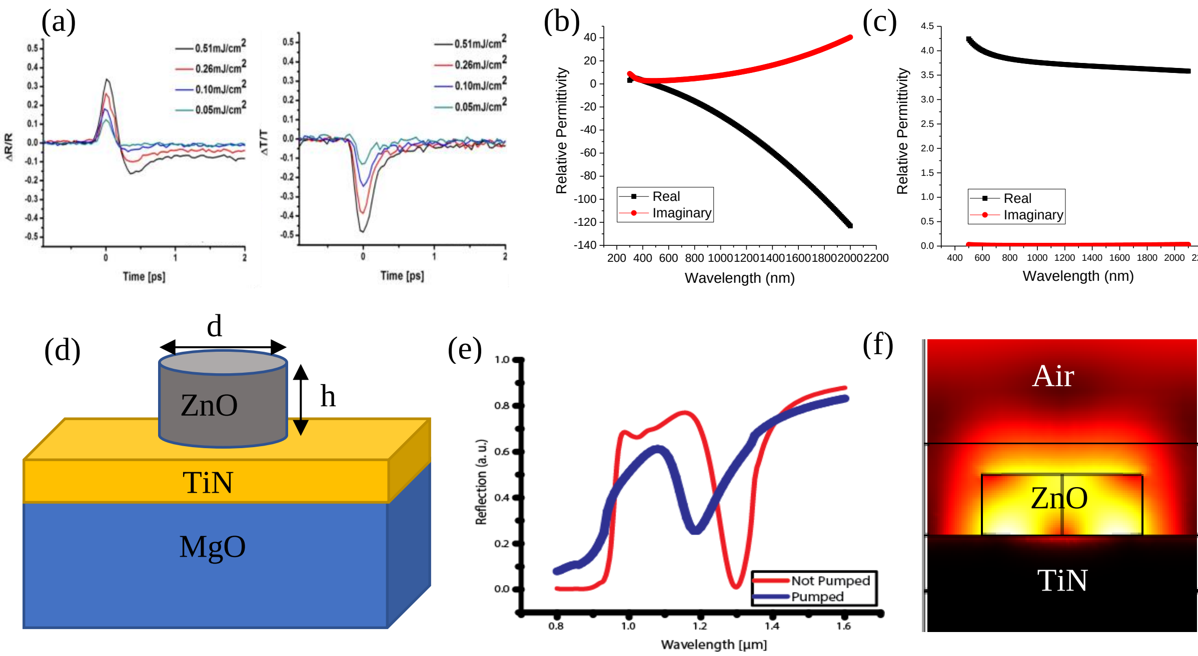

Figure 1: (a)Transient relative changes in reflection and transmission for a 1.4 micron thick ZnO film with a 325 nm, 200 fs pump-pulse, probed at 1300 nm. (b) Relative permittivities of 200 nm TiN film epitaxially grown on MgO. (c) Relative permittivities of as-grown ZnO film on TiN. (d) Schematic of the dielectric-loaded resonator structure. (e) Simulated reflection spectra of the disk without pumping (red) and with pumping (blue), assuming a steady-state, continuous wave pump at 325 nm of the lowest intensity shown in (a). (f) Normalized electric field profile of the resonator at 1300 nm, without the pump.

3. Conclusion

We experimentally demonstrated ultrafast carrier-dynamics and high reflection and transmission modulation in undoped zinc oxide films. An ultrafast, optically tunable metasurface has been designed and optimized through simulations to have a high on-off ratio of 17.4 dB at the telecom wavelength of 1.30 μm. The results of this project would be a significant milestone on the path to achieve terahertz level on-chip modulation with photonic circuits, and the design of ultrafast, dynamically tunable metasurfaces on a CMOS-compatible material platform.

4. Acknowledgement

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5. References

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