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An indium tin oxide metasurface filter for terahertz applications: Design, fabrication, and characterization

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In this paper, using a cross-shaped complementary Indium Tin Oxide (ITO)-based metasurface design, the transmission of THz radiation is shown to be filtered within the 3 dB level from maximum in the frequency range of interest ($\sim$333 GHz). Various metasurface structures primarily composed of cross-shaped openings with a 400 micron unit cell size are patterned on top of 1750 micron thick fused silica substrates. They are patterned using UV lithography methods after the films were grown using DC sputtering. The fabricated structures were characterized using Terahertz Time Domain Spectroscopy (THz-TDS) measurement technique. The measured transmission agrees well with the simulation of the structure for four different samples with different geometries. These results suggest that metasurface and/or metamaterial patterns based on ITO in visibly transparent media can be utilized for filtering of frequencies in the long wavelength spectrum. These types of filters can be very useful in the near future for THz communication and security applications.

Keywords: Metamaterial; indium tin oxide; metasurface; terahertz; filter.

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1. Introduction

The terahertz (THz) region is defined to lie between millimeter waves and long wave infrared, roughly from 300 GHz to 10 THz.[1] In recent years, advances in this field have had important implications for industry and military applications such as imaging,[2] medical sciences,[3] homeland security,[4] communication and spectroscopy.[5] These advances have brought about a need to be able to control the amplitude and phase of the THz radiation. Since metamaterials have an unnatural electromagnetic response because of the subwavelength composite structure that shows unique electromagnetic behavior due to its topology and inclusions, they can be the solution to controlling the principles behind light-matter interaction in the THz region.[6] Single and double negative (both ε and μ) metamaterials have been shown to be useful for many applications such as sensors,[7] modulators,[8] superlenses,[9] antennas,[10] perfect absorbers.[11]

THz frequency range metasurface structures are typically composed of a dielectric substrate and patterned metals such as gold, silver and copper. The high conductivity of the metal is important to enhance the transmission of the THz radiation through the structure. For this reason, in recent years, superconductor-based metamaterials have been developed to achieve modulation and tunability by controlling temperature and the applied magnetic field.[12,13] Although metal-based metamaterials have many advantages such as ease of production, patterning and high conductivity, they are not transparent in the visible region. While graphene is being investigated as an alternative because of its tunable conductivity and transparency is the visible region, it still remains a challenge to pattern.[14] Due to its exceptional physical, optical and electrical properties, Indium Tin Oxide (ITO) has been researched and developed heavily in the optoelectronic industry. Its transparency in the visible region makes it an indispensable material in solar cells where it is used as electrodes.[15] Recent interest in the development of communication technologies near the THz frequency region has spurred interest in the development of visibly transparent conductive surfaces that can transmit these higher frequencies while shielding others such as microwaves. For these reasons, ITO is a perfect candidate for metamaterial filter applications in the THz frequency range. Depending on the properties of the filter, fabricated structures based on ITO thin films on dielectric substrates can have broad use in future applications in the field of THz communications.

In this paper, an ITO-based metasurface cross-filter structure with different dimensions were patterned using UV lithography on top of fused silica substrates and characterized with a home built Terahertz Time Domain Spectroscopy (THz-TDS) system. The THz-TDS measurements were compared against simulations done in CST microwave studio®, the results show that high quality grown ITO films can be used as visibly transparent metasurface filters in the THz range.

2. Simulation, Fabrication and Characterization

Four different ITO-based metasurfaces are designed and simulated using CST Microwave Studio Frequency Domain Solver. Detailed shape and dimensions of the different structures are shown in Fig. 1.

Unit cell of each designed metasurface is kept constant at 400 μm. Dielectric function and loss tangent of fused silica substrate are determined by measuring the substrate with the THz-TDS system. Sheet resistance of ITO layer is measured by a four-point probe. The measured electrical permittivity and average loss tangent of fused silica are 3.98 and 0.05, respectively. ITO layers are simulated using

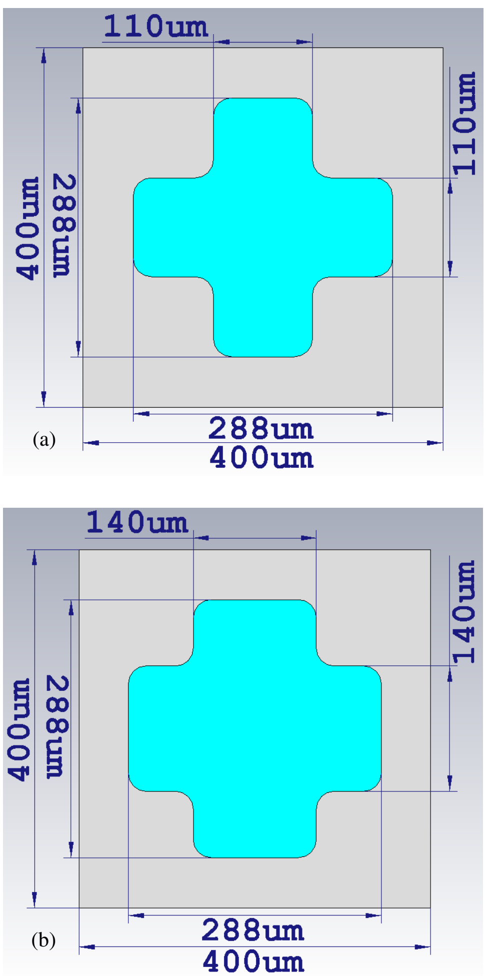

Fig. 1. Schematic representation of ITO cross-metasurface unit cell (a) dimensions of sample I and (b) dimensions of sample II, III and IV.

surface impedance method and according to measurement sheet, resistance taken as 7.5 Ω/sq. Compared to a free standing structure, the resonant wavelength of a patterned structure on a dielectric substrate shifts according to Eq. (1)

$$\lambda_r = \lambda_{r0}\sqrt{(n_1^2 + n_2^2)/2}\,, \tag{1}$$

where λ_{r0} is the free space wavelength and $n_{1,2}$ is the refractive indices of the materials on both sides of the structure.[16] According to the simulation results, the resonance frequency of all metasurfaces examined here lies near 0.333 THz.

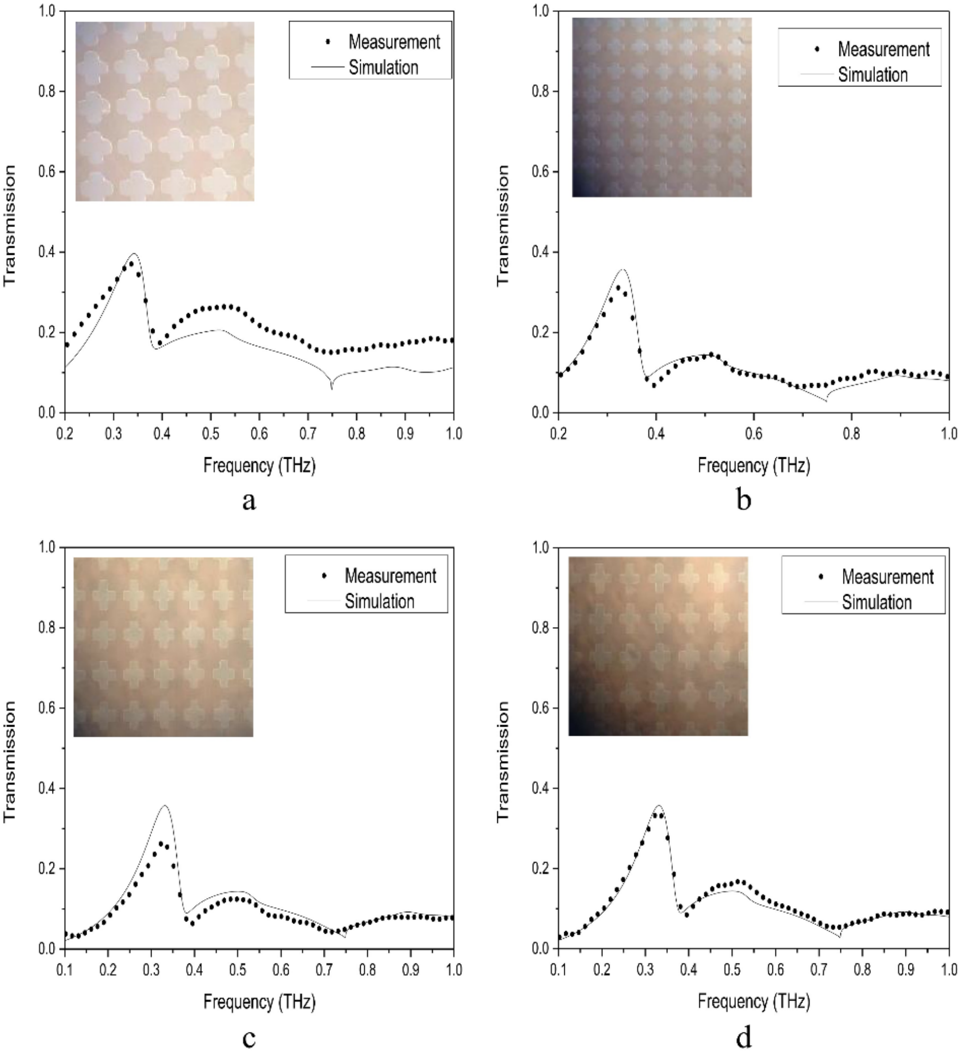

Fig. 2. Simulation and measurement of ITO metasurfaces on fused silica. (a) Sample I, (b) sample II, (c) sample III, (d) sample IV.

For fabrication of the metasurface, first, fused silica substrates are coated with ITO through DC magnetron sputtering and patterned through UV lithography.[17] UV lithography is carried out by coating, then soft baking of the ITO-coated substrates with light sensitive photoresist is carried out in a spin coater at 2000 rpm. Afterwards, the samples are masked and exposed to UV radiation and placed in NaOH solvent. Hard baking is carried out after rinsing the samples. Patterned photoresist is etched via ion beam etching system in high vacuum. Final cross shape complementary pattern is achieved by dissolving the photoresist in acetone.

Metamaterials are characterized by THz-TDS system that has a 3 THz bandwidth in free space. Bandwidth of the measurements was limited to about 1 THz during measurements mainly due to the slight absorption profile of the fused silica and the shift of the THz beam focus. THz beam focuses onto the samples using TPX lenses to a measured spot diameter of about 5 mm. Measurements were performed in an enclosure with dry nitrogen purged atmosphere.

3. Results and Discussion

As seen from Fig. 2, THz measurement shows a peak at 0.333 THz and this is well-matched with simulation results. On average, the resonance near 0.333 THz exhibits a profile where the maximum transmission within 0.1 THz bandwidth is more than 50%.

4. Conclusion

THz applications are gaining interest with the development of novel materials which can show both metallic and dielectric behaviors. Here, ITO is shown to be a medium which can show useful conductive properties in the THz frequency region. Patterned in a cross-metasurface structure, the transmission curves are measured with THz-TDS for four samples and compared with simulations. The high quality of the grown films and the observed resonance peak for this design show that ITO can be an effective medium for THz filter applications. The minor differences observed between the samples depend primarily on pattern quality. Metasurface filter designs such as these are encouraging for future THz and sub-THz communications since below 500 GHz many atmospheric transmission windows exist. Instead of using fused silica as a substrate, similar designs can be done using glass since it is fairly transparent under 600 GHz.

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