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Elastomer-based flexible THz metasurfaces for sensing applications

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Summary:

For THz sensing systems, reconfigurable metasurface is a key issue for obtaining miniaturized, fast and cheap spectral scanning systems in the THz domain. This paper presents the manufacturing and characterization of flexible elastomer, PDMS (polydimethylsiloxane)-based THz metasurfaces. Numerical models were applied to analyze the system THz properties. Measurements proved the usability of proposed flexible THz sensors. For a 25% deformation, a decrease of resonant frequency by 8% (~ 20 GHz) was obtained.

Keywords: Terahertz; metasurface; flexible sensors; elastomer; PDMS;

Introduction

THz sensing has a great potential for many applications in wireless communication [1], imaging [2], material analysis [3], wearable sensors [4], and biomedical detection [5]. Active modulation of THz metamaterial (MM) devices can be achieved by mechanical, electrical, magnetic, and optical control [6]. Flexible substrates enable the effective tuning of the THz MM resonance frequency under various mechanical loads such as bending, folding, twisting, compressing and stretching without causing the system to degrade even under repeated multiple loading [7] where the materials and the device components must exhibit long-term stability, especially good adhesion and no layer wear or cracking. Often, rigid materials such as Au, Al, Mo, Ni, Ti, are used as a conductive layer [4] in combination with flexible materials such as polyvinyl alcohol (PVA), polyimide (PI), polydimethylsiloxane (PDMS), polyethylene glycol naphthalene dicarboxylate (PEN) [6].

Optimization of such flexible and tunable MM is obtained by (i) low permittivity of the substrate in order to maintain the resonance strength and hence the bandwidth of the MM and (ii) low loss (absorption coefficient), to maximize the transmission propagation through the substrate. Properties such as low Young’s modulus ($7.5\cdot 10^{4}$ GPa) and low absorption (13 cm^{-1} at 1 THz) are attributes that make elastomers (PDMS) suitable substrates choice for flexible, tunable MMs utilized as a filter or sensor.

Numerical Model

Numerical calculations were performed using the Finite Element Method (FEM) in Comsol Multiphysics software. The 3D-model geometry of a single element of the THz metasurface (MS) is shown in Fig. 1. $\varepsilon_r = 2$ was used for relative permittivity of PDMS. Numerical analysis was performed for a conductive layer with a thickness of 10 µm and conductivity of aluminum ($3.77\cdot 10^{7}$ S/m). The application of periodic boundary conditions enables to perform analysis of the whole MS only with a single structural element with significant reduction of numerical analysis time [8].

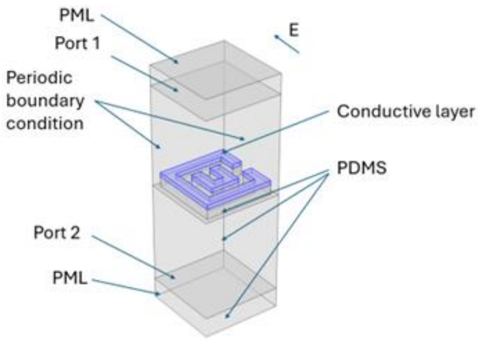

Fig. 1. Schematic view of the numerical model utilized in the simulation (MS element: double split ring resonator; PML: Perfectly Matched Layer).

Metasurface Fabrication

For the production, a silicon wafer was coated with 1.1 µm thick Parylene-C (temperature: 110 °C, pyrolysis at 740 °C, pressure at 3 Pa, coating time: 1 h 26 min). To produce the elastomer, a PDMS spin-coating (10:1 base to agent, Sylgard 184 elastomer) was applied (400 rpm, 60 sec), followed by defoaming, curing (110°C for 30 min) and O_2 plasma flash activation (100 W, 30 sec). The thickness of the PDMS layer was approx. 165 µm. Al sputter coating (500 nm), and Al structuring with nLOF 2070 photoresist (7000 rpm, 60 sec, expose time: 5 sec, post bake: 115 °C, development time: 240 sec) was applied. Al was etched in a phosphoric acid etching mixture (PWS 80-16-4(65)) at 47 °C, the photoresist was removed and the flexible MS structure was peeled off (Fig. 2).

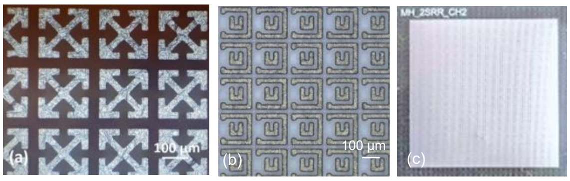

Fig. 2. (a), (b) Microscope pictures of Al coating on elastomer surface with various MS elements, and (c) full chip surface of 1.5 cm x 1.5 cm.

Results and Discussion

The results obtained for the double split ring resonator structure (experimental example in Fig. 2 (b)) using the numerical model are presented in Fig. 3. There are two major resonances for frequencies f_{r1} = 0.24 THz and f_{r2} = 0.71 THz as presented in Fig. 3(a). The numerical analysis indicates a strong effect of conductivity on the amplitudes of the transmission coefficient where for a pronounced resonance a conductivity of $\sigma > 1 \cdot 10^6$ S/cm is needed. Fig. 3(b) shows the dependance of transmission coefficient $|S_{21}|$ on conductivity for f_{r1} and f_{r2}. The highest amplitudes were obtained for the conductivity of Al $\sigma = 3.77 \cdot 10^7$ S/m.

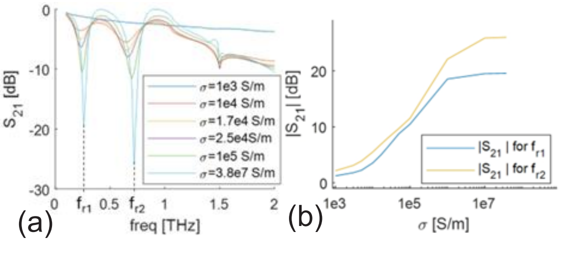

Fig. 3. Results of numerical simulations of double split ring resonator-based MS: (a) transmission coefficient $|S_{21}|$ frequency responses for various values of conductive layer electrical conductivity, (b) dependence of the resonant curve amplitude on conductive layer electrical conductivity.

For the proposed Al layer, the measured de-embedded frequency responses of MSs are presented in Fig. 4(a). The obtained resonant frequencies are in good agreement with the simulation results shown in Fig. 3(a). To prove the applicability of the actively configurable filter, an experiment was carried out in which the device was mechanically stretched by 25% (affecting e.g., gaps sizes in structural elements of MS). Fig. 4(b) shows a tuning of the primary resonance frequency (f_{r1}) of about 8% due to stretching of 25%.

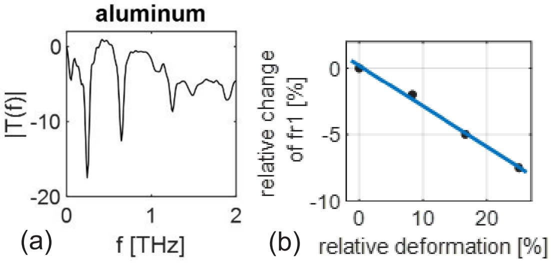

Fig. 4. (a) De-embedded measured transmission frequency responses of MS with conductive layers made of Al, and (b) results of sensor stretching experiment.

Conclusion

THz waves interact effectively with good conductors such as Al. Simulations were conducted to assess the impact of electrical conductivity on the transmission coefficient S_{21} of the THz MS. Performed measurements proved the usability of proposed flexible sensors. For 25% deformation, which is far below the maximum stretching of PDMS (ca. 60%) an 8% decrease of resonance frequency (~ 20 GHz) was observed.

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