Metasurfaces based on Functional Materials in THz and Optical Regions

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Abstract. In this paper we present the properties of metamaterials and metasurfaces composed of resonant micro/nano-structures in which their tunable electromagnetic (EM) properties can be achieved by employing the substrate or resonant structures consisting of functional materials such as polydimethylsiloxane (PDMS), Vanadium-dioxide (VO₂), shape memory alloys (SMAs) or in general smart materials. Using a mechanical stretching PDMS substrate for a metasurface, reflectance and transmission of electromagnetic (EM) wave can be remarkably altered. Moreover, by employing resonators consists of Nitinol (NiTi) split ring resonators (SRR) which transforms to complete ring resonator (CRR) thermally, the resonance wavelength and its modal behaviour are affected. Furthermore, the chiroptical activity of planar optical metasurfaces composed of L-shape heterogeneous (Ag-VO₂) dimer is studied as well. It is shown that by increasing temperature from room temperature to 81°C , the observed optical activity (OA) at 690 nm has been raised ~ 50%, because of the occurred phase transition.

1. Introduction

Nowadays, metamaterials and metasurfaces have emerged as artificial elements which have great impact on manipulating of incident fields. These structures composed of sub-wavelength resonators have been introduced in broad range of frequency from microwave to optic. The conventional metamaterials and metasurfaces exhibit fixed characteristics after fabrication which is undesirable in many applications where a degree of freedom is necessary. Tunable metamaterials and metasurfaces are appropriate solutions to cope with this problem. The interaction of these tunable structures with incident field can be actively controlled by an external stimulation. Various approaches have been exploited to obtain tunability in metamaterials and metasurfaces which are categorized in two main groups namely configuration of structure and changing the electromagnetic properties of substrate and resonators. Polydimethylsiloxane (PDMS) which is highly flexible polymer is categorised in the former group. Since this material is stretched in any direction mechanically, it is a good candidate for substrate using in tunable metamaterials and metasurfaces [1]. Moreover, insulator-metal-transition (IMT) materials which are a class of phase-transition materials have attracted increasing interest in the recent years. Among them, Vanadium dioxide (VO₂) is in the center of attention because of changes in its electrical properties near room temperature [2]. Phase transition may accompany different macroscopic effects. For instance, Nitinol (NiT) which is a conventional form of shape memory alloys
SMAs) thermally changes its shape, used in tunable metamaterials and metasurfaces [3]. In this paper, metasurfaces consist of aforementioned materials have been considered. These materials can be stimulated thermally and mechanically leading to a metasurface with tunable EM properties, in terahertz and optical regions.

2. PDMS: Highly Flexible Material

A highly tunable metasurface with an array of a nested double U-shaped nano-resonators as comprising elements on PDMS substrate is shown in Fig.1 (a). PDMS has distinguished features namely low dielectric loss, low thermal conductance and excellent mechanical durability. Thanks to the latter one, this polymer can be mechanically stretch in any direction which leads to tunable interaction with incident field. In the proposed structure [1], the reflectance and transmission of EM-wave can be remarkably altered by mechanical stretching a PDMS substrate of the metasurface, causing a controllable gap between the two strongly coupled resonant-U structures. This controllable gap plays significant role in corresponding variations in the equivalent capacitance and inductance among U-shaped elements which has great impact on shifting resonance frequency (Fig. 1(b))

Fig. 1 (a) Schematic of the metasurface designed based on the NDU array on PDMS substrate and the direction of the mechanical stretch. (b) Tunable reflection spectra of the metasurfaces based on the proposed NDU, under applied strain (initial: green-curve, 20%: blue-curve, 50%: red-curve, relaxed: dark-curve) along the incident-wave polarization [1].

3. NiTi: Shape Memory Alloy

One of the most conventional shape memory alloys is NiTi which manifests typical thermal hysteresis behaviour in its phase transition properties between two distinct temperatures: Austenite (51°C) and Martensite (31°C). In this section, a metasurface composed of NiTi ring type structure is considered. The geometry and dimensions of this structure is shown in Fig.2.

Fig. 2 (a) Schematic of a metasurface composed of CRR made of NiTi in high temperature (w=6 μm and r=44 μm) with the lattice constant \( a = 140 \) μm. By increasing temperature, the CRR transforms to SRR. (b) Schematic of a metasurface composed of SRR made of NiTi in low temperature (w=6 μm, r=44 μm and g=10μm) with the same lattice constant.
The electrical permittivity of the ring type structure in Austenite and Martensite temperatures were extracted from [3] and used in related simulations. As seen in Fig.2 (b), the resonator is a split ring resonator (SRR) in low temperature (a gap in y-direction) which shows transition behaviour to a complete ring resonator (CRR) by increasing temperature (Fig.2 (a)). The incident field with different modes (TE and TM modes) is illuminated on proposed metasurface (-z direction) and transmission and reflection spectra in two aforementioned cases (CRR and SSR) are depicted in Fig.3 (a). The NiTi CRR shows the same behaviour in TM and TE mode of incident field resonates at 400μm, which stems from symmetry in this case. By decreasing the temperature, the NiTi CRR transforms to SRR. In this case by illuminating the NiTi SRR with TM mode, one resonance takes place in obtained spectra. The observed resonance of NiTi SRR can be attributed to the second (higher-energy) resonant mode of the SRR, as its electrical field distribution at resonance wavelength is shown in the inset of Fig.3 (b). However, in this case it is inferred that the first resonance is out of the wavelength range in which the electrical permittivity of NiTi is available. It is noteworthy that in TE mode, the wavelength resonance of NiTi SRR is as same as NiTi CRR.

![Fig.3. Transmission and reflection spectra of metasurface composed of NiTi in (a) high temperature and (b) low temperature.](image)

4. VO₂: Insulator-Metal Transition Material

VO₂ is an IMT material in which an abrupt change in structure and electrical properties happens thermally. This material is a monoclinic insulator at room temperature and converts to a rutile metallic structure by increasing temperature (82°C). This transition accompanies striking variations in its optical and electrical properties which make this material preferable in tunable metamaterials and metasurfaces. In [4], the interactions of electromagnetic waves with VO₂ nanoparticles in optical and millimeter wave ranges have been explored. However, in this section the chiroptical properties of metasurface composed of L-shape heterogeneous (Ag-VO₂) dimer is studied. Although the metasurface with Au-Ag L-shaped dimer as comprising elements exhibit chiroptical activity, this characteristic is unchangeable after fabrication [5]. The introduction of VO₂ to this type of metasurfaces leads to variation in optical activity as VO₂ undergoes insulators to metal transition. Fig. (4) shows the geometry of proposed structure. In order to investigate temperature effect on chiroptical characteristics, the electrical permittivity of VO₂ at room temperature and above Tc are used [6]. According to previous literatures, 2D structures show different behaviour before right hand and left hand polarization incident fields which manifests itself in transmission conversion [6]. This parameter is known as optical circular conversion dichroism (O-CCD) and defined as: $T_{RL} - T_{LR}$. The result show that by increasing temperature from room temperature to 81°C, the observed optical activity (OA) at 690 nm has been raised ~ 50%, because of the significant changes occurred in optical properties of VO₂ nano bar.
Fig. 4 (a) Schematic of a metasurface composed of L-shaped heterogeneous (Ag-VO$_2$) dimers (W=20 nm, L=100 nm and G=10 nm) with the lattice constant $a = 300$ nm. (b) Optical spectra of polarization conversions caused by optical activities in two different states of VO$_2$ (insulator/metal). It is evident that metasurface in the metallic state of VO$_2$ shows more efficient conversion than insulator phase.

5. Conclusion

To summarize, we have shown that EM interaction of metasurfaces and metamaterials composed of micro/nano-structures as comprising elements with incident field can be actively tuned by using substrate or resonant structures consisting of functional materials such as polydimethylsiloxane (PDMS), Vanadium-dioxide (VO$_2$), and shape memory alloys (SMAs). These materials are stimulated by an external excitation such as mechanical stretch, heating and cooling. As a result, electromagnetic or optical properties of these metasurfaces are efficiently controlled. The effects of smart materials used in metasurfaces structures are obviously observed in transmission, reflection spectra as well as the resonance frequency and wavelength.

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