INTEGRATING MICROSYSTEMS WITH METAMATERIALS TOWARDS METADEVICES

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ABSTRACT

Metamaterials, artificially engineered materials with extraordinary and controllable effective properties, have expedited the development of photonic and optical devices. The electric permittivity and magnetic permeability of metamaterials can be tailored efficiently by changing the structural design of metamaterials. Recent research has mainly focused on tunable, reconfigurable, and nonlinear metamaterials towards the development of metamaterial devices, namely metadevices. Microsystems, or microelectromechanical systems (MEMS), provide powerful platforms to control the effective properties of metamaterials and integrate various functions into metamaterials. In this paper, we present the fundamentals of metamaterials, integration schemes of MEMS and metamaterials, and outlooks for metamaterial enabled photonic devices.

KEYWORDS

Microsystems, MEMS, metamaterials, metadevices,

INTRODUCTION

Electromagnetic metamaterials are an important type of artificially engineered materials composed of arrays of subwavelength unit-cell structures with tailorable effective optical properties, such as effective permittivity and permeability. The responses of metamaterials mainly depend on the structural design of the unit cells rather than their chemical composition, enabling flexibilities in designing their effective optical properties across the entire EM spectrum from low to high frequencies [1-4]. Starting from the experimental realization of negative refractive index [5], which existed in theory for a long time [6], metamaterials have enabled a wide range of appealing applications, including invisibility cloaking [7], superlensing [8], and perfect absorption [9], with their engineered properties. To further enhance the functionality of metamaterials, recent research is gradually focusing on tunable, reconfigurable, nonlinear, and sensing metamaterials and shifting from fundamental research to practical applications, which is boosting the development of metamaterial devices, or metadevices [10]. In metadevices, metamaterials with dynamically tunable properties enables the modulation of the amplitude and phase of electromagnetic waves and the manipulation of near-field interactions and nonlinear responses. Compared to functional optical devices constructed with natural materials, metadevices exhibit larger tunability, more compact dimension, and higher degrees of freedom.

The principle of tunable metamateirals was developed in the infant stage of metamateirals and was first demonstrated via electrical gating [11]. In this initial work, a terahertz metamateiral was patterned on the GaAs substrate. By applying a bias voltage , the electric property of the GaAs in the vicinity of the metamaterial was modulated, which in turn tunes the responses of the metamaterial, including the resonant frequency, amplitude, or phase. Following this work, reconfigurable magnetic responses, chirality, absorbance, and beam steering have been enabled by changing the material properties of the metamaterial unit cells [10].

In addition to changing the properties of the materials that comprise the metamaterials, mechanically changing the structure of the compositing unit cells is an alternative approach to modulate the metamaterial response [12]. As compared with tunable metamaterials enabled by their material properties, mechanically tunable metamaterials are more stable and more accessible to individual meta-atoms, and also capable of achieving larger dynamic range and tunability, such as broader frequency tuning ranges. Integrating metamaterials with MEMS makes mechanically reconfiguring the electromagnetic response possible. Moreover, the micromachining process widely employed in MEMS advances the development of metamaterials [13]. For example, flexible and tunable metamaterial perfect absorbers have been developed using the surface micromachining processes. A variety of functionalities can be achieved with the tunable metamaterials and will be introduced below.

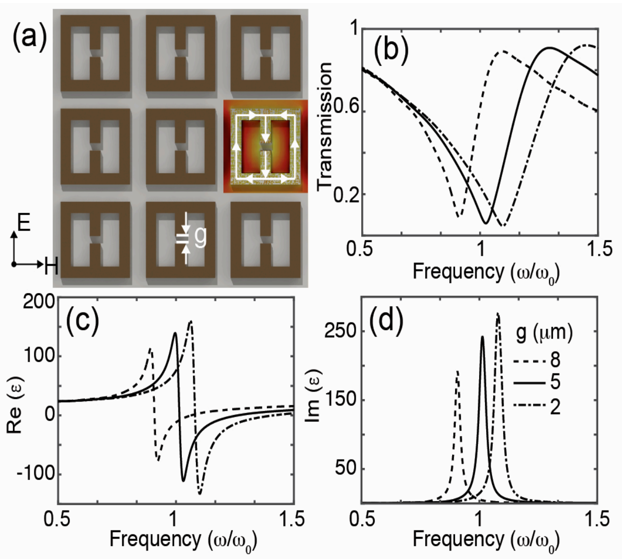

Figure 1. (a) A typical metamaterial consisted of electric split ring resonantors. (b) The simulated transmission response of the metamateirals. The real part (c) and the imaginary part (d) of the effective permittivity extracted from the metamaterial response.

In order to validate the effect of the mechanical modulation, we studied the response of a typical metamaterial via simulation. As shown in Fig. 1a, an array of electric split ring resonators (ESRRs) forms a typical isotropic metamaterial. For a specific geometry, a dip is observed in the transmission response, as shown in Fig. 1b, corresponding to the LC resonant mode of the metamaterial. The resonance frequency is determined by the effective inductance and capacitance in the equivalent circuit mode of the unit cell. The variations in the unit cell dimension induce changes in the effective inductor and capacitor. As the gap in the metamaterial unit cell increases, the resonant frequency of the metamaterial shifts to higher frequencies since the effective capacitance decreases. The effective properties of the metamaterials can be extracted by fitting the simulated metamaterial response. As shown in Figs. 1c and 1d, metamaterials exhibit Lorentz-like complex effective permittivity. For instance, the real part of the permittivity can be tuned from negative to positive. The results demonstrate that we can efficiently manipulate the effective properties of metamaterials by altering the structural design of the unit cells. In the following section, different approaches for tuning the metamaterial properties will be presented.

TUNING MECHANISMS

A variety of MEMS actuation mechanism are compatible with metamaterial design and can be employed to tune the response of metamaterial efficiently, as shown in Fig. 2. Some implementation schemes are detailed in the following subsections.

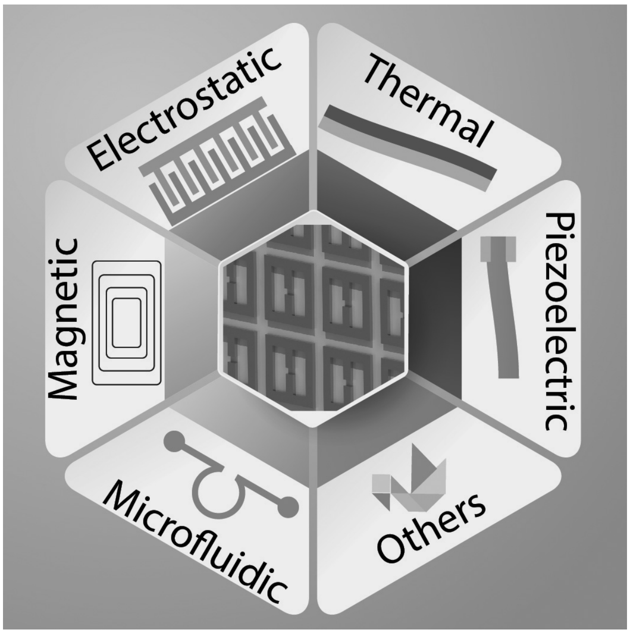

Figure 2. Different actuation mechanisms, including electrostatic, thermal, piezoelectric, and magnetic actuators, microfluidic channels and other structural designs (e.g., flexible and origami), can interact with meta-atoms to produce metamaterials with nontrivial tunability.

Comb-drive actuators

Comb-drive actuators are widely employed as sensing and actuating mechanisms in microsystems, including gyroscopes, RF switches, and micromirror s and scanners, etc. [14] Comb-drive actuators can accurately generate large in-plane and out-of-plane linear displacement as well as rotations. A well-designed comb-drive actuator can be employed to uniformly drive the deformation of unit cells in the metamaterials. For example, the in-plane comb-drive actuator has been used in actuating the capacitive gap of the split ring resonators to form a frequency tunable metamaterial [15].

Other than single layer metamaterials, comb-drive actuators can be employed to modulate the response of the metamaterial consisting of dual-layer metamaterials [16]. We fabricated one layer of split ring resonators (SRRs) with a silicon comb-drive actuator and another layer of fixed split ring resonators on a silicon nitride thin film, followed by bonding the two layers to form a broadside coupled metamaterials. The unit cell is illustrated by the inset in Fig. 3a. There are strong magnetic and electric coupling between the two layers. The coupling factors α and β denote the magnetic and electric coupling factor. By actuating the movable layer along x direction to generate a lateral displacement (Δ), the coupling factors can be altered, thus the response of the metamaterial is modulated. We can calculate the change of coupling factors using Lagrangian approach [17]. When the SRRs are aligned, the magnetic coupling factor is positive while the electric coupling factor is negative, and the coupling effect is strong. In the frequency response (Fig. 3b), there are two resonant dips due to the frequency splitting induced by the strong coupling. As the lateral displacement increases, the coupling effect decreases and the resonance frequency merges together. When the lateral displacement is ~18 μm, the coupling factors become zero, indicating negligible coupling between the two layers. From the transmission response for varied lateral displacement, the capability of tuning the metamaterial response using MEMS actuators has been demonstrated.

Electrostatic cantilevers

Another widely employed MEMS actuators is the electrostatic cantilever. One major application is the radio frequency (RF) switches [18]. The cantilever, with the compact form factor, can be integrated in the metamaterial unit cells [19].

One example of cantilever-based metamaterials is the tunable transmission quarter waveplate [20]. As shown in Fig. 4a, a copper cantilever array was patterned on a slightly doped silicon substrate, which was coated with a 400-nm-thick silicon nitride insulation layer. The cantilever response varies as the incident polarization angle changes, due to anisotropic properties of the metamaterial unit cells. For the x-polarized incident wave, the transmission response exhibits a strong resonance, which can be modulated by actuating cantilevers, as shown in Fig. 4b. For the y-polarized incident wave, the metamaterial exhibits no resonance in the terahertz frequencies, independent of the applied voltage to the cantilevers. Anisotropic properties of the cantilever metamaterial give rise to the ability of polarization conversion. As shown in Fig. 4c, when there is no voltage applied, the linearly polarized incidence can be converted to circular polarization. As the voltage increases, the polarization of the transmission changes to elliptical polarization gradually. When the voltage is 40 V, i.e. the pull-in voltage of the cantilever, the transmission is a linearly polarized wave.

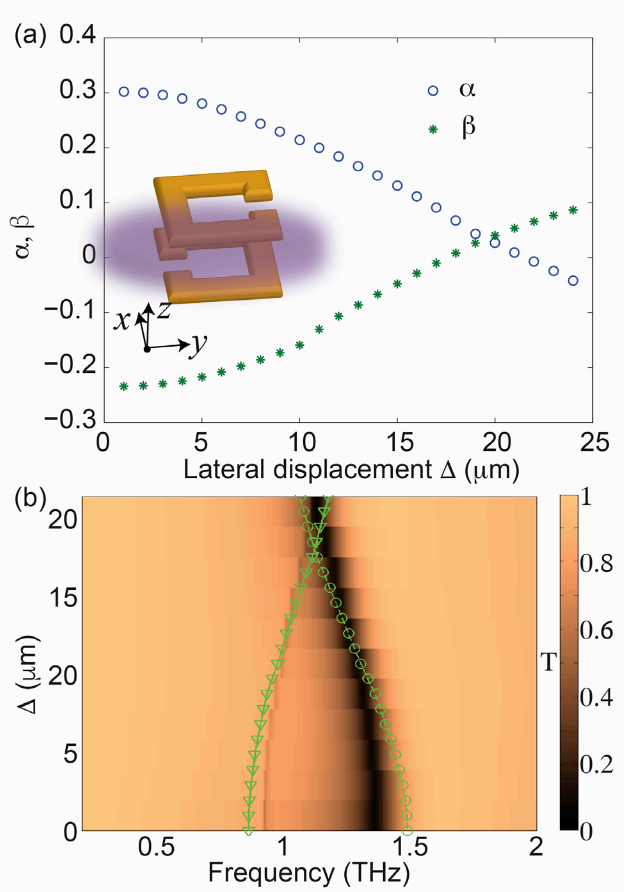

Figure 3. (a) The magnetic and electric coupling factor for the broadside coupled split ring resonators (BC-SRRs) with varied lateral displacements. Inset: the unit cell of the BC-SRRs. (b) The transmission response of the BC-SRRs for different lateral displacement. The green line represented calculated resonance frequency based on Lagrangian theory.

In addition to polarization conversion in transmission, the cantilever-based metamaterials can switch the polarization operating in reflection mode [21]. In theory, the cantilevers integrated with metamaterials also achieve tunable wavefront deflection, focusing, and hologram generation.

Thermal actuation and others

In addition to electrostatic actuators, thermal actuation is another important driving mechanism used in MEMS. Thermal actuation utilizes the differences in the thermal expansion of materials to generate mechanical displacements using temperature fluctuations. For example, a bi-material cantilever was integrated with the unit cells of the metamaterial, such as SRRs [22]. The response of SRRs highly depends on the angle between the incident wave and the plane of SRRs. When a temperature increase was applied to the metamaterial, the metamaterial unit cells bended up, which altered the angle between SRRs and the

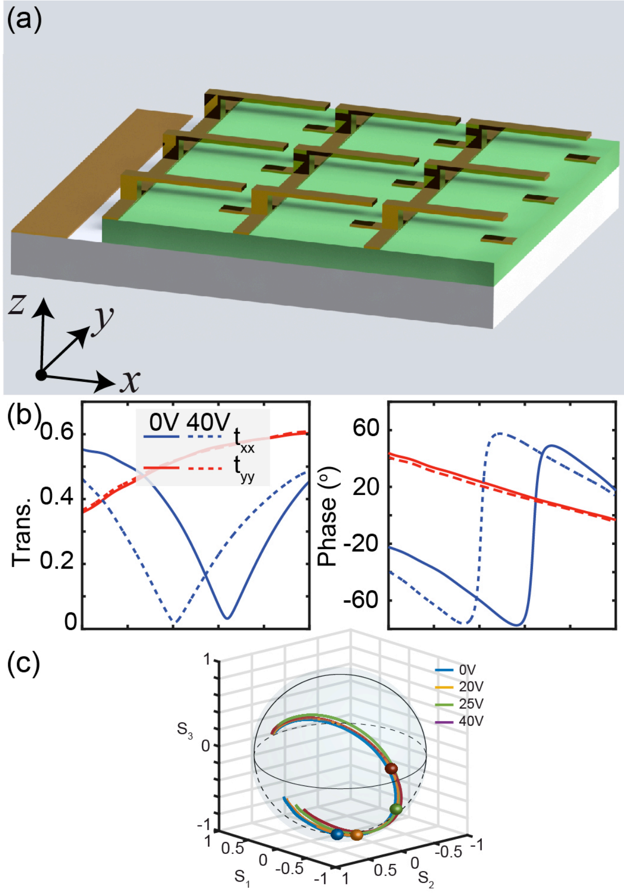

Figure 4. (a) Schametic of the cantilever metamaterials. (b) The amplitude and phase of tranmission response at varied applied voltages. (c) The Poincare sphere plot of the metameteiral transmission response at different voltages, desmonstrating the tuanble quarter waveplate.

incident wave. The transmission amplitude of the metamaterial can be efficiently modulated. Thermal actuation is a candidate to detect electromagnetic radiation. Metamaterial absorbers can be integrated with the bi-material cantilever [23] working as a detector. The metamaterial interacts with the incident electromagnetic wave, absorbing the radiation. The absorbed radiation was converted to heat via the Joule heating effect. The thermal energy changes the curvature of the bi-material cantilever, which can be measured to detect the electromagnetic radiation.

Magnetic and piezoelectric actuation also have significant potential in metadevice applications. Magnetic actuation is based on the Lorentz force experienced by a current-conducting wire under an external magnetic field, which can induce the magneto-optical effect when integrated with metamaterials [24]. Piezoelectric actuators can be integrated into metallic metamaterial unit cell to control the unit cell geometry, similar to the electrostatic cantilevers [25]. Besides solid-state actuators, microfluidic channels can be patterned into an array, which carries liquid metals to form electromagnetic metamaterials [26]. By controlling the shape and filling ratio in the arrayed fluidic channels, the response of the metamaterials can be tailored. Recently, the emergence of novel mechanical structural designs, such as microscale and nanoscale origami and kirigami, provides an efficient way to achieve mechanically tunable metamaterials [27, 28].

CONCLUSION

Different actuation mechanisms used in MEMS have been integrated with metamaterials to construct metadevices, which can efficiently manipulate the amplitude, phase, absorption, and polarization state of electromagnetic waves. Future efforts in integration of metamaterials with MEMS will be focused to control the response of metamaterial unit cell, forming randomly accessible metamaterials (RAMMs), to achieve on-demand optical response of the metamaterials. The RAMMs will allow dynamic beam forming, including beam focusing and steering, holographic imaging, and orbital angular momentum generation, by controlling the actuation via the MEMS actuators in a single device. Such devices may advance the development of some crucial systems, such as light detection and ranging (LiDAR) and 5G communication.

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