A Flat Lens with Tunable Phase Gradient by Using Random Access Reconfigurable Metamaterial

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The concept of metamaterials, electromagnetic media structured on sub-wavelength scale, has created a platform of new opportunities for manipulating light across the entire electromagnetic spectrum. Metamaterial with manageable dispersion allows access to unusual permittivities and permeabilities, leading to negative index,[1,2] zero epsilon,[3] giant chirality,[4] or exotic and useful hyperbolic dispersion anisotropy.[5] Metamaterials can form “invisible” metallic structures and exhibit extraordinary resonant transparency.[6–9] Controlling boundary conditions with metamaterial offers perfect absorbing media[10,11] and “magnetic” mirrors.[12] Metamaterials are now widely exploited to enhance nonlinear, switching and light emission[13] performance of conventional active materials. Metamaterials allow waveform manipulation[14] and offer exciting opportunities for cloaking,[15,16] waveguiding,[17] and localization of light. Moreover, metamaterials are now used as a platform for exploration and modeling of new physical effects[18,19] and developing practical sensor solutions.[20,21] These thrilling technological prospects have stimulated a wide search for developing metamaterials with tunable and switchable properties using Microelectromechanical Systems (MEMS), phase change media, liquid crystal, magnetic media, and superconductors.[22–26] Efficient modulation of reflection of metamaterial array in the terahertz and sub-terahertz parts of the spectrum can also be achieved by injecting current into the supporting semiconductor substrate[27] or into a wire loop continuously connecting all metamolecules.[28] In addition, controlling physical shape or mutual position of metamolecules in metamaterial arrays allows for a very efficient tuning of their characteristics, which can now be achieved with megahertz bandwidth in the optical part of the spectrum.[28]

One of the most exciting breakthroughs based on metamaterials is the planar lens. Traditional optical lenses tailor the incident wavefront by accumulating the spatial phase difference induced by their geometries, which are typically difficult to be manufactured, e.g., aberration-free lens. Furthermore, the tunability of traditional lens is limited by the low refractive index contrast and mechanical properties of the transparent materials available in nature. Therefore, compact lens arrays are required for most lens-based devices such as cameras and microscopes, which are difficult to be minimized. Researchers are now exploring planar metamaterials with spatially variable characteristics as diffraction grating[10–12] and for focusing.[33–35] The planar metamaterial lenses tailor the wavefront by spatial phase gradient induced by the predesigned metamolecules, which cannot be tuned once fabricated. The ability to control resonant properties of every individual metamolecule in a planar metamaterial will offer an ultimate freedom for dynamically shaping wavefronts via reconfigurable spatial phase gradient, which is essential for applications such as tunable flat lenses, dynamic holograms, spatial intensity, and phase modulators with sub-wavelength pixilation. However, metamolecules in a planar array are difficult to be individually tuned using current techniques based on integrating lump active elements in the metamolecules (transistors or diodes), current injection, or suppression of superconductivity. Those methods depend for modulation on undesirable Joule losses[16,17] and require a network of wires, individual electrical connections to all metamolecules,

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which will inevitably interfere and could spoil electromagnetic resonant properties of the metamaterial.

Here we report for the first time a proof-of-principle demonstration of a planar metamaterial where resonant properties of every individual metamolecule can be continuously controlled at will, which is called a random access reconfigurable metamaterial (RARM). RARMs are passive structures that are designed to control wavefront of external source of radiation. They shall be distinguished from phased antenna arrays that are active structures, shaping radiated pattern by controlling phase and intensity characteristics of every emitter through a complex feed arrangement. Using the developed RARM, we also provide the first demonstration of a metamaterial lens that is tunable in focal distance at will. To achieve RARM, we have created an array of cavities that can be filled with liquid metal[38–41] in a controllable fashion[42], using microfluidic technology and pneumatic valves. A microfluidic network addressing every individual element of the array provides the mechanism to dynamically change the filling factor of resonators and thus their resonant electromagnetic properties at will, continuously and with random access. Such individually addressable cavities of sub-wavelength size form a metamaterial array of sub-wavelength resonators where modulation of transmitted wavefront is achieved practically without Joule losses[43] via changing the spatial phase gradient of the array. Our metamaterial does not have massive moving parts characteristic to comb-driven MEMS metamaterial[44] while by using pneumatic valves the proposed solution minimizes the network of conductive elements that could disturb electromagnetic properties of the array and can be used with metamolecules of broad variety of shapes, from simple antennas to complex connected and disconnected 3D structures. Our proof-of-principle demonstration is based on microfluidic elements allowing RARMs operating in microwave regime. However, with recent progress in nanofluidics (for instance, the flow of liquids through carbon nanotubes is being investigated)[45] one can envisage a realization of nanocapillary RARM that could translate the concept into higher frequencies, including the optical range.

The metamaterial reported here consists of a 2D square array of metallic split rings and two perpendicularly placed metal gratings (Figure 1a). The metal gratings consist of 1 mm wide copper wires with period spacing of 2.5 mm, which is fabricated on 0.635 mm thick Taconic substrate (TLY-5-520, $\varepsilon_r = 2.2$). The split ring element has a radius of 2 mm in a 60 × 60 lattice with periodic spacing of 5 mm, which has a total footprint of 300 mm. It is designed to operate in the GHz range from 12 to 18 GHz (Ku band). The split ring metamolecules are formed by filling liquid mercury into the ring-shaped microcavities. If completely filled with mercury the ring metamolecule exhibits a dipole absorption resonance at the wavelength linked to the half-length of the ring. The resonance wavelength can be progressively reduced if a section of the ring is removed by introducing a gap into the ring. This can simply be achieved by substituting the liquid metal in the cavity with a gas bubble. To create and control the gaps of the rings individually, they are connected by microchannels to pneumatic valves, which regulate air pressure in the channels. By increasing the pressure in the channel, air pushes mercury away from the ring cavity, substituting it with an air bubble (Figure 1b-c). The process can be made continuous and fully reversible by changing the balance of air and mercury pressures. Here mercury is chosen for its low melting point (−38.8 °C) and high electrical conductivity (1.04 × 106 S m−1), which is only one order of magnitude lower than that of copper (5.96 × 107 S m−1). The metamaterial is supported on a polymethyl methacrylate (PMMA, $\varepsilon_r = 2.57$) substrate of 1 mm thickness while the architecture of microchannels and cavities is imbedded into a polydimethylsiloxane (PDMS, $\varepsilon_r = 2.69$) layered structure of 2 mm thickness. Ring cavities are located in the layer bonded with the PMMA substrate that also hosts mercury filling channels. Narrow air channels directed across the rings connect each cavity with the vertical air loading channels that are linked to the pattern of pneumatic valves and air inlet in the layers above. The control system is fabricated within a PDMS layered structure of 1 mm thick. In the heart of the air control system is a purpose-designed ternary valve multiplexer, addressing metamolecules in the array individually (see details in the Supporting Information, Figure S2). The metamolecules are different row by row along the $x$-direction, which creates a 1D spatial phase distribution.

Here, we illustrate the opportunities provided by the flexibility of random access metamaterial by functionalizing it into a tunable flat lens (Figure 2). The microfluidic layer with liquid metal rings functions as a polarization converter of the linear polarized excitations as the slope angles between the symmetric axes of the rings and the incident electric field are

![Figure 2](image-url)

**Figure 2.** Schematic of tunable flat lens. a) The randomly addressable metamaterial can be used as a flat lens with tunable focal distance when resonant properties of a split ring in the array are altered by changing the metal filling fraction. The RARM is formed by loading liquid metal into the ring microcavities fabricated in transparent dielectric. b) The liquid metal (light grey) is injected into the microchannels and filled in the wide channels with controlled pressure. c) The gap is defined by regulating air pressure in the pneumatic valves, injecting air (dark grey) from the narrow channels. d) The extra liquid metal in the wide channel are expelled by air.
either 45° or 315°. The two metal gratings enhance the cross-
polarization transmission due to the Fabry–Pérot resonance. The phase and amplitude modulations of the transmitted electromagnetic wave are highly depending on the gap opening of the metamolecules. Figure 3a shows the phase and amplitude of the cross-polarized transmission as functions of the gap openings and orientations of the metamolecules. Here, the incident electric field is along the y-direction with the frequency of 16 GHz. The metamolecules with different gap openings are numerically characterized under periodic boundary conditions. The transmission phase can be tuned continuously with a range of 2–π while maintaining the normalized amplitude larger than 0.7. Figure 3b,c shows the phase profile when the incident wave passed through each metamolecule. Here, the wavefront can be tailored via changing the gap opening and orientations of the metamolecules individually. For the purpose of demonstrating a convex lensing function, the incident wave frequency was chosen at 16 GHz.

Experimental results of electromagnetic wave focusing with RARM are presented in Figure 4. Here the metamaterial is illuminated by a plane wave that propagates along z-direction, normal to the plane of the metamolecules array and is polarized along the y-direction. All measurements are performed in a microwave anechoic chamber using a vector network analyzer with horn antenna as the wave source and a monopole antenna mounted on an xy scanner as a probe. To map the transmitted field, the receiving probe is scanned at different z distances from the sample with steps of 5 mm. During the experiment, the air inlets are sealed using the microplugs for the sake of the stability and safety issues. The experimental results and the corresponding simulation results of different phase gradient distributions are shown in Figure 4a–c, when the designed focal length is 5λ, 10λ, and 15λ, respectively. The 3D full Maxwell numerical modeling of the electric field intensity distributions at xz plane are shown in the first column to compare with the experimental results of xz plane and xy plane in the second and third columns, respectively. The simulation is done by using Computer Simulation Technology (CST) microwave studio with the periodic boundary along y-direction and open boundary along x- and z-directions. The diffraction efficiency of the flat lens is defined as η = P/Pi, where P1 and P0 are the total optical power measured at the hotspots and total input power measured without the sample, respectively. In the experiment, the measured diffraction efficiency is approximately 10%, which is much larger than most flat lens design. The diffraction efficiency can be further increased by maintaining the transmission coefficient during the gap tuning, which can be realized by the optimization of the cavities. The corresponding spatial phase distributions are shown in the fourth column, which are
obtained by hyperbolic lens equation. The $xz$ and $xy$ cross-sections illustrate that the beam can be confined into an intensity linear hotspot with FWHM $= 2.1 \lambda$ when the measured focal length $F = 5.1 \lambda$. Figure 4a–c shows that the focal length $F$ can be tuned from $5.1 \lambda$ to $15.2 \lambda$ by adjusting the spatial phase gradient. Here, the focal length is defined as the distance between the central of the hotspot and the surface of the flat lens. The measured focal lengths agree with the 3D simulation well as shown in Figure 4.

In conclusion, a RARM formed by casting liquid metal microwave resonators through microfluidic channels is demonstrated to have function as reconfigurable wavefront manipulation, which has been illustrated by showing a tunable flat lens. The RARM can be used as densely integrated tunable lens array, which has potential applications in high resolution display, sensor, and imaging systems. We expect that in the future RARM will be developed for the entire electromagnetic spectral range up to optical frequencies. This will make possible various applications such as 3D holographic displays for mobile phones, high-performance devices for space division multiplexing in the next generation telecommunication networks, and adaptive wavefront correction devices, to name just a few.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Note: The author first names were missing from the author byline on initial online publication; these were added on August 20, 2015; Figure 1 and 3 were also reset.

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