TUNABLE FLAT LENS BASED ON MICROFLUIDIC RECONFIGURABLE METASURFACE

W. M. Zhu1, Q. H. Song1,2, L. B. Yan1, W. Zhang1, P. C. Wu1, L. K. Chin1, Z. C. Yang1, Z. X. Shen1, T. W. Deng1, S. K. Ting1, H. Cai1, Y. D. Gu3, D. L. Kwong3, T. Bourouina2, Y. Leprince3 and A. Q. Liu1†
1School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798
2Université Paris-Est, UPEM, Marne-la-Vallée, Paris F-77454, France
3National Key Laboratory of Science and Technology on Micro/Nano Fabrication Institute of Microelectronics, Peking University, Beijing 100871, China
4Temasek Laboratories, National University of Singapore, Singapore 117411
5Institute of Microelectronics, A*STAR (Agency for Science, Technology and Research) Singapore 117685

ABSTRACT
A tunable flat lens is demonstrated based on reconfigurable metasurface, which is realized via changing the phase gradient of the metasurface in sub-wavelength level. The sub-wavelength metamolecules are formed by enclosing a liquid metal plug within microfluidic cavities, which can be tuned by changing the geometry of the metamolecules. The tunable flat lens is consisted of soft material with controllable functionalities. In simulation, the tuning of the focal length from 5λ to 7λ is demonstrated as the proof of concept. This reconfigurable metasurface can be used as a standard guideline to design different electromagnetic wave manipulation systems in realizing the dynamic control of beam steering, anti-reflection and focusing functionalities etc.

KEYWORDS
Optofluidic metamaterials, microfluidic, metasurface

INTRODUCTION
The history of the lenses can be dated back thousands of years ago, which is among the earliest technologies developed by human beings [1, 2] Nowadays, lenses technology has been applied to vast applications, which not only better our daily life but also function as scientific tool for us to further explore the world. The functions of lenses are now more complex than a simple magnification or a solar light focusing device discovered by ancient Egyptian and Greek. Complex lenses systems with several lenses are required for single functions such as camera, telescope and microscope etc. Therefore, the sizes of the lenses systems have now become bottlenecks of the compact design of most optical devices using lenses system. For example, the thicknesses of most smart phones are limited by the length of the cameras, which cannot be further miniaturized due to the number and thicknesses of the lenses used in cameras. As the current lens making technology is reaching the physics limitation of the traditional lenses, lenses based on new physics principle is a desire to fulfil the everlasting demands of lens systems with more compact sizes and multiple functionalities.

Metamaterials allow waveform manipulation and offer exciting opportunities for cloaking, waveguiding and localization of light. Moreover, metamaterials are now used as a platform for exploration and modelling of new physical effects and developing practical sensor solutions. Metasurface has now been intensively studied as a promising paradigm for lenses designs, which enables us to engineer the spatial distribution of the amplitude, phase and polarization response of the incidence using sub-wavelength optical scatters named as metamolecules [3-10]. The phase changes induced by the metasurfaces are resulted from the interaction between the metamolecules and the incident light other than the propagation effects as in the traditional lens and phase shifters. The metasurfaces can be made smaller than wavelength as only one layer of metamolecules are required, which can be either metal particles or apertures on metallic films with sub-wavelength sizes. The metasurface offers a promising approach for the design of an optically-thin lens with desired phase and amplitude modulation of the incidence. For example, the metasurface lenses [11, 12] are possible to be used for compact lens systems design by reducing the sizes and number of the lenses, which cannot be achieved by using traditional curved lenses. However, the abrupt phase change induced by the metasurface is highly dependent on the resonance nature of the metamolecules, which makes most of the current metasurface designs not only low in efficiency, but also highly dependent on the frequencies and polarization states [13-18]. The most feasible solution to address those issues is to use reconfigurable metasurface, which can be adapted according to the incident wavelength. More importantly, the reconfigurable metasurface offers dynamically controlling of the phase and amplitude modulation of the incidence, which results in multiple functionalities [19, 20]. Therefore, ground-breaking researches for reconfigurable metasurfaces that can achieve these unmet objectives are in strong demands for practical applications of the metasurface flat lens. Here we report a proof-of-principle demonstration of a planar metamaterial where the shape and the resonance properties of every individual metamolecule can be continuously controlled by microfluidic system, which is called microfluidic reconfigurable metasurface and functions as a tunable flat lens.
Figure 1: The schematic of (a) the tunable flat lens. (b) the middle layer with reconfigurable open rings. The yellow parts represent the liquid metal which is controlled by the air pressure within the channels.

Figure 1 shows the tunable flat lens, which consists of a middle microfluidic metasurface layer and two metal gratings perpendicular to each other. The geometries of the metamolecules can be changed dynamically by shifting the liquid metal plugs within the microfluidic channels. The phase gradient is depending on the rotation angle and the shifting distances, which can be dynamically adapted to response different incident angles, frequencies and polarization states. Figure 1(b) illustrates the design of the tunable flat lens, which is made of a square array of metallic split rings in two dimensions. The split ring metamolecules are formed by filling liquid metal into the ring-shaped microcavities. When completely filled with the liquid metal, the metamolecule exhibits an electric dipole absorption resonance at the wavelength linked to the half-length of the ring. The resonance wavelength can be progressively reduced when a section of the ring is removed by introducing a gap into the ring, simply by substituting the liquid metal in the cavity with a gas bubble as shown in the inserts. The lens function is realized by changing the phase gradient to a hyperbolic profile.

Figure 2 shows the working principle of the tunable flat lens. In traditional curved lens, the required phase differences are accumulated by different optical lengths of the incident light using the various thicknesses of the lenses, which is very difficult to be reduced to sub-wavelength level.

RESULTS AND DISCUSSIONS

Figure 2 shows the working principle of the tunable flat lens with reconfigurable metasurface. The phase gradient of the tunable flat lens is controlled by the modulation of the sub-wavelength metamolecules.

Figure 3: The graph of the fabricated tunable flat lens. (a) The overview of the middle layer. The channels are fabricated on the PDMS cover which is bonded to PMMA substrate spin coated with PDMS. The (b) and (c) show the individually tuning of a metamolecule when the air is pumped into the open ring (b) and expelled from the open ring (c).
Figure 4: The measured (left column) and simulated (right column) optical intensity distribution of the tunable flat lens when the phase gradient is tuned. The focal length has been gradually increased from $5\lambda$ to $7\lambda$ as shown in (a) to (e), which show good agreements with the simulation results in the right column.

The low refractive indices contrast between air and most transparent materials in nature (Fig 2a) makes it difficult to achieve optically-thin flat lens using refractive optical components. The reconfigurable metasurface is realized by changing the phase and amplitude modulation of each metamolecules thus changing the phase gradient (Fig. 2b) and further increasing the freedom in controlling window. Figure 3 shows the liquid metal metasurface with a two-dimensional square array of metallic split rings. The split ring metamolecules are formed by filling liquid mercury into the ring-shaped micro cavities. 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 metasurface is supported on a Poly methyl methacrylate (PMMA) substrate of 1-mm thick while the architecture of micro-channels and cavities is imbedded into a polydimethylsiloxane (PDMS) layered structure. Figure 4 shows the simulated optical intensity distribution when the phase gradient of the metasurface flat lens is tuned. The incidence is plane wave with 15 GHz frequency. The focal length of the flat lens is tuned from $5\lambda$ (Fig. 4a) to $7\lambda$ (Fig. 4e) as shown in the right column. The left column shows the schematics of the equivalent refractive lens of the optofluidic metamaterials.

In conclusion, a tunable flat lens with liquid metal metasurface is designed, fabricated and experimentally demonstrated. We expect that in the future optofluidic materials 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, beam steering and adaptive wavefront correction devices, to name just a few.

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CONTACT
†A. Q. Liu, +65-67904336; eaqliu@ntu.edu.sg