Dynamically Controlling Electromagnetic Wave with Tunable Metasurfaces

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***Abstract*—Dynamic control of electromagnetic (EM) wave propagation (both the amplitude and phase) is essential to many practical applications. The recently developed two dimensional metamaterial — the metasurface, provides more convenient method to manipulate EM wave in a designable way within subwavelength distance. Here we incorporate electrical tunable elements into the metasurface designs to realize dynamic manipulation of EM wave propagation. We will show that the tunable metasurface inspired by the equivalent principle design can provide independent and dynamic tuning for the transmission magnitude and phase. Detailed theoretical analysis, simulation as well as experiment on prototype of tunable metasurfaces will be demonstrated. As an application example, we will also show our recent work on designing a planar Huygens lens that could achieve dynamic focusing through phase control of the metasurface.**

Keywords*—*metasurface; electromagnetic wave transmission; reflection; phase control; planar Huygens lens.

I. INTRODUCTION

Metamaterial — the concept of artificial material, has attracted enormous amount of interests in the passing decade due to its intriguing electromagnetic (EM) properties that have not been observed in existing natural materials. The large variety of the structured artificial 'atoms' that compose the metamaterials has promised different unexpected physical phenomena, ranging from the negative permittivity and permeability to invisibility cloaking of EM wave, which extend the ability of manipulating EM waves with great freedom [1-3].

Recently, a new branch of metamaterial family - the metasurface, has been developed which is an ultrathin sheet of periodic structure with reduced dimensionality. Such two dimensional concept has attracted much attention due to its great ability of controlling the EM wave flow distinctly different from those observed in the bulk counterpart, as well as its much convenience in fabrication [4-8]. For example, it has been found that the nonconventional far-field EM wave responses of ultrathin metasurfaces could deviate from classical reflection and refraction laws [4, 5].

Most of the metasurfaces are composed with subwavelength building blocks of passive metallic and dielectric resonators; therefore, once the structures are designed and fabricated, their EM properties and spectral responses cannot be changed. However, dynamic control of EM wave propagation is often demanded in many practical applications. Here in this presentation we will show our recent attempts to incorporate tunable or controllable elements into the metasurface designs to realize arbitrary and dynamic control of EM wave propagation. We will report our attempt on equivalent principle inspired tunable metasurface design. It enjoys the advantage of independent tuning for the magnitude and phase in either transmission or reflection. The equivalent principle is employed to analyze the required surface electric and magnetic impedances of a passive metasurface to produce either arbitrary transmission magnitude and phase or arbitrary reflection magnitude and phase. Based on this general design method we will also show an application example: a planar Huygens lens that is capable of dynamic focusing of the incident EM plane wave with tunable focal position.

II. ARBITARY CONTROL OF EM WAVE PROPAGATION

Transmission and reflection are two fundamental properties of the EM wave propagation through obstacles. Both of them can be characterized as complex quantities with both magnitude and phase. Arbitrary control of wave propagation means to have a full control for these four factors independently, which is often demanded in many EM engineering applications such as the reflect-array [4-6], EM absorber [7, 8], or frequency selective surface [9, 10], etc.

The equivalent principle is one of the fundamental theorem of electromagnetics [11]. It allows arbitrary electromagnetic field at both sides of a surface by introducing electric and magnetic current on the surface to satisfy the boundary condition of the field. Traditionally, this principle is mainly used in theoretical analysis because the effective magnetic current cannot be easily generated in non-magnetic medium. However, it inspires a new way to manipulate the transmission and reflection of the EM waves when combined with the metasurface concept. For example, a Huygens metasurface composed of both electric and magnetic dipoles can achieve certain surface electric and magnetic impedances [12]. Under the plane wave illumination, surface electric and magnetic current are induced, which can produce the scattered field so that total transmitted field has the designed wave front and the reflected field is suppressed. In fact, the metasurface employing the equivalent principle allows the independent design of the magnitude and phase in either transmission or reflection with its physical thickness much smaller than the working wavelength.

By rigorous analysis of a lossless metasurface with the equivalent principle, we can get the following equations that relate the required surface electric and magnetic impedance (Z_e, Z_m) of the metasurface to the given transmission and reflection coefficients (T, R), respectively:

$$Z_e=\frac{\eta}{2}\frac{1+(R+T)}{1-(R+T)},\quad Z_m=\frac{\eta}{2}\frac{1+(R-T)}{1-(R-T)}, \tag{1}$$

where, η indicates the free space wave impedance.

Now we consider to realize such a lossless impedance surface at microwave band to achieve both transmission phase and magnitude control. We propose a simple two dimensional periodic structure, as illustrated in Fig. 1(a). The unit cell is composed of an electric dipole-like element composed with parallel LC resonator and two identical magnetic dipole-like elements composed with metallic small loops so as to provide the needed surface electric and magnetic reactance. To dynamically control the EM wave propagation, we also incorporate active circuit elements into the unit cell. Here we employ several varactors integrated into the unit cells as shown in the Fig. 1(a) as pink blocks so that the surface impedance of the proposed metasurface can be dynamically tuned. The black lines stand for the high resistive bias lines to supply bias voltage on the varactors, which are almost transparent to the EM waves.

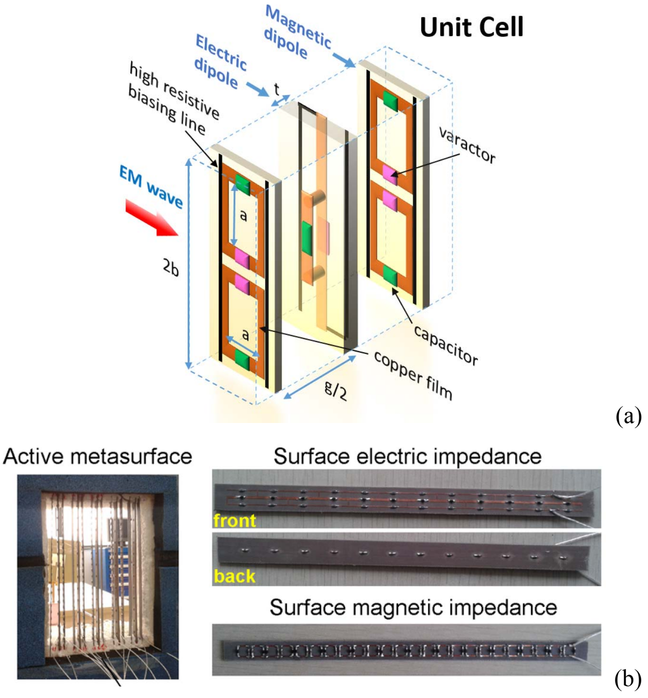

Fig. 1. Schematic of the proposed unit cell of the metasurface (a), and one of the fabricated samples (b) of the tunable metasurface that could achieve dynamic control of EM wave propagation.

By carefully choosing the geometric parameters and the capacitors of the LC resonator and metallic loops, we can change the surface electric and magnetic impedance of the whole metasurface to the required values for arbitrary transmission or reflection control. Furthermore, by biasing the varactor to tune its capacitance, we can dynamically adjust the resonance frequency of both the LC tanks and the loops, therefore the impedance curves can be shifted with respect to the frequency such that the metasurface's property can be adjusted. This feature can be used to easily generate the wanted scattering EM field distribution according to the EM equivalent principle. We will demonstrate the detail design procedure of the metasurface in the presentation to achieve arbitrary control of the transmission phase and magnitude.

As an example, we roughly show here one of the metasurface samples (shown in Fig. 1(b)) that can be used to continuously control the transmission magnitude while keep the transmission phase nearly zero. First, through (1) we can obtain the required electric and magnetic surface impedance, and then we construct certain unit cell and use equivalent circuit analysis to get the required geometric parameters and the capacitors in the unit cell. The practical tuning range of the varactors will enable the changing of the resonance of the surface impedance thus lead to a continuous variation of the transmission magnitude. Fig. 2 illustrates the calculated transmission magnitude and phase around the working frequency of 3 GHz for the ideal lossless metasurface design. The four curves correspond to different biasing on the varactors. It is found that the transmission magnitude can be tuned from 0.1 to 0.9 with the transmission phase close to zero at 3 GHz.

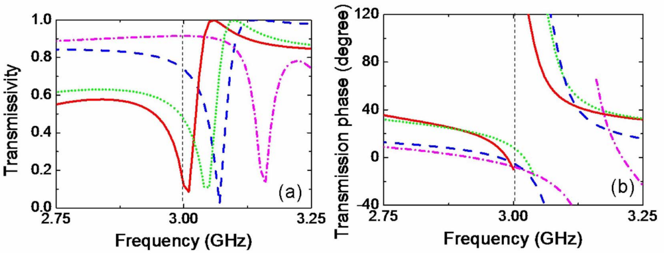

Fig. 2. Calculated transmission magnitude (a) and phase (b) on the designed metasurface around the working frequency of 3 GHz. The four curves correspond to different biasing on varactors.

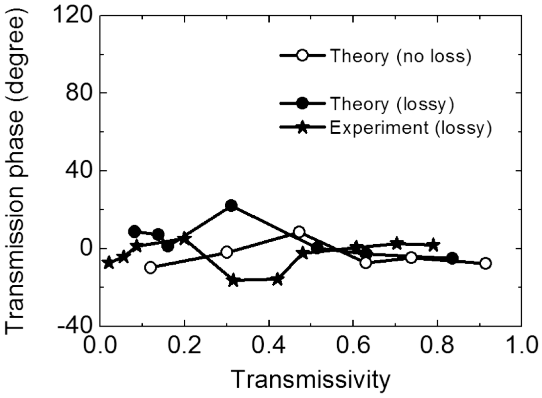

Fig. 3. Transmission phase variation at the working frequency while the magnitude is continuously changed.

To verify both the theoretical and simulation results, we fabricated the tunable metasurface and conducted transmission measurement. The substrate is low loss F4B board. The fabricated metasurface is composed of 5 by 12 unit cells. We measured the transmission of the metasurface in a microwave anechoic chamber with two lens antennas to validate our theoretical analysis and the design proposal, and the results are displayed in Fig. 3. We found that the experimental results roughly agree with the calculations for both lossless and lossy cases, which indicates that for the transmission phase near zero degree, the loss effect is trivial and the transmission magnitude has a large tuning range almost from 0 to 1. We will show more examples for the arbitrary and independent control of both the propagation magnitude and phase in the presentation.

III. EXAMPLE: DYNAMIC FOCUS OF PLANAR LENS

As we show in the previous section, we have proposed a scheme to design tunable metasurface so that the induced surface electric and magnetic currents can be tuned dynamically. By this way, we can independently and dynamically control either transmission magnitude or phase. As an application example of the proposal, we show the recent work of designing a Huygens planar lens that can achieve dynamic focusing.

With the concept of metasurface, ultra-thin planar lenses can be constructed through certain phase retardation profile to achieve EM wave diffraction, depletion or focusing [12-14]. For example, a gradient metasurface can focus terahertz radiation down to a spot size of approximately one wavelength [14]. A gradient phase profile along the metasurface could change the planar wavefront from an incident plane wave to a curved one to achieve a fine focus as schematically illustrated in Fig. 4. To insure a high power efficiency of the planar lens the transmission magnitude of each unit cell in the metasurface should keep close to unity while providing different phase retardations. The previous proposal provide us a convenient way to independently control the transmission magnitude and phase which could be directly applied to construct such a planar Huygens lens.

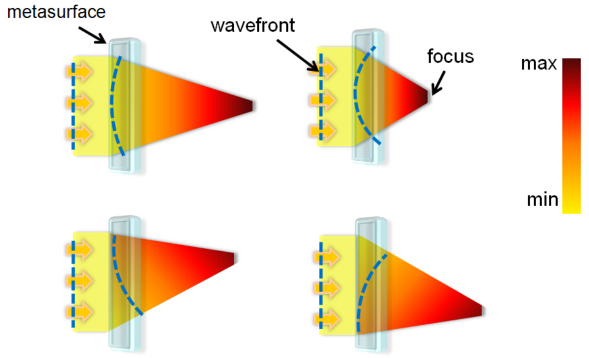

Fig. 4. Schematic of dynamic focusing through different transmission phase profiles obtained with a planar metasurface. Dynamic focusing along the horizontal direction (upper row) or the vertical direction (lower row) can be achieved by changing the corresponding phase profiles (dashed lines).

We employ a similar unit cell design as shown in Fig. 1(a) to achieve near unity transmission magnitude but with variable phase changes. By incorporating varactors with tunable capacitance into the unit cell, the phase changes can be further controlled upon certain biasing. This will enable us to dynamically change the phase retardation profile to pre-defined gradients to realize different focal point. If we change the curvature of a symmetric phase retardation distribution with respect to the center of the metasurface lens, a dynamic change of the focal point along the horizontal direction could be obtained as shown in the upper row of Fig. 4. However, if we realize an asymmetric phase retardation profiles, a dynamic change of the focal point along the vertical direction could be realized as indicated in the lower row of the Fig. 4.

To prove the proposed concept of planar Huygens lens, we construct a metasurface with one row of different unit cells possessing certain tunable phase retardation profile and test its focusing performance in a two dimensional planar waveguide system with a plane wave irradiation. We conduct both full wave simulation and experimental verification. Fig. 5 shows the calculated electromagnetic field mapping upon changing the phase profile on the metasurface lens through different biasing on the varactors. It is quite obvious that different focal points are observed in the three field mapping snap shots. The focal point can be dynamically tuned within a range of about four wavelength along the *y* direction. The tuning of the focal point along the *x* direction is also verified by applying different biasing on the varactors.

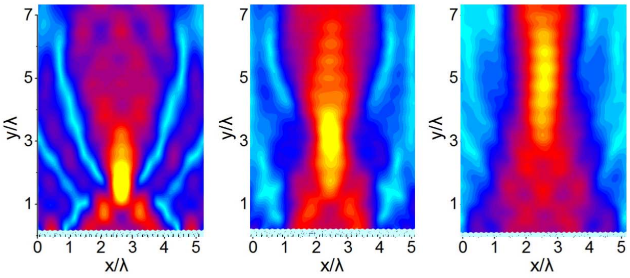

Fig. 5. Two dimensional electric field mapping snap shots upon different biasing on the varactors to create different phase retardation profiles on the metasurface lens (located in the lowest side) indicating that the focal point (bright yellow region) can be changed along the *y* axis. The coordinates are in the unit of one wavelength.

We will present the detailed theoretical analysis and numerical simulation, as well as the experiment validation of proposed planar Huygens lens that can achieve two dimensional dynamic focusing at microwave frequency. The proposed approach can be applied to many cases where fine beam focusing and positioning is needed, such as dynamic imaging system and smart antennas. We also believe that such scheme can be scaled to higher frequency such as the terahertz range.

IV. CONCLUSIONS

We incorporate active circuit elements into the design of metasurfaces to dynamically and arbitrarily control the electromagnetic wave transmission magnitude and phase. We believe the proposed design scheme and the demonstrated examples could indicate the significant ability and potential applications of tunable metasurfaces for dynamic control of the electromagnetic wave propagation.

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