

Controlling Waves with Metasurfaces

S. Maci

Dept. of Information Engineering, University of Siena, Via Roma 56, 50124, Siena, Italy (E-mail: macis@diisi.unisi.it)

Abstract

Metasurfaces constitute a class of thin metamaterials, able to support surface wave propagation. In their simpler configuration, they are constituted by sub-wavelength size patches printed on thin grounded or ungrounded dielectric substrates. By averaging the tangential fields, the metasurfaces may be characterized by homogenised isotropic or anisotropic boundary conditions (b.c.). These b.c. can be synthesized by homogeneous equivalent impedance. If the impedance is spatially uniform, it supports surface-wave propagation with planar wavefront. The impedance can be spatially modulated by locally changing the sizes/orientation of the local printed elements; this imposes a deformation of the wavefront which addresses the local wavector along not-rectilinear paths. In fact, the modulated anisotropic impedance imposes a local modification of the dispersion equation and, at constant operating frequency, of the local wavevector. The general effects of metasurface-modulation are similar to those obtained by transformation optics (TO) in volumetric inhomogeneous metamaterials, namely re-addressing the propagation path of an incident wave. Alternatively, periodic modulation can transform surface waves to leaky waves thus leading to an antenna with a possible shaped beam.

1. Introduction

Metasurfaces (MTS) are thin metamaterials constituted by an arrangement of printed elements whose dimensions are smaller than the free space wavelength (Fig. 1). The technology of MTS is quite simple and the relevant advanced applications are mostly based on quasi-analytical design. MTS may be distinguished as penetrable and impenetrable. A penetrable metasurface (sometimes called metafilm) consists of a planar distribution of small periodic scatterers in a very thin host medium. Its effective properties can be studied by applying generalized sheet transition conditions [1], [2] which allow one to characterize a metasurface in terms of an unambiguous anisotropic sheet impedance tensor.

Impenetrable metasurfaces, which are those treated in this paper, are realized at microwave frequencies through a dense periodic texture of small elements printed on a grounded slab. By averaging the tangential field, a metasurface can be macroscopically described through impedance boundary conditions. This leads to the definition of a “surface impedance tensor”, which links the average tangential electric field to the average tangential magnetic field. When the shape of the elements is regular enough (Fig. 1 a), the impedance tensor becomes a scalar quantities and the effect of the boundary condition is isotropic with respect to both the direction of the incident field and the direction of the surface-wave propagation. When the shape contains additional features, like slots, grooves or cuts, the impedance is anisotropic; the anisotropy can be controlled well for element with a single axis of symmetry (see Fig. 1b).

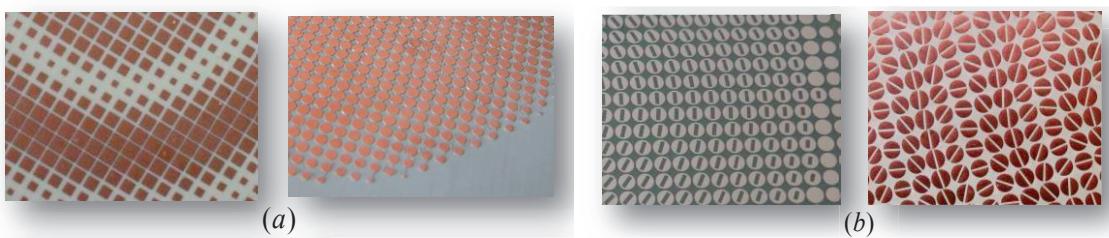


Fig. 1 MTS at microwave frequencies consisting of small patches with variable sizes printed on a grounded slab; (a) isotropic MTS formed by square or circular patches with variable dimensions (b) anisotropic MTS formed by circular patches with slots or cuts inside. The patches are positioned at the centre of the unit cell, whose size is assumed uniform. Control of waves can be achieved by MTS modulation; namely, modulating (statically or dynamically) the dimensions of the constituent elements along the surface. The MTS modulation can be distinguished into three objectives:

- i. MTS Modulation for transforming the transmission/ reflection wave-front [3]-[5]
- ii. MTS Modulation for transforming the wavefront of surface-wave/plasmonic-wave [6]-[12]
- iii. MTS Modulation for transforming surface-wave into leaky-waves [13], [15]

Objective *i* is schematized in Fig. 2 with reference to the case of a beam deflection after transmission through a MTS. In the same figure, objectives *ii* and *iii* are also exemplified: a point source placed on a MTS lens launches a cylindrical surface wave which eventually becomes a plane wave at the beginning of a periodically modulated MTS. The MTS modulation transform the planar-wavefront SW it into a leaky wave (iii). In the following subsections, the three cases will be analyzed.

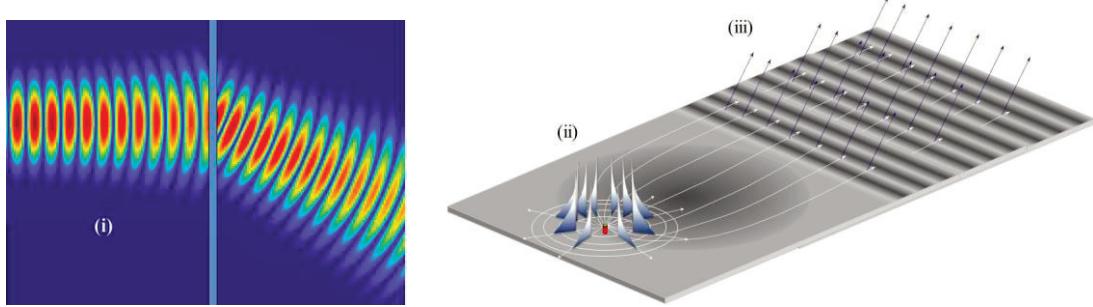


Fig. 2 Three main application of MTS: (i) anomalous transmission, (ii) surface-wave wavefront (curvilinear ray-path) control; (iii) SW to LW transformation.

2. Modulated MTS for Transforming transmitted or Reflected Wavefront

The objective *i* is very popular nowadays in light-wave applications; the Capasso's group [3] have demonstrated that intensity, phase, and polarization of light rays can be changed using a hologram-like design decorated with nanoscale subwavelength elements. Several devices can be conceived using this concept, like MTS with a constant interfacial phase gradient that deflect light into arbitrary directions; MTS with anisotropic optical responses that create light beams of arbitrary polarization over a wide wavelength range; planar MTS lenses that generate nondiffracting Bessel beams or waves with spiral phase. Microwave version of the above concept has been presented in the papers by Grbic [4] and Eleftheriades [5] which formalized the concept through the use of the equivalence theorem. In the above papers, the design goal is designing local subwavelength scatterers which, subjected to an assigned incident wavefront, synthesize those equivalent currents necessary to form a predefined transmitted wavefront.

The modulation of the wavefront can be also used for shaping the phasefront of a reflected waves. In this case the reflector becomes very similar to a reflectarray, except for the fact that the elements are subresonant. This technique may be useful for improving performance of shaped reflector surfaces in contoured beam space applications [16] (Fig. 2). Infact, it is quite difficult to illuminate two regions of Earth from the same reflector using two feeds, unless the two regions have nearly the same shape. Furthermore, demanding requirements on the radiation pattern may lead, after a physical optics (PO)-based synthesis, to rather large deformations (bumps) of the reflector, which may cast shadows on the reflector surface when seen from the feed. These impairments can be overcome by properly modulating the surface impedance of the reflector. The use of an anisotropic impedance could also improve the antenna performances in terms of cross-polar component of the radiated field.

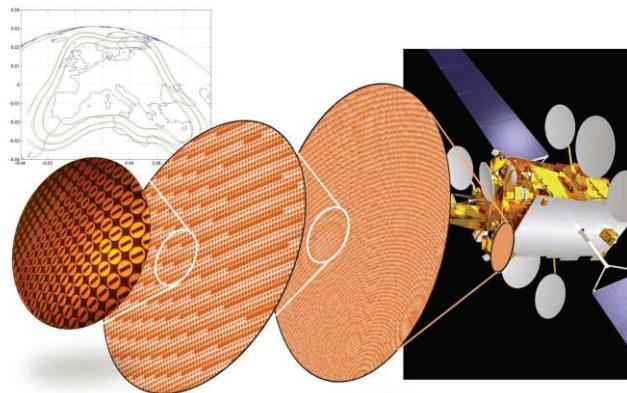


Fig. 3 modulated MTS printed on a shaped reflector for earth coverage

3. Modulated MTS for transforming surface-waves Wavefront

Control of surface wave wavefront identifies ultra-thin microwave devices based on surface-waves, like for instance Luneburg, Rotman, Eaton, and Maxwell's fish-eye flat lenses [8],[9],[11],[12]. A solution at terahertz and infrared frequencies is obtained in [10] by using surface plasmon polaritons on a graphene monoatomic layer, where the graphene conductivity is tuned by using static electric fields. Modulating the impedance boundary conditions, leads to addressing surface waves along local curvilinear paths. The impedance modulation, obtained by changing the sizes of the local patches, imposes a local modification of the dispersion equation and, at constant operating frequency, of the local wavevector. In [7], this phenomenon is synthetically referred to as "metasurfing". The general effects of metasurface-modulation are similar to those obtained by transformation optics (TO) [17] in volumetric inhomogeneous metamaterials. TO is a general framework for solving inverse scattering problems based on simulating spatial coordinate transformations with distributions of metamaterial properties. The most famous use of TO is concerned with invisibility cloaks [18, and references therein].

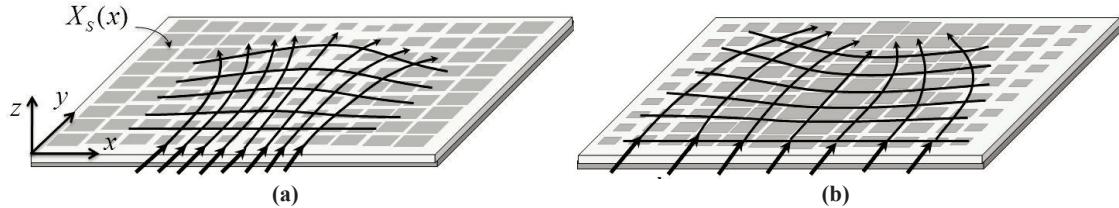


Fig.4 Example of curved-wavefront SW supported by an impedance modulation. (a) diverging wavefront, (b) converging wavefront.

The modulation of the wave vector obtained through the change of size of the subwavelength printed elements produces a change of the phase velocity and propagation path of the SW supported by the metasurface. A simple example is illustrated in Fig. 4. Fig. 4a shows a MTS consisting of a uniform rectangular lattice of printed square patches modulated in size along x , with smaller sizes toward the centre and larger sizes toward the side. Assume that this MTS is excited at a certain section $y = y_0$ with a TM surface *plane* wave by a congruence of parallel equi-length wavevectors. As the wave progresses along y , the larger value of reactance imposes a local decrease of k_t at the centre and increase at the periphery. Correspondingly, the local phase velocity decreases at the periphery and increases at the centre, thus producing a diverging wavefront. This forces the wavevector to modify its direction, so as to maintain its amplitude consistent with the dispersion equation of the local reactance value. The opposite occurs when the patches are larger at the centre and smaller at the periphery (Fig. **Errore. L'origine riferimento non è stata trovata.**b). The congruence of rays forms, in this case, a converging wavefront that may focus the field in a point.

As mentioned, this phenomenon can be exploited to construct surface wave lenses. An example of Maxwell's fish-eye lens is shown in Fig. 5.

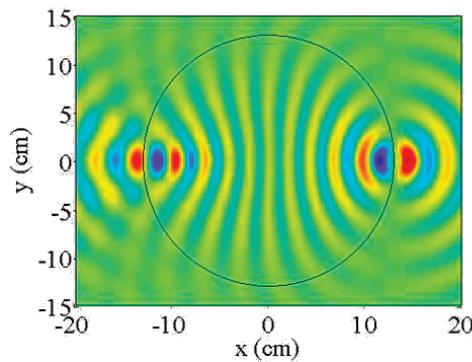


Fig.5 Example of a Maxwell's fish eye lens.

4. Modulated MTS for transforming surface-waves in Leaky waves

P When a periodic modulation of MTS is designed in a direction of propagation, a surface wave may radiate by Bragg effects. This means that the surface wave excited on the modulated MTS undergoes a transformation into a leaky wave. This approach is gaining success in ultrathin antennas with single point-source feeding [13][14]. For their light weight, these antennas find applications in space satellite shaped-beam communication and data-downloading.

A first design of the antenna impedance modulation can be obtained from the interference between the aperture phase associated to the desired radiation pattern and the surface wave phase distribution generated by the feeder on the average impedance.

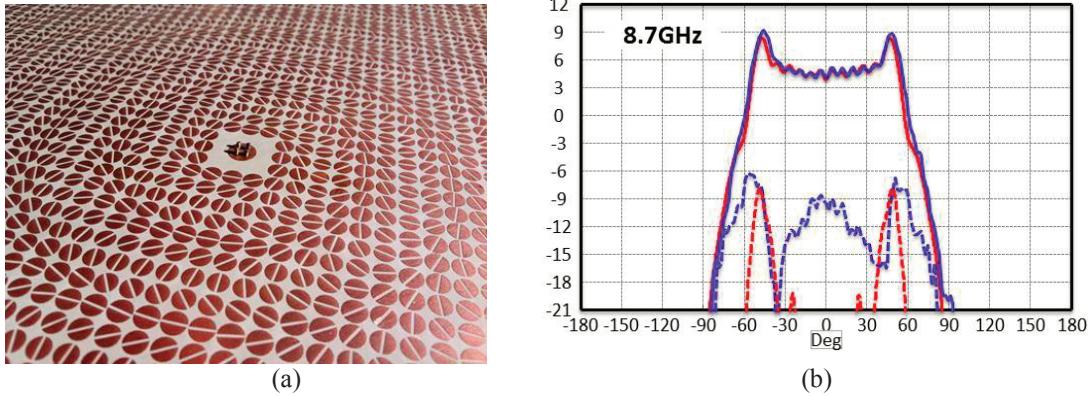


Fig.6 modulated metasurface antenna with isoflux shaping; (a) probe feeding and MTS layout; (b) measured radiation pattern (blue line) compared with simulations (red line).

When the SW interact with the so obtained modulated impedance, a leakage occurs which reconstruct the desired radiation pattern. Moreover, designing an appropriate tensorial impedance surfaces, leads to a desired polarization of the aperture field. Metasurface antennas can be excellent candidates for space applications. Indeed, they can be manufactured by means of low-cost technologies, and they exhibit extremely low mass, flatness, and low profile. Furthermore, they can be excited by simple embedded feeding points. All of these characteristics match very well the usual requirements for space antennas, and renders MTS antennas competitive with reflectors.

An example of isoflux-pattern MTS antenna for data satellite link is shown in Fig. 6 [15]. An isoflux pattern provides a uniform power flux density over a defined portion of the visible Earth surface by compensating with different radiated density power the different path loss. This is a very common requirement for data transmission antennas on satellite platform for Earth observation missions. In a first approximation, one can think of an isoflux pattern as a conical beam with a certain level of gain at the broadside. A conical isoflux-shaped beam can be easily obtained by exploiting the interaction of a cylindrical surface wave and an azimuthally symmetric impedance modulation. The antenna surface can be viewed as composed of radial sectors, each radiating a circularly polarized field toward an off-axis angle around 60 degrees. A small patch at the centre is useful to adjust the gain level at broadside, realizes the impedance match with the feeding system and increase the efficiency of power launched in the surface wave. The X-band prototype in Fig. 6 is an extremely flat and light antenna (thickness around 1.6 mm, weight less than 1Kg) with a diameter of about 60cm, which has been built with the same PCB process used for standard printed circuit. The surface is constructed by anisotropic elements to obtain a circular polarization.

5. Conclusions

In this short paper, we have illustrated three different phenomena and relevant applications in which the use of Metasurfaces leads to innovative engineering solutions. Several additional examples will be shown during the oral presentation.

6. Acknowledgement

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7. References

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