QMD 10:15 am–12:00 pm

Room: 201

Metamaterials

Jeremy J Baumberg, Univ. of Southampton, UK, Presider

QMD1 10:15 am

Microwave Transmission through Metamaterials in Free Space

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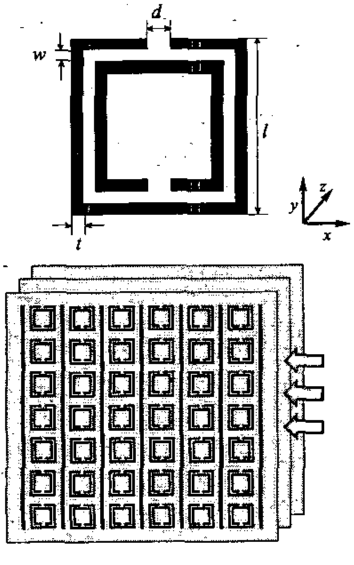
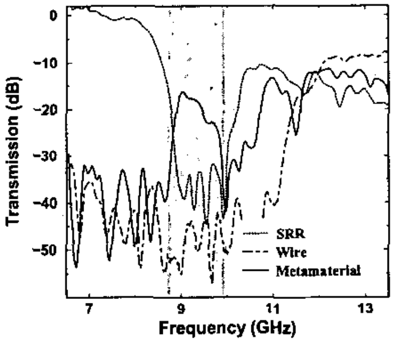
Recently, the composite metamaterials, which was first theoretically proposed by Veselago in 1968,[1] have inspired great attentions due to interesting physical properties and novel applications.[2,3,4,5] The electric and magnetic behaviors of materials are determined by two important material parameters, ε (dielectric permittivity) and μ (magnetic permeability). Together the permeability and the permittivity determine the response of the material to the electromagnetic radiation. Generally, ε and μ are both positive in ordinary materials. Negative dielectric medium at microwave domain can be obtained by arranging thin metallic wires periodically.[6] Below plasma frequency, dielectric permittivity will take negative values. Pendry *et al.* proposed negative magnetic permeability by using special configurations of metals, named as split ring resonator and swiss roll capacitor.[2]



QMD1 **Fig. 1.** [Top panel] Schematic drawing of a single SRR with parameters $l = 3$ mm and $d = t = w = 0.33$ mm. [Bottom panel] The schematics of composite metamaterial consisting of thin wires and SRRs. The structure is consisted of $N_x = 25$, $N_y = 25$, and $N_z = 20$ unit cells, and each unit cell has dimensions $a_x = 5$ mm, $a_y = 3.63$ mm, and $a_z = 5$ mm. The thickness of thin wire is 0.5 mm.



QMD1 **Fig. 2.** Measured transmission spectra corresponding to thin wires, SRRs, and metamaterials.

In order to investigate properties of metamaterials, we constructed a composite structures which consists of periodical arrangement of thin copper wires and SRRs on a circuit board (see Fig. 1). We first measured the transmission spectra of the thin wire and SRR mediums individually. The measurements are performed in free space by using a HP 8510C network analyzer and microwave horn antennas. Figure 2 exhibits the measured transmission spectra of SRRs (dotted line), thin wires (dot-dashed line), and the composite metamaterials (solid line). The SRR medium exhibits a stop band extending from 8.7 to 10.3 GHz. The thin wire structure has a plasma frequency around 11.3 GHz. As shown in Fig. 2, there appears a transmission band for the composite metamaterial within the stop bands of SRR and thin wire structures.

In summary, we investigated the transmission properties of composite metamaterials at microwave frequencies. We observed that a passband is formed within the forbidden transmission bands of thin wire and SRR structures.

References

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QMD2 10:30 am

Chiral Gratings—a New Class of Polarization Sensitive Metamaterials

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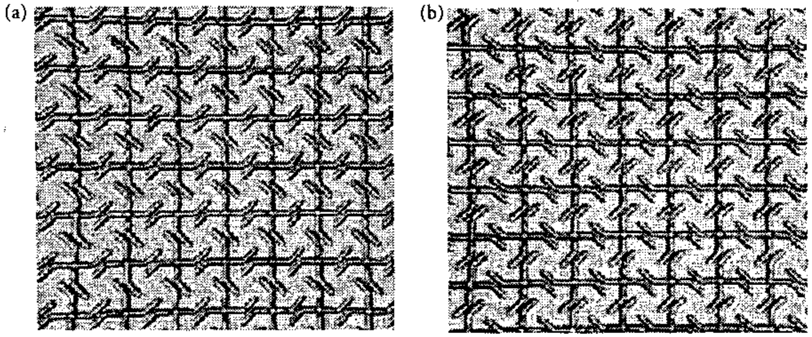
Recently a new group of layered planar and quasi-planar metamaterials has emerged which promise unique polarization characteristics. Metallic bilayered structures with chirality and inductive coupling are predicted[1] to show huge optical polarization rotatory power resembling that of liquid crystals. The semi-chiral planar gratings described here belong to a distinctively different class of 2D structures known as planar chiral structures.[2] By definition, two planar chiral objects of different chirality cannot be brought into congruence, unless they are lifted out of the plane by rotating by 180° about an axis in the plane of the structure. A gammadion is an example of such an object. It was expected that planar chiral structures would have pronounced polarization properties when interacting with light,[3] however, to the best of our knowledge, this has never been confirmed experimentally. Here we report what we believe is the first experimental demonstration of such polarization activity.

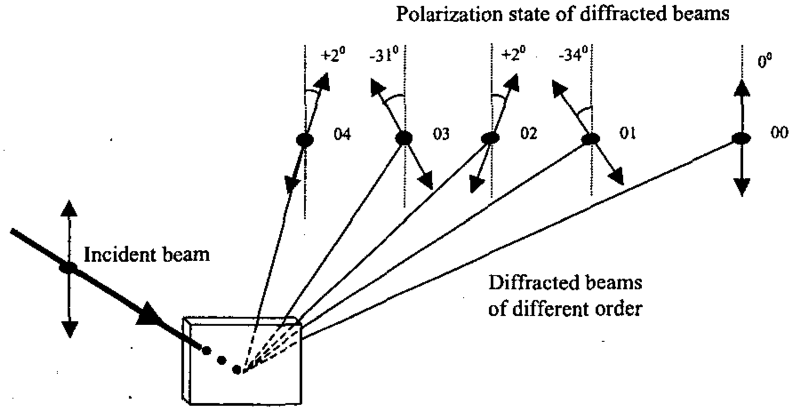
Gold semi-planar chiral gratings were manufactured on silicon substrates using a combination of direct-write electron beam lithography and either ion beam milling or a lift-off process. We have manufactured two-dimensional gratings consisting of regular square patterns of gammadions or anti-gammadions. We have studied a range of gratings with different pitches, containing gammadions of various characteristic sizes ranging from 700 nm to 4 μm, and different senses of chirality as illustrated on Fig. 1. A typical grating has an area of approximately 1.0×1.0 mm^2, with a density of gammadions of between 6×10^5 cm^{-2} and 6×10^6 cm^{-2}.

These gratings show a well-defined rectangular diffraction pattern as illustrated in Fig. 2. The polarization properties of the diffracted waves have been investigated at a wavelength of 632 nm for S and P polarizations at an angle of incidence of 60°. The polarization state of the diffracted beams was found to be different from that of the incident beam. In general the diffracted beams become elliptically polarized and the polarization azimuth rotates. Rotations in excess of 30° were seen. It should be noted that for S and P incident polarizations no polarization change is expected on reflection from an isotropic unstructured interface. For a given diffraction order the polarization azimuth rotation was found to have opposite sign for samples, which only differ in their handedness. On the same sample different diffraction orders show different polarization azimuth rotation, as illustrated in Fig. 2.

Another startling feature of these samples has been their ability to alter the perceived color of reflected light when viewed through a low magnification polarizing microscope, even though the typical feature sizes of these structures are much



QMD2 **Fig. 1.** Optical micrographs of two-dimensional gratings of (a) left and (b) right handed gammadions. In both cases the grating pitch is 5 μm.



QMD2 **Fig. 2.** Polarization azimuth rotation of light diffracted from a chiral grating. Only one row of diffracted beams (in the plane of incidence) is depicted for simplicity of presentation. The angles of rotation given are for gammadion grating with pitch of 5 μm and characteristic size of the gammadions of 2 μm.

larger than the characteristic wavelength in question.

We believe that the strong polarization effects reported here result from the chirality imposed by the patterns of gammadions enhanced by plasmon effects due to the nanostructuring of the metal film in which they are cut. It is clear that such structures have the potential to yield many new and intriguing applications in optoelectronics and other areas.

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QMD3 Invited **10:45 am**

Left Handed Metamaterials and Intrinsic Negative Index of Refraction

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Propagating electromagnetic waves in Left Handed Metamaterials (LHM) were introduced by Smith et al., in 2000 confirming Veselago's prediction in 1964 of their "reversed" behavior. We will discuss LHMs, their properties, and potential applications.

QMD4 **11:15 am**

Optical Elements Based on Space-Variant Pancharatnam-Berry Phase Manipulation

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The Pancharatnam-Berry phase is a geometrical phase associated with the polarization of light. When the polarization of a beam is made to traverse a closed loop on the Poincare sphere, the final state differs from the initial state by a phase factor equal to half the area encompassed by the loop on the sphere.

Recently, we demonstrated a Pancharatnam-Berry phase that accompanied space variant polarization state manipulations in the space domain.[1] When circular polarization was converted into radial polarization, our calculations and experiments indicated a geometrical phase that left a clear signature on the far-field image of the beam.[2]

In this paper we demonstrate novel optical phase elements based on the space-domain Pancharatnam-Berry phase. Unlike diffractive and refractive elements, the phase is not introduced through optical path differences, but results from the geometrical phase that accompanies space-variant polarization manipulation. We analyze Pancharatnam-Berry phase optical elements (PBOEs) that consist of space varying, (transversely inhomogeneous) waveplates with constant retardation, and space-varying fast axis orientation. We realized such PBOEs for CO_2 laser radiation at a wavelength of 10.6 μm using computer-generated space-variant subwavelength gratings.[3]

Figure 1(a) illustrates the concept of PBOEs by use of the Poincare sphere. Circularly polarized light is incident on a waveplate with a space varying fast axis whose orientation is denoted by $\theta(x,y)$. The resulting polarization is space-varying since it depends on the local orientation of the waveplate. Thus, the beam at different points traverses different paths on the Poincare sphere, resulting in a space-variant phase-front modification originating from the Pancharatnam-Berry phase. For incident circular polarization, the resulting beam has two components, the zero order and the diffracted orders. The amount of energy in each component depends on the retardation of the grating. The zero order has the same polarization as the original beam and undergoes no phase modification. Whereas, the diffracted orders have a polarization orthogonal to that of the incident beam and undergo a phase modification equal to $2\theta(x,y)$, which we call the Diffractive Geometrical Phase (DGP). The DGP can be utilized to form novel optical elements.[4]

Figure 1(b) illustrates the geometry of a Pancharatnam-Berry phase diffraction grating for CO_2 laser radiation realized using subwavelength dielectric gratings. The retardation of the grating was $\phi = \pi$, leading to 100% efficiency in the diffracted order. Figure 1(c) shows the DGP when the incident beam has left hand circular polarization, as well as the experimental measurement of the far-field intensity. The DGP resembles a blazed grating and all the energy is located in the first order to the left. When the incident polarization is right hand circular polarization the DGP is blazed in the opposite direction, and the energy is diffracted to the first order on the right. We have also realized other PBOEs such as spiral Pancharatnam-Berry phase elements, indicating the ability to form smart phase elements based on geometrical phase.

References

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