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Active Controllable Single Side Double S-shaped Metamaterial

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Abstract| In this paper, a 1D active controllable metamaterial (as shown in Fig. 1) is experimentally realized by adding varactor diodes to the single side double S-shaped Left-handed material. When the external bias voltage of the varactor is changed, the results of the power transmission experiment conducted on the metamaterial sample in Fig. 2 demonstrate that the frequency range of the passbands of the sample becomes tunable and the phases of the experimental S_{21} shown in Fig. 3 shifts, which indicates the e®ective refractive index at a ¯xed frequency within the passbands of the material is controllable. Such tunable structure gives feasibility to realize active radome in the future.

Isolation Study in Antenna Systems Using Left-handed Metamaterials

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Abstract|The suppression of mutual coupling between antennas has been reported using high impedance surfaces, such as EBG (electromagentic bandgap) substrates. Since the propagation of electromagnetic ¯elds is forbidden inside EBG substrates within certain frequency ranges, the in°uence of surface modes can be mitigated, which leads to a reduction of the mutual coupling between antennas. However, the sizes of EBG structures are usually of the same order as the operating wavelength, which yields to large substrate sizes. Furthermore, EBG materials usually operate in a narrow frequency band, which is an undesired property.

In this paper, we present a systematic study on the isolation between two antennas using strati¯ed media of right-handed material, left-handed material, Mu-negative material and Epsilon-negative material. We ¯rst study the guidance conditions of the surface wave mode for these media with single layer grounded slab. We show that the coupling level is much smaller if no surface modes exist comparing to the situation when surface modes exist. Therefore, the coupling between antennas is mainly contributed by the surface wave propagation along the interface. However, the coupling value can not be obtained simply based on the guidance condition analysis. In order to evaluate the ¯eld along the interface, we propose two methods: the spectral domain method and the asymptotic analysis. The spectral domain method extends the applications to include left-handed materials, mu-negative materials and epsilon-negative materials. The asymptotic analysis uses the integral formulation to evaluate the ¯elds through branch cuts. The ¯eld results from both methods are con¯rmed by simulations using CST microwave studio. Both methods are then further applied to design the slab parameters for the best isolation. An optimized design is proposed for the single layer grounded slab. At last we proposed an isolation design using metamaterial slab composed of split-ring resonators. The results show that a good isolation level can be achieved.

Two-dimensional Cross Embedded Metamaterials

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Abstract| Traditional two dimensional (2D) left-handed metamaterials were composed of honeycomb structures. In this paper, we experimentally realized a 2D S-shaped metamaterial structure with cross embedded form. We show that metamaterials with cross embedded arrangements exhibit wider left-handed band and lower loss than honeycomb structures.

Negative Refractive Metamaterial Composite of Pure Dielectric Resonators

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Abstract|This paper demonstrates left-handed properties can be realized by simple dielectric resonators. A theoretical analysis as well as experimental measurement of an array of high dielectric resonators arranged either periodically or randomly is presented.

Figure 1 shows the unit cell con¯guration of a standard high dielectric resonator and the theoretical calculation of the e®ective permittivity and permeability. A double negative can be found around 7 GHz. Figure 2(a) shows the BST samples used in experiment. Figures 2(b) and (c) show the negative refractions of both periodically and randomly arranged prisms, respectively. The double refraction occurs due to the mismatch between the prisms and air. According to Figures 2(b) and (c), the two prisms behave in the same way which is signi¯cantly di®erent from photonic crystal whose properties strongly depend on the periodicity and arrangement.

The left-handed properties of simplest high dielectric resonators are validated theoretically and experimentally. By utilizing nano-machining technologies, a whole-dielectric Terahertz LHM is expectable in the future, since dielectrics with high permittivity exist in Terahertz band.

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Experimental Study of the Transmission Property of Anisotropic Left-handed Materials

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Abstract| We study the transmission property of an anisotropic metamaterial slab exhibiting negative permittivity and negative permeability along some speci¯c directions. The wires aligned with the *y* direction yields a permittivity $''_y(!)$ described by a Drude model, while the axis of the - rings is aligned with the *x* axis, yielding a permeability ^1_z described by the Lorentz model (propagation direction is along the *z* axis). The resonant and plasma frequencies were retrieved from simulation results. It is discovered from theoretical calculation that the Brewster angle increases as the frequency decreases. A sample of such left-handed material slab is fabricated and experimental results are provided which corroborate the theoretical predictions.

Realization of Left-handed Materials Using Ferroic Materials

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Abstract|With negative permittivity and negative permeability, left-handed materials (LHMs) exhibit many unusual and attractive properties. Since the ¯rst LHM were realized in 2000 by D. R. Smith et al. using split-ring resonators (SRRs) and using metallic wires, much attention has been paid on designing LHMs via various arti¯cial metallic patterns to achieve better left-handed properties. Hence, LHM was always regarded as structure rather than material, the so-called metamaterials. Because of the equivalence of the metallic structure and homogenous medium, it becomes interesting and signi¯cant to realize LHM by homogenous medium. Therefore, it will provide a new way to understand the physics insight in the LHMs from a microscopic point of view.

To obtain negative permeability, the intensity of induced magnetization in the medium should be greater than and antiparallel to that of the magnetic ¯eld, which is infeasible for a steady state. The same thing happens to negative permittivity. Although negative parameters can not be obtained in equilibrium, they can be achieved based on resonance mechanism. For example, SRR generates negative permeability using magnetic plasma resonance, and metallic wires generate negative permittivity using plasma resonance. In conventional materials, various resonances can also be used to realize negative permeability and negative permittivity. Ferroic materials, such as ferromagnet and ferroelectric, are good candidates to realize negative parameters because they exhibit strong response to external ¯eld.

Simultaneously under a steady magnetic ¯eld and an orthogonal alternating magnetic ¯eld, ferromagnet will exhibit ferromagnetic resonance in microwave band. The resonance occurs when the frequency of alternating magnetic ¯eld equals to the natural frequency of spin's precession around the direction of steady magnetic ¯eld. The resonance frequency is determined by the intensity of steady magnetic ¯eld and the intrinsic character of ferromagnet. Above the resonance frequency, permeability will turn negative, owing to the phase lag of magnetization to alternating magnetic ¯eld. Hence, ferromagnetic resonance can contribute to the realization of LHM using homogeneous medium. Meanwhile, magnetic domain wall resonance may also generate negative permeability.

In view of the comparability of ferromagnet and ferroelectric, ferroelectric can also generate negative permeability in microwave band. In the ferroelectric, dipoles rotate under the alternating electronic ¯eld. When the frequency of alternating electronic ¯eld equals to the natural frequency of dipole rotation, dipole resonance occurs. The cations oscillate around the position of equilibrium driven by the external alternating electronic ¯eld. The ion resonance exists at higher frequency than dipole resonance. Moreover, the complex domain structure in ferroelectrics also provides them some other resonances in a certain frequency range.

The realization of LHMs using ferroic materials can extend the research domain of LHM. It can make LHM no longer equal to metamaterial. And the realization of LHMs using ferroic materials will miniaturize the microwave devices.

Tunable Metamaterials Based on Nematic Liquid Crystals

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Abstract|Electrically tunable negative permeability metamaterial consisting of periodic array of split ring resonators (SRRs) in¯ltrated with nematic liquid crystals is demonstrated. Transmission measurement shows that the transmitted resonance dip of the metamaterial shifts towards low frequency as the applied electric ¯eld increases. The maximum shift is about 210MHz and the shift can be continuously and reversible adjusted. Numerical simulation shows that the permeability of the metamaterial is negative near the resonance frequency and the frequency range with negative permeability can be dynamically adjusted and widen about 200MHz by the applied electric ¯eld. An applied electric ¯eld changes the alignment of the liquid crystal directors and hence the dielectric constant of the structure, which permits dynamically tuning the negative permeability and provides a convenient means to add adaptive features to the metamaterials.

Rigorous Study of the Magnetic Resonances in Metallic Double Split Rings: Lower Frequency Limit and Bi-anisotropy

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Abstract| As the building blocks of recently discovered left-handed meta-materials (LHM), metallic ring systems have attracted considerable attention recently. Since most LHM's were built upon the principle of e®ective medium theory, to realize an LHM sample with a good quality, one naturally requires the building block to be as *subwavelength* as possible and its *bi-ansiotropy* as small as possible. Previous theoretical understandings on such systems were achieved mainly through empirical theories or brute-force numerical computations. Recently, we established a rigorous approach for metallic ring systems and applied it to study the electromagnetic (EM) eigenmodes of a single spilit ring resonator (SRR) [1].
Here, we extend the rigorous theory to study the electromagnetic (EM) resonances in double split ring systems, with ring radius given by R, wire radius by a and ring-ring separation by d [2]. The inter-ring interactions split each single-ring mode to two modes with di®erent symmetries, and the bi-anisotropy of each mode is suppressed as two rings approach. We ¯nd an analytical expression, ±!=! » 2 ln(2d=R)=[3 ln(2a=R)], to determine the frequency shift of the fundamental (magnetic) mode compared to the single-ring SRR mode. We further derive a lower frequency limit for the magnetic resonance $!_{lim}$»(c=R)pln(1=2)=[4 ln(a=R)]. Finite-di®erence-time-domain simulations on realistic structures are in good agreement with numerical calculations based on the rigorous theory.

Negative Refraction in Composites with Array of Coplanar Metallic Double Rings

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Abstract| It is well known that metamaterials consists of metallic wires and split ring resonators (SRR) can have negative index of refraction. However, in order to show the negative

refraction alternating magnetic ¯eld should be perpendicular to the plane of SRR. This causes many di±culties in applications. In this work, other than the metamaterials, we have proposed a structured composite made of array of coplanar double rings, and demonstrate the composite has negative refraction. With the all-in-one-plane property, the element dimension of the composite is reduced and the composite is much easier to fabricate. In addition, the composite shows isotropy in the double rings plane other than the metamaterials is anisotropy. This provides the conveniences for the real applications.

The analysis shows that the array of outer rings forms an e®ective plasma media, which exhibit an e®ective negative permittivity under the plasma frequency. The gap between the outer and inner rings excites resonance, which provides e®ective permeability *¹*. Changing the gap can alter the resonance frequency of the structure. By a careful design of the dimensions of the double rings and the gaps, we have obtained negative values of refraction index in a particular range of frequency near the resonance.

With simulated S parameters of the composite, a standard EM parameters retrieval method is used to get e®ective *"* and *¹*. The results assert that this structure is a kind of single negative media, which has negative permittivity but positive permeability.

Full wave simulation is used to con¯rm the analysis. Using the FEM method, the simulation in done on a wedge made of the double rings composite. The simulation result is shown in the ¯gure. We can ¯nd that the beam incident on the interface of the wedge and air refracts to the same side of the normal as the incident wave. This demonstrates that index of refraction of the composite is negative.

Frequency Selectivity of THz Transimission of Sub-wavelength Metal Fractal Structures

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Abstract| We present experimentally that resonant transmission of single fractal slits on the free-standing copper foil in the frequency range of 90 GHz to 0.8 THz. The transmission spectra with multiple pass bands and band gaps are studied by means of THz time-domain spectroscopy. THz transmission under di®erent polarization for a 7-level fractal pattern is analyzed. The transmission spectra with the di®erent levels of fractal slits are compared and discussed.