Artificial diamagnetic metamaterial loaded sub-wavelength waveguide with reduced bianisotropic effect: design, fabrication and characterization

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In this study, we investigate sub-wavelength transmission through C band rectangular waveguide which includes uniaxial anisotropic magnetic metamaterials (TSSRRs). Initially, the reflection, propagation and phase angles for TSSRRs loaded rectangular waveguide has been evaluated using numerical techniques (FEM) and than for same dimensional loaded waveguide, scattering parameters (S11) and E-H plane propagation for different angles have been observed experimentally. Miniaturization of rectangular waveguides with artificial diamagnetic media has been proved both numerically and experimentally.

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1. Introduction

Electromagnetic properties of any bulk media have been described by electric permittivity (ε) and magnetic permeability (μ). These parameters are exhibitors of electromagnetic (EM) fields' effect on bulk media. Recently, artificially designed EM structures for specific macroscopic properties have received considerably interest within scientific community [1]. Artificial dielectrics composed of discrete obstacles or scatters, extensively studied in 1950's [2]. The wavelength of applied fields are much longer than one unit cell ($\lambda >> unitcell$) in this composed media, in other words it could be thought as effective media and the electromagnetic properties of that media could be described in terms of effective permittivity and permeability, different of Bragg diffraction and photonic crystals. Although photonic diffraction could be achieved with scatters of which electrical lengths are on the order of wavelength, such as frequency selective surfaces (FSSs) and photonic crystals, it couldn't be possible to describe them with conventional EM parameters; dielectric permittivity and magnetic permeability.

Meta-materials exhibit very different properties than both photonic crystals and conventional dielectric media such as left handedness (LH) [3], backward wave (BW) [4], reverse Vavilov-Cherenkov radiation [5], negative magnetic permeability [6], perfect focusing [7] and negative refraction [8] that couldn't be possible to achieve with another way.

Meta-materials generally composed of two different inclusions that used to realize electrical and magnetic response, separately. The dimensions of these inclusions are much less than the wavelength to mention about effective medium characteristics means effective permittivity and permeability. These types of media could be used to compensate lagging in a conventional wave slab since that media exhibits phase advance [9].

Nowadays, meta-material application areas have been enlarged with many different disciplines to realize novelty properties such as waveguide miniaturization [10, 11], sub-wavelength imaging [12], cloaking objects [13], magnetic resonance [14] and antenna gain improvement [15], etc. One of these important novel application areas is waveguide technology. Although planar type structures have been preferred than waveguides, there are still inevitable antenna applications such as antenna arrays.

It is well known that in a rectangular waveguide, one of the transversal dimensions have been equal or greater than one half of wavelength to provide minimum EM boundary conditions. Below this cut off frequency, EM boundary conditions couldn't be satisfied and EM waves couldn't propagate in waveguides. Although by filling the waveguide with dielectric, the reduction of dimensions could be realized but high loss characteristic of dielectrics for microwave range is one of the unavoidable problems.

To realize negative permeability, split ring resonators (SRRs) have been used frequently. One of the applications is minimization of waveguide by reducing cut off frequency [9]. It was experimentally proved that SRR loaded waveguides shows sub wavelength transmission below cut-off frequency for dominant TE mode (TE_{01}), so it could be possible to reduction of waveguides transversal dimension below one half of a wavelength [11]. Since magnetic response have been achieved with resonance phenomenon, it has been possible to propagate EM waves in a small frequency band.

In this study magnetic effect will be realized using TSSRR (two symmetric split ring resonator) type inclusions. Using finite element method (FEM) S parameters and phase angle will be obtained for TSSRRs loaded rectangular waveguide and transversal dimension reduction will be investigated. For the same dimension structure and waveguide will be designed experimentally and both reflection coefficient and E-H plane will be observed.

2. Numerical analysis of TSSRRs loaded waveguide

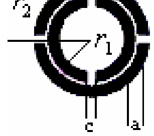
It has been experimentally improved that SRRs could be used to achieve diamagnetic properties in effective media [5]. But the major problem was its chiral like bianisotropic effect caused from asymmetry to the central axis:

$$\vec{D} = \varepsilon \vec{E} - j\xi \vec{B} \tag{1}$$

$$\vec{H} = -j\xi\vec{E} + \frac{1}{\mu}\vec{B} \tag{2}$$

This type of inclusions could exhibit magnetic response due to both electric and magnetic fields. When they have been excited by incident wave which have perpendicular electric field E to gaps, it could be possible to observe bianisotropic effect due to the asymmetric splits on the rings. So the problem is to minimization of anisotropy in loaded media that exhibits negative permeability. To make suppression to the bianisotropic excitations, SRR rings have been divided by two splits (TSSRRs). So both electric coupling to the magnetic resonance and vice versa have been ignored. One of the numerical solution techniques to solve artificial media composed of TSSRRs is finite element method (FEM). TSSRRs have been oriented on –z axis and the dimensions of it have been shown in Fig. 1. These dimensions have been chosen to be used in C band waveguide miniaturization.

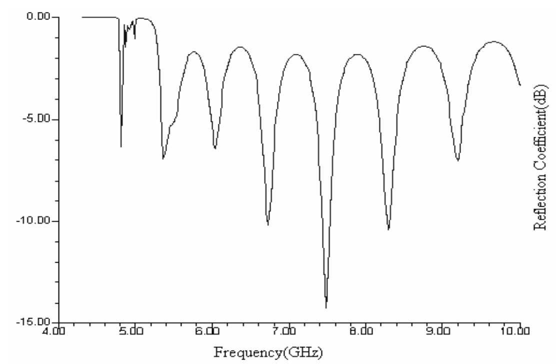
They have been configured in two dimensions and we assigned TSSRRs as perfectly electric conductor (PEC) otherwise it is too difficult to solve with computer configuration. These TSSRRs have been designed in a C band waveguide (620mils-1370mils-5000mils) which have parallel and perpendicular walls assigned as PEC.



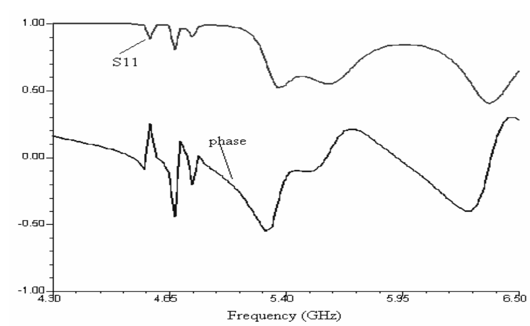
a	20 mil
r_1	130 mil
c	30 mil
r_2	200 mil

Fig. 1. TSSRR and dimensions.

The distance between closed inclusions and ports has been chosen $\lambda / 4$ for evanescent field decay. The solution frequency range was between 4.5GHz-10GHz hence the mesh dimensions have been assigned according to 10 GHz. The applied field was TEM to -z, E field was in the direction of -y and H field was parallel to the TSSRR's central axis from WR187. Since it couldn't possible to hold solely the inclusions in waveguide, they have been defined on one side of dielectric FR4 and the thickness of FR4 is 60 mils. Reflection begins from 4.8GHz with a narrow band and it repeats after 5.45 GHz as shown in Fig. 2 (a). The phase is negative for these resonance frequencies and this proves backward wave phenomenon (Fig. 2 (b).



(a)



(b)

Fig. 2. Reflection coefficient: (a) Reflection phase; (b) of loaded waveguide.

3. Experimental results

TSSRRs loaded waveguide have been designed experimental to compare numerical and theoretical solutions. The TSSRRs have been designed on one side of dielectric substrate FR4 with 8 μm electrodeposited copper foils using standard etching process. Although some other types of inclusions have been used to achieve diamagnetic properties, TSSRRs have been used to minimize bianisotropic effect observed from SRRs. The dimensions of the inclusions are same with numerical simulations. WR90 and WR137 type of rectangular waveguides include source and magnetic metamaterial placements; respectively (Fig. 3). One side of the metamaterial loaded waveguide was open ended for propagation.

Twenty TSSRRs were placed along the centre of WR90 and two of these inclusions were out of ends to achieve more propagation from waveguides. The dimensions of TSSRRs and waveguides are same with numerical simulations. Reflection from structure measured by the same source antenna in WR137. The lattice constant between adjacent elements is 30mils and reflection coefficient was measured between 5GHz-7.5GHz using HP8362B vector network analyzer in an anechoic chamber.

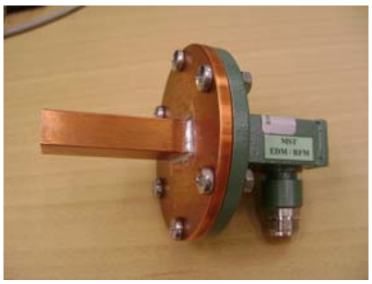


Fig. 3. Two attached waveguides for measurement of reflection coefficient (S11) and E-H planes.

Although the cut-off frequency for WR90 is approximately 6.5GHz, reflection coefficient reduces down to -10dB at 5.5GHz and at 5.65GHz S11 parameter reduced to minimum value; -32dB (Fig. 4). This pass band frequency is approximately 1 GHz less than the normal cut off frequency so constituted negative transversal permeability caused transmission well below boundary condition satisfaction. In other words transmission less than cut off frequency exhibit negative magnetic effect. This means that fifteen per cent miniaturization of waveguide transversal dimensions could be possible. So boundary condition limits for waveguide have been beyond and it has been realized to transmit EM waves any frequency band not depend on the transversal dimensions. Since energy conservation law these transmission below cut-off could be realized only a narrow band frequency range.

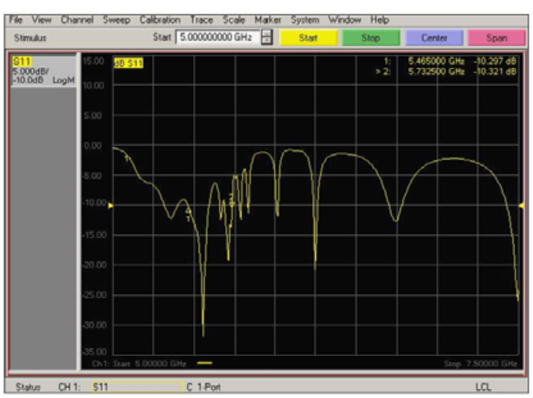


Fig. 4. Reflection coefficient for waveguide loaded with SSRRs inclusions (S11).

It must be proved that the transmission must be good enough for propagation. These results are in good agreement with numerical analysis with some discord results from fabrication errors. One of the other important tempers for loaded waveguide is the electromagnetic propagation from the open ended waveguides at frequency below cut-off frequency. Waveguide miniaturization theory was proved by making measurements at 5.5GHz at that frequency the lowest S11 value was observed.

The co-polar and cross-polar electric field values were measured as a function of the antenna receiving angle. At zero angles the co-polar transmission was approximately zero decibels, so good transmission properties have been achieved below cut-off frequency (Fig. 5).

Co-polar and cross-polar magnetic field values were measured according to changes on received antenna angle at 5.65GHz (Fig. 6). Co-polar transmission from waveguide is good at zero angles. As a result, below the cut-off frequency of waveguide, a sufficient transmission have been observed for both E and H plane.

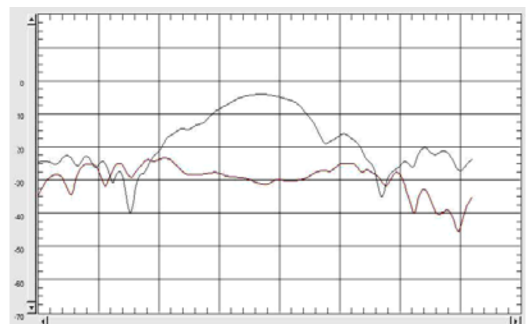


Fig. 5. Copolar and cross polar E plane for open ended waveguide.

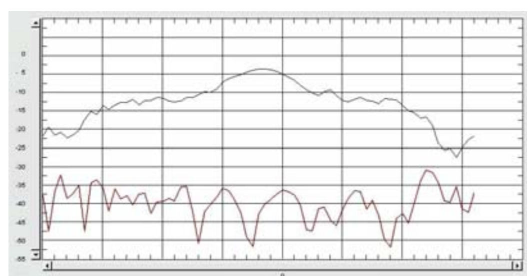


Fig. 6. Copolar and cross polar H plane for open ended waveguide.

3. Conclusions

It has been demonstrated both theoretically and experimentally that TSSRRs loaded waveguide exhibits propagation well below cut off frequency. This means that subwavelength waveguide have been obtained using negative magnetic metamaterials and waveguide miniaturization could be possible by this method. Reflection coefficient phase have been simulated for maximum transmission band below cut-off frequency. Backward wave propagation has been proved, since phase lagging properties. Radiation properties of both E and H plane for metamaterial loaded waveguide have been observed.

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