The Effect of Length of TSSRRs Loaded Substrate on WG Miniaturization

Muharrem Karaaslan[1], Faruk Karadag[2], and M.Zeki Kurt[2]

[1] Telecommunication Laboratory, University of Mersin , Çiftlikköy,Mersin,Turkey
mkaraaslan@mersin.edu.tr
[2]Science and Letter Faculty, University of Cukurova Balcali,Adana, Turkey
fkaradag@cu.edu.tr, mzkurt@cu.edu.tr

Abstract

In this study, the effect of uniaxial anisotropic magnetic artificial media composed of TSRRs type magnetic dipoles on a rectangular waveguide-WR90 have been observed. Different length and number of TSRRs have been placed in WR90 and effect of reflection coefficient have been observed. Miniaturization of rectangular waveguides with artificial diamagnetic media and subwavelength propagation has been proved experimentally.

1. Introduction

Electric permittivity (ε) and magnetic permeability (μ) are macroscopic parameters of electromagnetic (EM) fields' effect on bulk media or vice versa. The main difference between man made materials and natural materials is qualitatively. At Last decade, man made EM composites for special macroscopic properties have collected considerably interest within scientific community [1].

The early studies on artificial dielectric structures begin in 1950's [2]. Wavelength of applied electromagnetic fields are much longer than the unit cell of man made structure named effective media that can be described with bulk electromagnetic parameters permittivity (ε) and permeability (μ), different than Bragg diffraction and photonic crystals [3,4]. Although it could be possible to achieve filter characteristic with frequency selective surfaces (FSSs) and photonic crystals (PC) that includes unit cell on the order of wavelength, but bulk EM parameters (dielectric permittivity and magnetic permeability) couldn't be used to describe their properties.

Metamaterials challenge to nature than photonic crystals and conventional dielectric media such as left handedness (LH) [5], backward wave (BW) phenomenon [6], reverse Vavilov-Cherenkov radiation [7], perfect focusing [8] and negative refraction [9]. Generally meta-materials consists of two different types of elements one is to realize electrical response such as wires, capacitive loaded strips (CLSs) and the other one is to achieve magnetic response such as split ring resonator (SRR) Both of these type of inclusions have dimensions much shorter than applied EM wavelength to mention effective medium characteristics. Since there is no natural media that exhibit negative permittivity and permeability, simultaneously, the effect of this hypotetical media to EM waves discussed by Veselago in 1968 [10]. In this study this media was named as "left handed media" (LHM), because EM wave components that includes electric field magnetic field and wave vector formed a left handed triplet with respect to Maxwell equations. One another important properties of LHM that was wave vector and pointing vector move opposite directions in a LHM and this resulted unconventional phenomenon such as inverse refraction, reverse Doppler shift, Goos-Hanchen Phenomenon and inverse Cherenkov radiation.

The design of effective media characteristics results with many different applications to achieve novelty properties such as, waveguide miniaturization [11,12], sub-wavelength imaging [13], cloaking objects [14], magnetic resonance [15] and antenna gain improvement [16,17]. The main tool to achieve negative magnetic effect is split ring resonators SRRs. These inclusions includes the metal part that behaves as inductor and gap between metal exhibits capacitive response. Equal L-C values causes resonance circuit and increased magnetic effect. One of the disadvantages of SRR is the asymmetric current flow on the metal parts and asymmetric capacitive effect that causes unwanted electric effect. To reduce this effect many different types of inclusions have been used such as ICSRRs [18] and C shape metals. Waveguide dimensions are important parameters to satisfy boundary conditions and minimization of that are one of the challenge issue for engineers. It is well known that the dimensions of waveguides must be half of wavelength to achieve propagation so that necessary boundary conditions is satisfied. One way to realize minimization is dielectric material replacement into waveguide and $1/\sqrt{\varepsilon_r}$ rational decreasement achieved. But high losses of dielectrics for higher frequencies is a problem and restrain the miniaturization applications.

One of the other way is to place magnetic inclusions into waveguides so that negative permeability is achieved and propagation have been observed below half of wavelength.

In this study two symmetric split ring resonator (TSSRRs) type inclusions have been used to realize magnetic effect and constitute negative magnetic media in a rectangular waveguide to achieve waveguide miniaturization (Fig. 1). Different length and number of TSSRRs designed on dielectric substrates, placed in waveguide and S11 values have been observed for each of them. The effect of the length and number on miniaturization have been obtained.

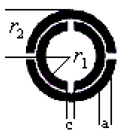


Fig.1. Two symmetric split ring resonator (TSSRRs)

2.TSSRR Loaded WG Miniaturization Measurement

The dimensions of waveguides have been a real problem to minimization of systems and miniaturization of waveguides is a challenge for microwave engineering. In this theoretical respect how could the dimensions reduced by fulfilling waveguides. For anisotropic media electromagnetic parameters [19];

$$\overline{\mu} = \mu_0\mu_r = \mu_0 \begin{bmatrix} \mu_i & 0 & 0 \\ 0 & \mu_j & 0 \\ 0 & 0 & \mu_k \end{bmatrix}; \overline{\varepsilon} = \varepsilon_0 \begin{bmatrix} \varepsilon_i & 0 & 0 \\ 0 & \varepsilon_j & 0 \\ 0 & 0 & \varepsilon_k \end{bmatrix} \quad (1)$$

EM waves must satisfy Maxwell free source equations;

$$\begin{bmatrix} \vec{\nabla} X \vec{E} \\ \vec{\nabla} X \vec{H} \end{bmatrix} = \begin{bmatrix} & -jw\mu_0\mu_r \\ jw\varepsilon_0\varepsilon_r & \end{bmatrix} \begin{bmatrix} \vec{H} \\ \vec{E} \end{bmatrix} \quad (2)$$

The wave equation for general situation must be [20];

$$\frac{1}{\mu_i}\left[\frac{\partial}{\partial j}\frac{\partial}{\partial k}E_k - \frac{\partial^2}{\partial k^2}E_j\right] - \frac{1}{\mu_k}\left[\frac{\partial^2}{\partial i^2}E_j - \frac{\partial}{\partial i}\frac{\partial}{\partial j}E_i\right] = k_0^2\varepsilon_j E_j \quad (3)$$

It is well known that in a waveguide TEM waves can not propagate since there is only one conductor in a rectangular waveguide so a rectangular waveguide supports only TM and TE modes. If the applied wave assumed TE to -i direction and the electric and magnetic parameters are as follows;

$$\mu_e = \mu_e' - j\mu_e'' \qquad \mu_z = \mu_b \text{ and } \quad \varepsilon_{x,y,z} = \varepsilon \quad (4)$$

Dispersion relation will be;

$$k_i^2 = (\varepsilon' - j\varepsilon'')(\mu_t' - j\mu_t')(k_0^2 - \frac{k_j^2}{\varepsilon\mu_l}) \quad (5)$$

k is the wave vector in media, k_0 is the space wave vector. If the permittivity is isotropic and only transverse component of permeability is negative, EM waves will propagate and transmission below cutoff frequency will be realized.

$$(k_0^2 < \frac{k_j^2}{\varepsilon\mu_l}) \quad (6)$$

The best way to observe waveguide dimension miniaturization depending on magnetic metamaterials is to attach two different waveguide to each other as shown in fig.2. One is used to apply EM waves by a coaxial cable. This waveguide is WR137 and cutoff frequency is 5 GHz. The attached waveguide is WR90 and cutoff frequency is approximately 6.5 GHz. It couldn't possible to propagate EM waves below 6.5 GHz in WR90, normally. But it could be possible to apply down to 5GHz from WR137. One side of magnetic metamaterial loaded waveguide is open to measure EM radiation. Firstly S11 parameters that are reflected from loaded WG will be measured for different length-number load. If S11 parameters magnitude is decreased in dB these means EM waves propagate below cutoff and radiate placing antenna to open end.

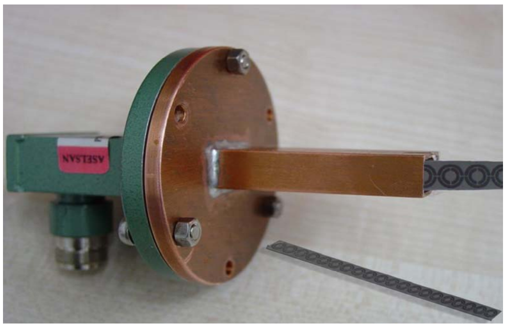


Fig.2. Attached WR90 and WR137 types of waveguides

The measurements observed with HP8362B vector network analyzer in an anechoic chamber and frequency range is 5GHz-7.5 GHz.The diffferent number magnetic inclusions have been placed longitudinally in WR90 type waveguide to realize anisotropic magnetic effect and how S11 is effected from number of ICSRRs will be measured. ICSRRs dimension inner radius - outer radius are 130mil and 200mil, respectively. Split length 30mil and the distances between two ring is 20mil.

The TSSRRs type inclusions have been designed on dielectric substrate FR4 with 8 electrodeposited one sided copper foils using standard etching process. The TSSRRs type inclusions used to minimize bianisotropic effect so ignored electrical polarization. Reflection-S11 from structure measured by the source antenna in WR137. The lattice constant between adjacent elements is choosen equal to split length.

Four different lengths dielectric substrate have been placed in same length WR90. To supply symmetry these substates placed in the middle of waveguide longitudinally and the magnetic component of EM wave must be applied to the center axis of TSSRRs otherwise it doesn't effect the inclusions; they don't behave as magnetic dipole polarizer. First one is 6cm length and has 10 TSSRRs. The S11 value is decreased below -10dB at 5.54GHz and transmission is possible below cutoff frequency 6GHz of WR90. Second one is 7cm length 11 TSSRRs dielectric substrate. The S11 value is below -10dB at 5.49GHz that is less than first one. First frequency of the S11 value below -10dB for 7.5cm-12cm TSSRRs inclusions substrate is 5.47GHz that is less than formers. So waveguide boundary condition limits growth and it has been realized to transmit EM waves any frequency that doesn't depend on the transversal dimensions. These transmission below cut-off frequency could be observed only a narrow band frequency range because of energy conservation law.

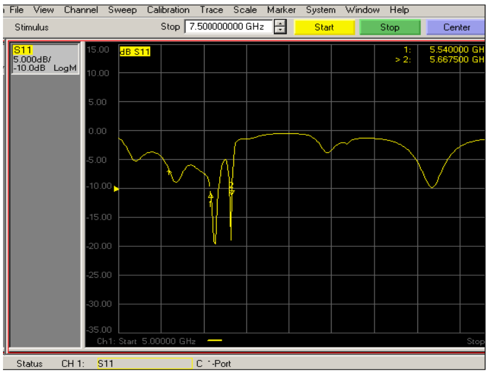
The last dielectric substrate contains 13TSSRRs- 8cm length and one TSSRRs at both end of the substrate is outside of waveguide to maximize radiation and electrical compatibility. The S11 value is below -10dB at 5.46GHz and the transmission looks like increased since S11 is below -30dB is much less than the measurement values before as shown in fig. 2.

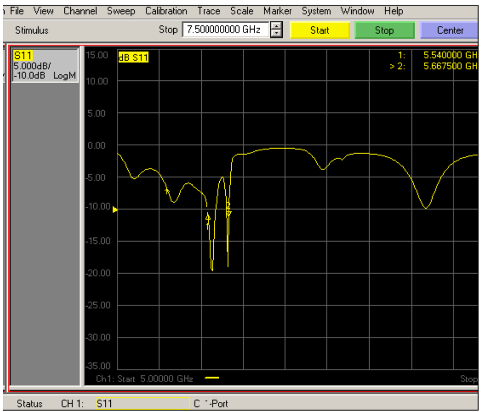
As a result for S11 TSSRRs substrate the cut off frequency decreased from 6.5GHz to 5.46 GHz and well transmission is observed with -32dB S11 reflection value. These means that at approximately 1GHz less than normal cutoff frequency transmission is achieved, since constituted negative transversal permeability. This means that fifteen per cent miniaturization of waveguide transversal dimensions could be possible. This result is a challenge for classical waveguides boundary conditions. One other result is that the number of inclusions and the

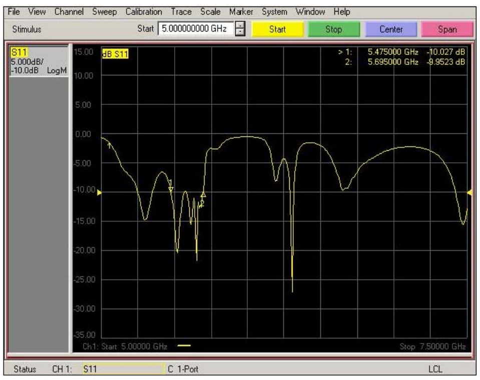
TSSRRs that are out of end are effect transmission and radiation of EM waves.

3. Conclusions

The subwavelength properties of rectangular waveguides loaded by resonant scatterers- TSSRRs type magnetic inclusions designed on a substrate have been studied. It has been revealed that different number and length TSSRRs magnetic resonant scatterers allow one to obtain a minipassband below the cutoff frequency of the rectangular waveguide. The measurements of different length are in good agreement with theoretical extractions. The miniaturization of waveguide have been observed for all different length substrate, especially for the last one that is longer than waveguide and some of TSSRRs are out of ends. As a result fifteen per cent miniaturization of waveguide transversal dimensions by using TSSRRs loaded waveguide have been revealed that is a challenge for classical waveguides boundary conditions that is good agreement with known literature data.







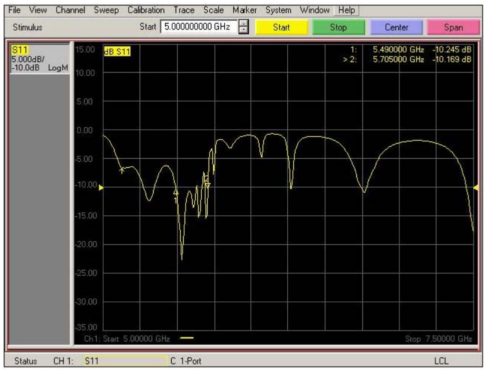


Fig.3. Reflection coefficient-S11 of waveguides that are loaded different length inclusions a. 6cm-10 TSSRRs b. 7cm-11TSSRRs c. 7.5cm-12 TSSRRs d. 8cm-13TSSRRs

4. References

[1] J. B. Pendry, A. J. Holden, W. J. Stewart and Youngs I.," Extremely Low Frequency Plasmons in Metallic Mesostructures" *Phys. Rev. Lett*, 76**,** 4773, 1996.

[2] S. B. Cohn, "Analysis of the metal strip delay structure for microwave lenses",*J. Appl. Phys*.,20, 257– 262,1949.

[3] C. Caloz, "Metamaterials, Transmission Line Theory and Microwave Applications", New York, 2005.

[4] G. Eleftheriades, K. G. Balmain, "Negative-refraction metamaterials Fundamental Principles and Applications", New York, 2005.

[5] J. B. Pendry, A. J. Holden, D. J. Robbins and W. Stewart, "Magnetism From Conductors And Enhanced Nonlinear Phenomena" *IEEE Trans. Microwave Theory Tech*., 47 2075, 1999.

[6] K. Aydin, Z. Li, L. Sahin, and E. Ozbay, "Negative phase advance in polarization independent, multi-layer negative-index metamaterials", *Optics Express*, Vol. 16, Issue 12, pp. 8835-8844, 2008.

[7] A. A. Zharov, I. V. Shadrivov and Y. S. Kivshar, "Nonlinear Properties of Left-Handed Metamaterials", *Phys. Rev. Lett.,* 91, 037401, 2003.

[8] J. B. Pendry, "Negative Refraction Makes Perfect Lens "*Phys. Rev. Lett.* 85, 3966, 2000.

[9] K. Aydin and E. Ozbay, "Negative refraction through an impedance-matched left-handed metamaterial slab", *JOSA B,* Vol.23, Issue3, pp.415-18, 2006.

[10] V. G.Veselago,"The Electrodynamics of Substances with Simultaneously Negative Values of ε and μ". *Sov. Phys.—Usp*., 10: 509 ,1968.

[11] R. Marques, J. Martel, F. Mesa, F. Medina, "Left-Handed-Media Simulation and Transmission of EM Waves in Subwavelength Split-Ring-Resonator-Loaded Metallic Waveguides." *Phys.Rev. Lett*., 183, 901-904, 2002.

[12]S. Hrabar, J. Bartolic, Z. Sipus, "Waveguide Miniaturization Using Uniaxial Negative Permeability Metamaterial" *IEEE Transactions On Antennas and Propagation,* 53 (1), 110, pp.192-195, 2005.

[13] P. Belov, C. Simovski, P. Ikonen, "Canalization of subwavelength images by electromagnetic crystals", *Phys. Rev. B,* **71**,193105, 2005.

[14] P. Alitalo, O. Luukkonen, L. Jylhä, J. Venermo, S. A. Tretyakov, "Transmission-line networks cloaking objects

from electromagnetic fields”,*IEEE Trans. Antennas Propag*. 56(2), 416, 2007.

[15] Z. Dong, M. Xu, S. Lei, H. Liu, T. Li, F. Wang, S. Zhu, “Resonance amplification of left-handed transmission at optical frequencies by stimulated emission of radiation in active metamaterials”,*Appl. Phys. Lett.,* **92**, 064101, pp.20974-20980, 2008.

[16] R.W. Ziolkowski and A**.** Erentok**, "**Metamaterial-based efficient electrically small antenna**s**," *IEEE Trans. Antennas Propag*., vol.54, no.7, pp.2113–2130, 2006.

[17] A. Erentok and R.W. Ziolkowski, "A hybrid optimization method to analyze metamaterial-based electrically small antenna**s**,", *IEEE Trans. Antenna**s** Propag.*, Volume 55, Issue 3, pp.731 – 741, 2007.

[18] F. Karadağ and M. Karaaslan, “Artificial magnetic media and PMC with non magnetic ICSRR inclusions”, *OAM-RC,* Volume 3, issue 4, pp. 390-393.

[19] D. J. Griffiths, " Introduction to Electrodynamics", Prentice Hall, New York, 1998.

[20] J. D. Jackson, "Classical Electrodynamics", Wiley, New York , 1998.