International Journal of Natural and Engineering Sciences 7 (1): 61-65, 2013
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Effection and Electromagnetic Coupling of Metamaterial in Waveguide Propagation

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Received: August 09, 2012
Accepted: September 14, 2012

Abstract

Using waveguides is inevitable in many applications. They have number of advantages rather than planar guiding structures such as lower loss, high power handling capability, absence of substrate mode losses and etc. Waveguides manufacturing cost and their size at low microwave frequencies are the biggest disadvantages. In this paper, an open ended waveguide antenna is loaded with broadside coupled omega shaped metamaterial, proposed. Because of supporting backward waves, it can radiate below the cutoff frequency of corresponding empty waveguide. This phenomena can use for miniaturization of them.

Keywords: Metamaterial; Backward waves; Braodside Coupled Omega Shape

INTRODUCTION

It is known from electromagnetic that for propagation of waves through a waveguide, its cross section width must be at least one half of wavelength [1]. In the last few years, there have been several new ideas which may lead to the miniaturization of waveguide. Classical method was done by filling it with a dielectric yielding to size reduction with factor $1/\sqrt{\varepsilon_r}$ relative to corresponding empty one, ε_r is relative permittivity of filling material [2], the disadvantage of this method is that it cannot be used as antenna because of low radiation from open ended port. Another approach is to use artificial perfect magnetic conductors (complex surfaces) in its walls that providing TEM propagation [3]. The electromagnetic properties of a material can be described by its permittivity and the permeability [2]. These two parameters macroscopically describe the effects of induced electric and magnetic polarization. After electromagnetic metamaterials introduced, the application of these materials was studied in antenna and guiding structures. Metamaterials (MTM) are artificial materials that cannot be found in nature normally, these materials generally composed of periodic conductor structures and dielectric substrate. They have few unusual attributes like the reversed Doppler Effect, negative refraction, reversed cherenokov radiation, and supporting backward wave propagation in a waveguide [4]. In miniaturization case, it will be used special filling material with transversal negative permeability, this kind of waveguide enable to support backward wave propagation. It means that wave propagation is possible at an arbitrary frequency below the cutoff frequency of corresponding empty one. Therefore the waveguide width can be smaller than half of wave length in filling material. This property is useful for reduction the size of it.

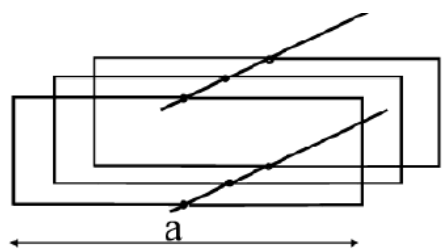
Transmission line Analyze

In this section, rectangular waveguide with filling material is analyzed. In nature all of materials have losses, but it is supposed filling material is lossless, therefore from lossless waveguide equations propagation factor is written in form of [3]:

$$k_y = \pm k_0\sqrt{\varepsilon_r \mu_{tr}\left[1-\left(\frac{f_c}{f}\right)^2\right]} = \beta_y \quad f_c = \frac{f_{co}}{\sqrt{\varepsilon_r \mu_{lr}}}$$

In above equation f is the frequency of the signal, whereas f_{co} and f_c are respectively the cutoff frequencies of an empty waveguide and same one that filled with material and ε_r is relative permittivity and μ_{tr} , μ_{lr} are the relative permeabilities in the transversal and longitudinal direction, respectively[2].

Waveguide can be analyzed with transmission line theory. It can be modeled as simple two-wire TEM transmission line with infinite number of short circuit shunt element of length a/2, (a is length of waveguide cross section). As shown in Figure 1.a this model can be represented by distributed series inductance associated with transverse permeability and parallel capacitance associated with metamaterial permittivity Figure 1.b if we consider that energy flow is along the waveguide, the longitudinal flow is responsible for existence of nonzero transversal magnetic field vector H_t and therefore existence of distributed inductance associated with μ_t and energy flow in shunt element induces longitudinal magnetic field H_l and it introduces distributed shunt inductance Figure 1.c [2].



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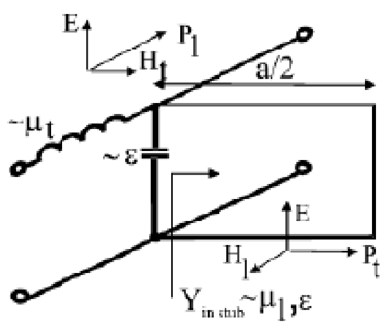

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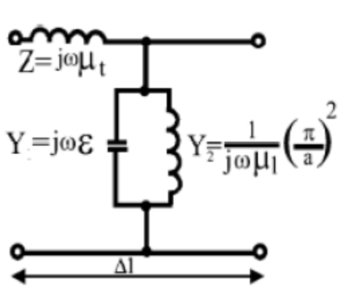


(c)

Figure 1. (a) Transmission line representation of a rectangular waveguide (b) Inductance and capacitance model (c) Equivalent circuit of a waveguide filled with uniaxial metamaterial [2].

When the filling material is uniaxial anisotropic metamaterial with negative transversal relative permeability, if the incident wave frequency is above the cutoff frequency of empty one ($f > fc$), the propagation factor becomes imaginary, so there is no propagation above the cutoff frequency. If the wave frequency is below the cutoff frequency ($f < fc$), the propagation factor will be real and the sign in front of square root will be negative. This shows that wave propagation is possible below the cutoff frequency and propagation exists due of supporting backward waves. In this condition the series inductance is negative and behaves as capacitance, and shunt element will be shorter than a quarter wave length, and shunt tank circuit in Figure 1.c operates below cutoff frequency and behaves as inductance. Furthermore equivalent circuit behaves as L-C line and supports backward waves [5]. This kind of waveguide has low pass behavior and can be supposed as dual of ordinary one with high pass behavior. Table 1 shows the effect of different filling materials in waveguide and transmission lines models which are reduced.

Tabel 1. Comparison of different filling material in waveguide.

Filling material	μ_r	ε_r	Equivalent Transmission Line Series element-shunt element $f < f_c$	$f > f_c$
Isotropic DPS	$\mu_{rl} = \mu_{rt} = \mu_r$ $\mu_r > 0$	$\varepsilon_r > 0$	$L - L$	$L - C$
Isotropic DNG	$\mu_{rl} = \mu_{rt} = \mu_r$ $\mu_r < 0$	$\varepsilon_r < 0$	$C - C$	$C - L$
Isotropic MNG	$\mu_{rl} = \mu_{rt} = \mu_r$ $\mu_r < 0$	$\varepsilon_r > 0$	$C - C$	$C - C$
Isotropic ENG	$\mu_{rl} = \mu_{rt} = \mu_r$ $\mu_r > 0$	$\varepsilon_r < 0$	$L - L$	$L - L$
Uniaxial MNG	$\mu_{rl} > 0$ $\mu_{rt} < 0$	$\varepsilon_r > 0$	$C - L$	$C - C$

METAMATRIAL DESIGN AND SIMULATION RESULTS

In this section the appropriate filling material is designed for our purpose. The split ring resonator (SRR) is one of the first designed structures, and is known as a negative permeability material [6]. But it main drawback is limitation on control the permittivity parameter. In order to obtain better resonance in some frequencies, the omega shaped structure is used [7]. Omega shaped metamaterial is combination of SRR and strip lines to control permittivity, but the medium parameters of this structure is coupled and tuning is less hard than SRR. It is composed of copper rings that have outer radius of 2.75mm and inner radius of 1.75mm, the slit width is 0.5mm and the length and width of strip lines are 4mm and 1mm respectively. Rings have been placed in both side of substrate 1.524mm thick krempel Akafle with relative permittivity of 3.4, Figure 2 shows the unit cell of metamaterial structure. The main factor of omega shaped structure designing is the size of unit cell that should be much smaller than the guided wavelength (λ_g). For miniaturization, the array of seven unit cells with size of 6mm, placed in summery plane of 42mm long section of standard X-band waveguide BJ-100 (cross section of 22.86mm x 10.16mm) in Z-direction with cutoff frequency of 6.6GHz, it is observed in Figure 3. According to equation (14b) [1], the value of λ_g is 40mm for this waveguide, the operating frequency is 10GHz. By Ansoft HFSS simulator, it is observed that the transversal effective permeability is negative around frequency of 4GHz as shown in Figure 4, and expected the backward wave phenomena. The simulation results demonstrated in Figure 5. According to the results, it is observed transmission occurs around frequency of 4.3GHz, is below the cutoff frequency of empty waveguide. The bandwidth of the backward wave propagation is governed by the dispersion property of filling material [2]. In above discussion, it is supposed material has no dispersion whereas in nature each material has dispersion, therefore this kind of antenna can support backward wave propagation only within the limited frequency rang.

If this structure is used as open ended antenna, it is observed from Figure 6, that propagation pass band is located below the cutoff frequency of the X-band waveguide with the bandwidth of 800MHz. In fact, X-band waveguide antenna is used in lower frequency band (C-band) that will be led to large size for wave propagation. Thus if it is wanted to use ordinary standard waveguide in above frequency range, it should be chosen the BJ-48 option with cross section of (47.549mm x 22.149mm) [8]. The dimensions of waveguide cross section is approximately twice of standard BJ-100 that is used for simulation, therefore the capability of using waveguide below the cutoff frequency can be useful for miniaturization of it.

CONCLUSION

It is carried out simulation of broad side coupled omega shaped metamaterial loaded X-band waveguide. According to simulation results, the transmission of filling metamaterial waveguide occurs around frequency of 4.3GHz that is below the cutoff frequency of corresponding empty one, because of supporting backward waves. This kind of waveguide has low-pass behavior and can be supposed as a dual of ordinary waveguides with high pass behavior. Simulation results also show that the open ended waveguide antenna that derives from filling waveguide, radiates around frequency of 4GHz with bandwidth of 800MHz. Using waveguide below the cutoff frequency, is effective for miniaturization.

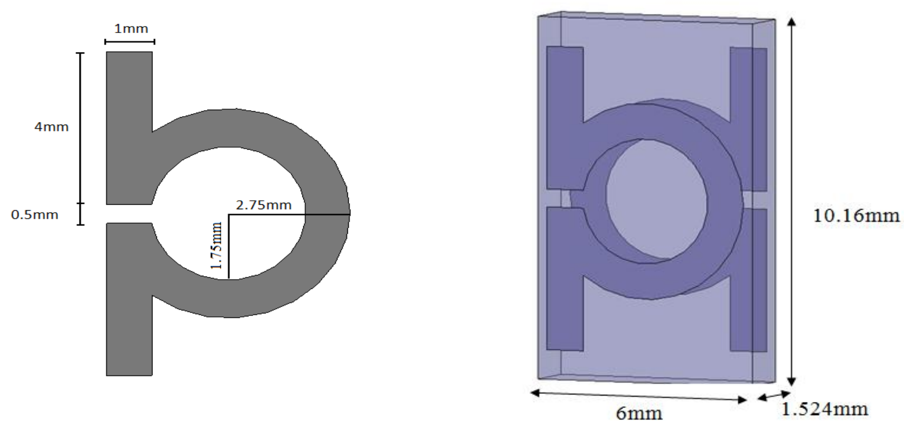


Figure 2. (a) Copper ring (b) unit cell of metamaterial structure

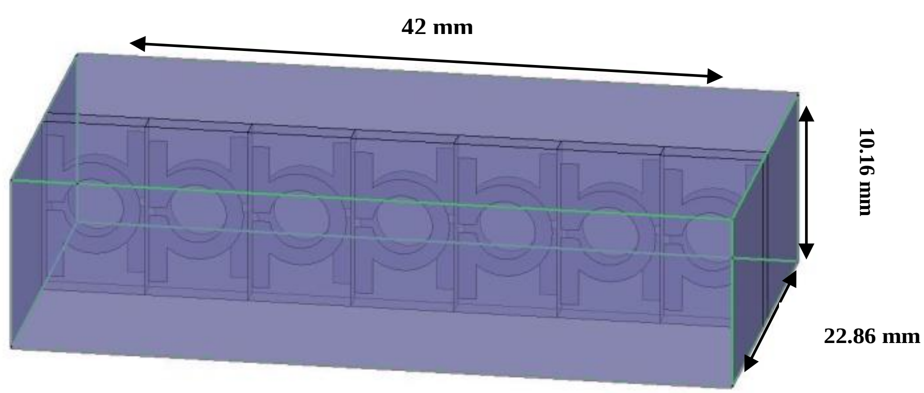


Figure 3. Schematic of filling waveguide with metamaterial

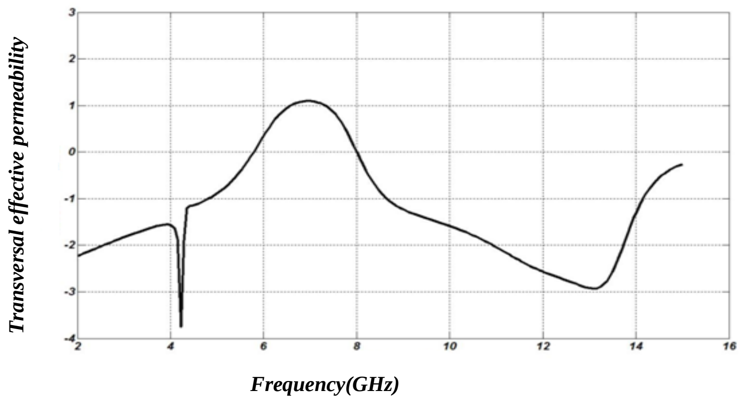
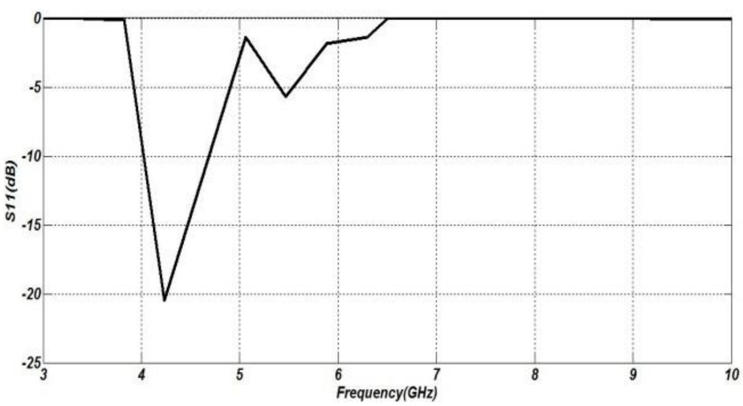


Figure 4. Transversal effective permeability of omega shaped metamaterial



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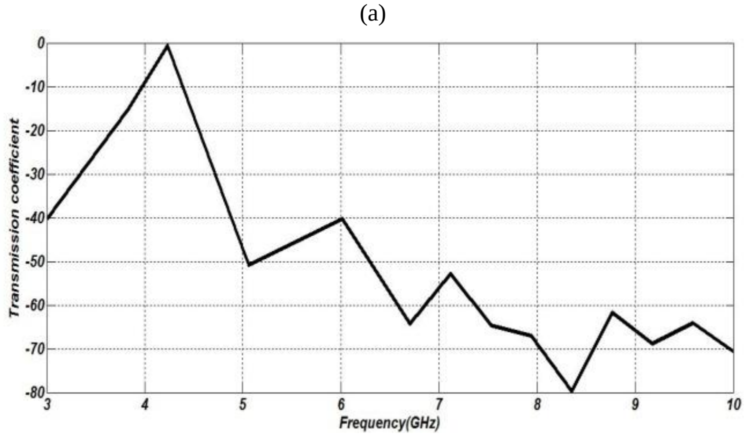

(b)

Figure 5. Parameters of filling waveguide (a) S_{11} (b) S_{21}

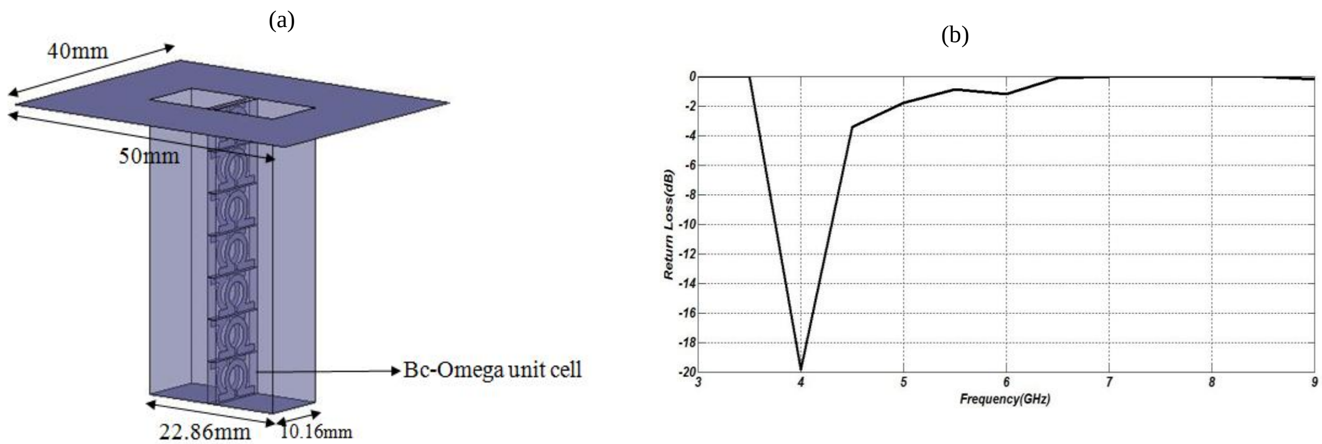

Figure 6. (a) Waveguide antenna with metamaterial structure (b) Return loss diagram

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