

## A NOVEL WAVEGUIDE BASED METAMATERIALS

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## 1. Introduction

Artificial materials with simultaneously negative epsilon and mu the so called metamaterials were theoretically proposed by Russian physicist Veselago [1] in 1968. But experimental verifications of such composite materials was done only recently by Schmidt et al in 2001 issue of Science [3] based on the earlier works by Pendry et al [2]. Several research works have been carried out worldwide for realization and applications of such materials in antennas, microwaves and optics and a special issue of IEEE Transactions on Antennas and Propagation October 2003 is entirely devoted to metamaterials [4]. Here we propose a novel and much more simplified kind of structure for realization of metamaterials: closely spaced square strip layers inside X-band rectangular waveguide. It is observed that for such periodic waveguide structures the epsilon and mu are simultaneously negative over a finite band of frequency, which is a necessary characteristics signature of metamaterials [1]. Such periodic structure has equivalent circuit that of the dual of the conventional LC transmission line and exhibits backward wave behavior, which are the intrinsic properties of metamaterials [5]. A hybrid MoM-immittance approach has been developed for efficient and accurate full-wave characterization of printed strips and slots of arbitrary shape and size inside layered waveguide [6]. This approach has been utilized to analyze the newly proposed waveguide based metamaterials.

## 2. Geometry and equivalent circuit

Figure 1(a) depicts the geometry of a double printed strip layers inside a rectangular waveguide. This periodic structure can be modeled by analyzing the properties of a single unit cell. S-parameters of an unit cell is obtained first using the hybrid MoM-immittance approach [6]. Following the method described in [6], equivalent circuits of an unit cell is extracted and it acts as the dual of the LC transmission line as illustrated in Fig. 1(b) over a frequency region of interest (9.97-10.15GHz). In the equivalent circuit of an unit cell, the series capacitance is due to the interaction of the two closely spaced strip layers whereas the two shunt inductances are for the two strip layers of the unit cell. The dimensions of the Fig. 1(a) are taken as  $w=10.0\text{mm}$ ,  $l=7.0\text{mm}$ ,  $h=1.0\text{mm}$ ,  $p=2.8\text{mm}$ ,  $a=22.86\text{mm}$ ,  $b=10.16\text{mm}$  and  $\epsilon_r=3.78$  of the dielectric layer for all the simulation works. This dimension is chosen from the list of extensive simulation works we have done for such kinds of structures. Only one plot for each graph is shown here just to highlight metamaterials phenomenon and for easier deciphering.

## 3. Backward wave

The normalized phase constant,  $\beta/k_0$ , of the periodic structure has been numerically calculated from the ABCD parameters obtained from the S-parameters through a standard transformation as described in [7]. From Fig. 2, it is seen that up to a certain cutoff frequency there is stopband ( $\beta/k_0=0$ ) and above this frequency, there is a passband ( $\beta/k_0 \neq 0$ ) then a stopband again. In the passband frequency region (9.97-10.15GHz), the group velocity ( $\partial\omega/\partial\beta < 0$ ) is antiparallel to phase velocity ( $\omega/\beta > 0$ ) and hence a backward wave behavior [5] is seen.

## 4. Negative epsilon, mu and refractive index

Epsilon, mu and refractive index are numerically calculated using the method described in [8] from the ABCD parameters. As illustrated in the Fig. 3, the real part of the permittivity goes negative from 9.97 GHz to 10.15GHz. Similarly, from Fig. 4, the regions for negative permeability are

7-9.35GHz and 9.97-13GHz. The dependence of various parameters like strip width ( $w$ ), length ( $h$ ), separation distance between two strip layers ( $h$ ) and the relative permittivity ( $\epsilon_r$ ) on the negative epsilon,  $\mu$  and refractive index is currently under investigation.

The amplitude of  $n$  is positive for 9.35-9.97GHz, negative for 9.97-10.15GHz, remains zero for all other frequency regions under consideration. The value of  $n$  reached its most positive value at 9.85GHz, passed through zero at 9.97GHz and then reached its most negative value at 10GHz as illustrated in Fig. 5. The electromagnetic (EM) waves will propagate in a medium that has a real index of refraction. If either  $\epsilon$  or  $\mu$  is negative, then  $n$  is imaginary and there will be no transmission through the periodic structure. If, however, both  $\epsilon$  and  $\mu$  are less than zero, EM waves will propagate through the medium, but negative root must be chosen and the group and phase velocity will be anti-parallel [9]. From Fig. 2, there are two forbidden or stop bands (7-9.35GHz and 10.15-13GHz), in these regions corresponding real part of relative permeability is negative whereas the relative permittivity remains positive (refer to Fig. 3 and Fig. 4). In the passband, for 9.35-9.97GHz frequency band there is forward wave (see Fig. 2) and consistently both epsilon and  $\mu$  are positive in Fig. 4 and Fig. 5 whereas for 9.97-10.15GHz frequency there is backward wave (refer Fig. 2) and corresponding epsilon and  $\mu$  are both negative (see Fig. 3 and Fig. 4).

## 5. Conclusion

The equivalent circuit of closely spaced strip layers inside waveguide has been extracted. It has been observed that the equivalent circuit is the dual of the conventional LC transmission line in some frequency region of interest thereby it acts a metamaterial in that frequency range. Further it has been verified that these kinds of structures has the properties of metamaterials like negative epsilon and  $\mu$ , backward propagation of wave in that frequency range. But the negative epsilon,  $\mu$  and backward wave propagation observed are for a very narrow frequency range. In future, we will consider various structures of strips to broaden the metamaterial frequency range.

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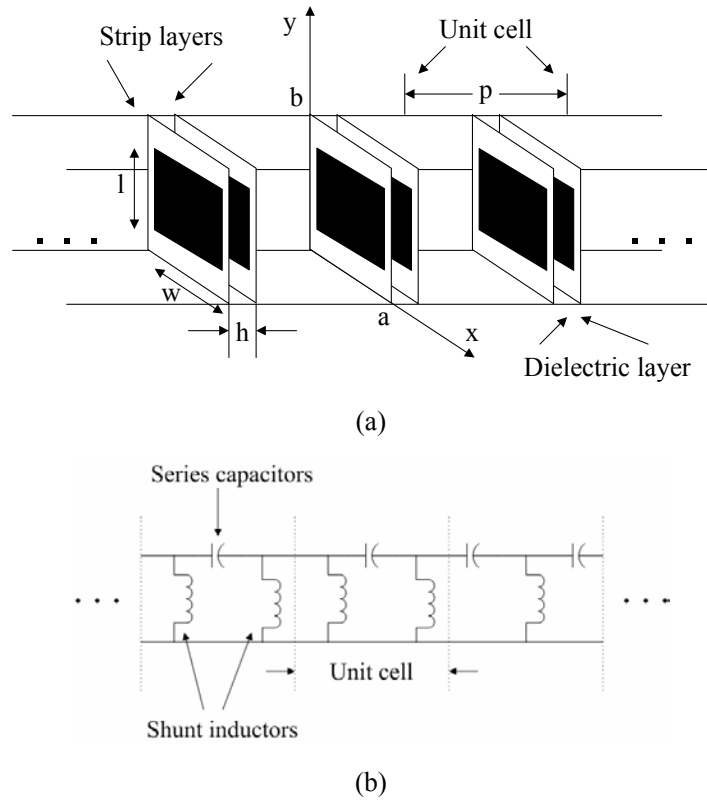


Fig. 1 (a) Geometry and (b) equivalent circuit of the waveguide based metamaterial

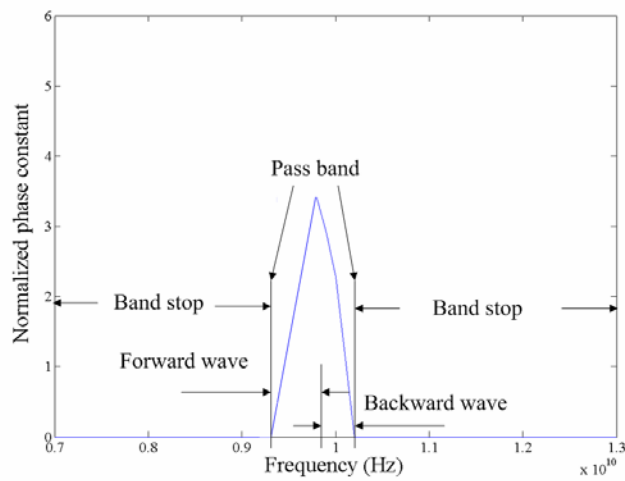


Fig. 2 Normalized phase constant vs frequency

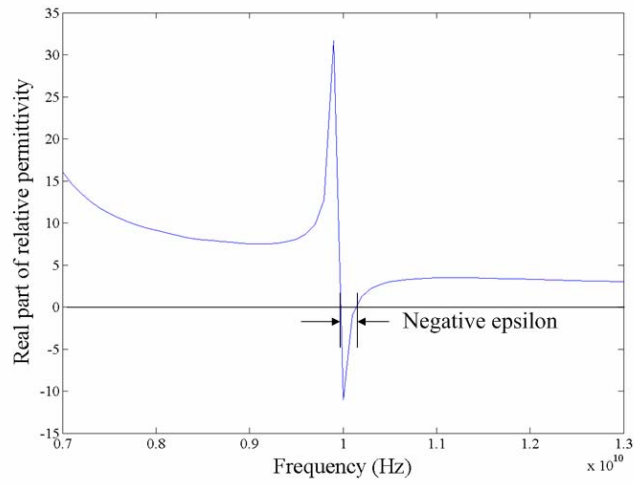


Fig. 3 Extracted real part of the relative permittivity vs frequency

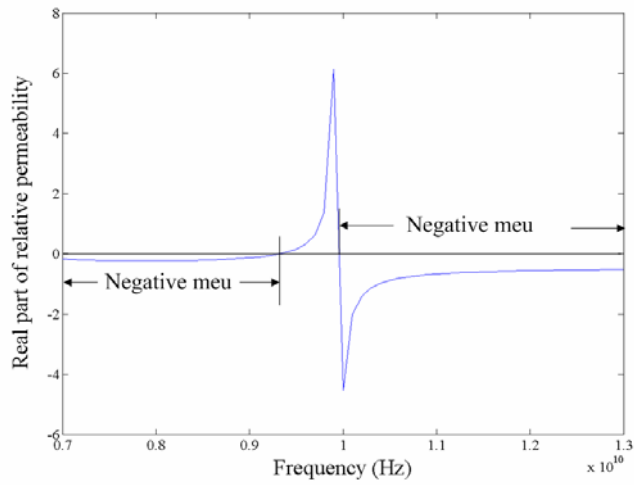


Fig. 4 Extracted real part of the relative permeability vs frequency

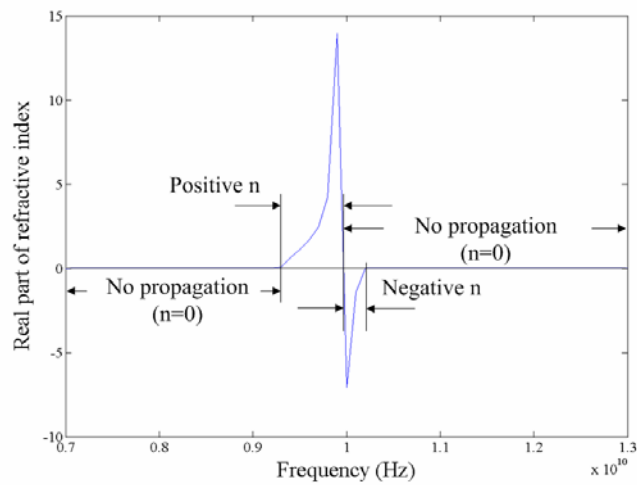


Fig. 5 Extracted real part of the refractive index vs frequency