CONTRA-DIRECTIONAL INTERACTION IN A NRD WAVEGUIDE COUPLER WITH A METAMATERIAL SLAB

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ABSTRACT

This paper addresses the use of metamaterials in the design of an NRD contra-directional coupler. The coupling between two parallel NRD waveguides, with the same phase constant but with antiparallel power flow provides new features that can be used in the design of novel devices for signal processing. We analyse the contra-directional interaction in a NRD waveguide coupler, in which, a metamaterial slab replaces one of the common isotropic slabs. The propagation of a backward wave in phase synchronism will cause a strong contra-directional interaction with significant interchange of energy.

INTRODUCTION

The analysis of unconventional media with both negative electric permittivity and negative magnetic permeability has recently received increased attention [1]-[3]. In such media, usually termed metamaterials, left-handed media or backward media, the direction of the Poynting vector is anti-parallel to the direction of the phase velocity [4]. However, most interesting effects associated to these media are not obtained by the media itself but in refraction at an interface with a conventional media. Actually, anomalous refraction occurs at a boundary between a metamaterial and a common dielectric medium [5]. On the other hand, phase compensation in paired dielectric-metamaterial layers can be used in the design of novel devices and components [6].

The fact that a metamaterial slab can support a backward wave means that the energy flows in the opposite direction to the wave propagation. Coupling between parallel waveguides possessing phase velocities of the same sign but with group velocities of opposite sign is known as contra-directional interaction. A contra-directional interaction occurs between the forward and backward waves propagating in a grating waveguide. Using a metamaterial slab, the same phenomena may occur between the modes of different parallel waveguides. This idea is addressed throughout this paper.

The application of complex media in the design of NRD (Non-Radiative Dielectric) waveguides [7], couplers [8] and other devices is a topic of great interest, since this waveguide finds large application in the millimeter wave regime. This paper addresses the application of metamaterials in the design of NRD directional couplers. In fact, the coupling between two parallel NRD waveguides, with the same phase constant but with antiparallel power flow provides new features that can be used in the design of novel devices for signal processing. In this paper, we analyze the contra-directional interaction in a NRD waveguide coupler, in which, a metamaterial slab replaces one of the slabs. In this case, phase synchronism between the forward and the backward waves will causes strong contra-directional interaction with significant interchange of energy.

A complete modal analysis for both LSE and LSM modes is presented in this paper. The operational diagram for the modes propagating in this structure is derived. Both the slab separation and the constitutive parameters are used to control the coupling coefficient between the elementary modes of the two-coupled NRD waveguides. The evolution of the power flowing along each waveguide as a function of the longitudinal coordinate is presented for different coupling lengths.

FIELD EQUATIONS

The structure under consideration is depicted in Fig. 1. It consists of a NRD directional coupler built with two coupled parallel NRD waveguides where, at least, a pseudochiral metamaterial slab replaces one of the dielectric slabs. The surrounding medium is the air.

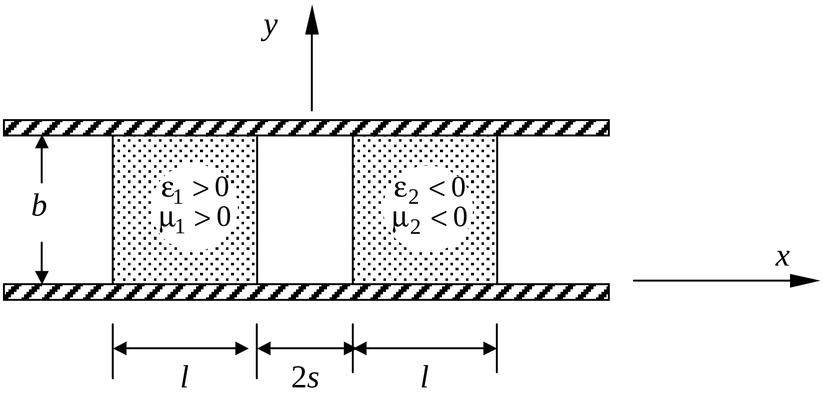

Fig. 1. Cross sectional view of two coupled parallel NRD waveguides, in which a metamaterial slab replaces one the common isotropic dielectric strips.

Herein, without loss of generality, an isotropic metamaterial is assumed although a uniaxial metamaterial [2] could also be considered. Therefore, the following general constitutive relations old

$$\begin{cases} \mathbf{B} = \mu_0\,\mu(x)\mathbf{H} \\ \mathbf{D} = \varepsilon_0\,\varepsilon(x)\mathbf{E} \end{cases} \tag{1}$$

where $\varepsilon(x)$ and $\mu(x)$ can be both either positive or negative. The modes supported by this structure as pure LSE and LSM modes. Considering plane wave propagation of the form $\exp[-j(\beta z - \omega t)]$, both LSE and LSM modes obey to the following dispersion relation:

$$\varepsilon(x)\mu(x)k_0^2 = k^2 + k_x^2(x) + k_y^2 \tag{2}$$

with $k_y = (2m+1)\pi/2b$ and $m = 0,1,2,...$

Moreover, for the LSE modes, the following transverse impedance can be defined

$$Z_0(x) = \frac{\omega\mu_0\mu(x)}{k_x(x)}, \tag{3}$$

while

$$Z_0(x) = \frac{k_x(x)}{\omega\varepsilon_0\varepsilon(x)}, \tag{4}$$

holds for the LSM modes.

The modal equation is derived by the transverse resonance method, according to the equivalent circuit depicted in Fig. 2:

$$\overrightarrow{Z}(x)+\overleftarrow{Z}(x)=0\,. \tag{5}$$

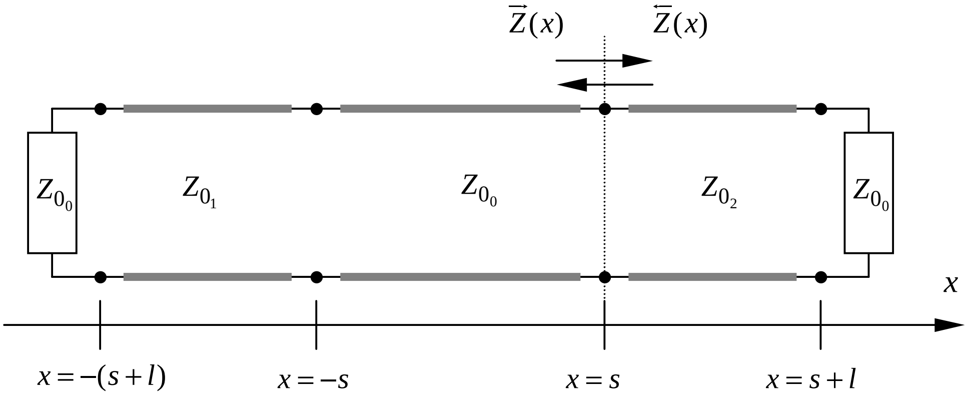

Fig. 2. Equivalent circuit for application of the transverse resonance method.

NUMERICAL RESULTS

A complete modal analysis for both LSE and LSM modes is presented in this section. The operational diagram for the structure is derived. Let β_a and β_s be the longitudinal wavenumbers of the first two symmetric and anti-symmetric LSM or LSE supermodes. It is shown known that both the slab separation and the constitutive parameters can be used to control the coupling coefficient between the elementary modes of the two-coupled NRD waveguides. Moreover, since phase synchronism will occur in this structure, one has

$$\delta=\frac{1}{2}(\beta_1-\beta_2)=0\,. \tag{6}$$

The power flow in each waveguide may be written as

$$\frac{P_1(z)}{P_1(L)}=\cosh^2\left[\kappa(z-L)\right] \tag{7}$$

with

$$P_1(L)=\frac{1}{\cosh^2(\kappa L)} \tag{8}$$

and

$$\frac{P_2(z)}{P_2(0)}=\frac{\sinh^2\left[\kappa(z-L)\right]}{\sinh^2(\kappa L)} \tag{9}$$

with

$$P_2(0)=\tanh^2(\kappa L) \tag{10}$$

where L is the coupler length, $\kappa = -jS$ and $S = (\beta_s - \beta_a)/2$.

The evolution of the normalized power flow along each waveguide is presented in Fig. 3 as a function of κz for $\kappa L = 1$.

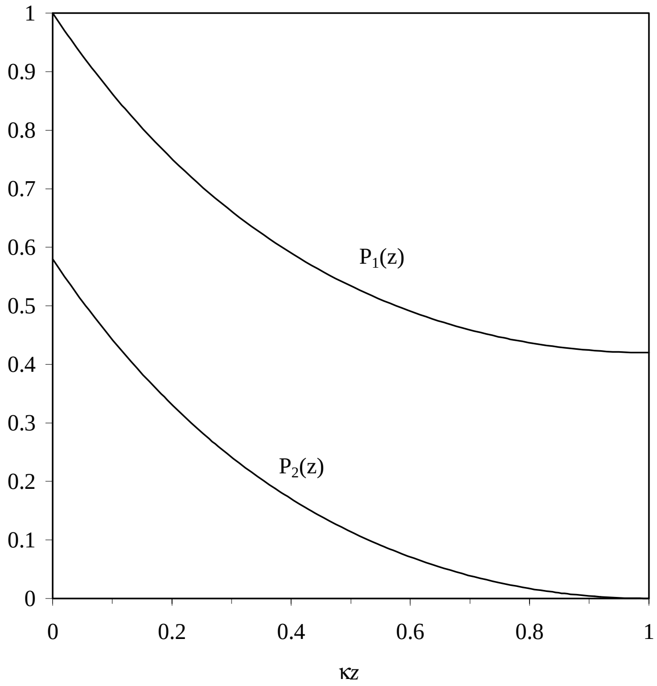

Fig. 3. Power flow in each waveguide as a function of z, for a directional coupler with $\kappa L = 1$.

CONCLUSIONS

A complete modal analysis for both LSE and LSM modes was presented in this paper. The operational diagram for the structure was derived. Both the slab separation and the constitutive parameters can be used to control the coupling coefficient between the elementary modes of the two-coupled NRD waveguides. The evolution of the power flowing along each waveguide was presented for different coupling lengths.

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