Theoretical and experimental demonstration of a microstrip directional coupler with enhanced performances by using plasma tubes

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Abstract

In this contribution, we present the theoretical and experimental demonstration of a microstrip directional coupler with improved coupling values by using plasma tubes. Regular microstrip couplers made of a single layer grounded substrate cannot provide high coupling values (i.e. greater than – 6/7 dB) due to the moderate mismatch between the characteristic impedances of the even and odd TEM modes supported by the structure. In order to overcome this limitation, we show that a very thin slab of a metamaterial with a negative and close-to-zero real part of the permittivity placed between the two microstrip lines is able to increase, under certain conditions, the coupling between the two lines with respect to conventional devices with the same topology. Some insights on the physical phenomena ruling the operation of this novel microstrip coupler and a complete set of design formulas for this component are given in the paper. Some full-wave numerical simulations are presented to verify the proposed idea and show the effectiveness of the design. Finally, when going towards the practical implementation of the component, we decided to use plasma tube technology to implement the metamaterial slab. The experimental work is currently on the way and we hopefully will present some measured results at the conference.

1. Introduction

Coupled microstriplines are useful modules in microwave technology. They find several applications, for instance, in the design of directional couplers, filters, delay lines, etc. The analysis, the design and the applications of coupled lines have been the subject of numerous papers in the past and most of the theoretical and practical aspects related to this structure have been fully considered along the years, so that, the salient features of the coupled lines find room in the basic textbooks of microwave engineering (see for instance [1]).

In a regular coupled microstripline it is not practical to achieve coupling values exceeding – 6/7 dB. This is basically due to the fact that the two quasi-TEM modes supported by the structure exhibit slightly different characteristic impedances. In the open technical literature, some solutions have been proposed to reach high coupling values by modifying the structure. However, all of them require increasing the original dimensions of the regular coupled lines [1]. The aim of this contribution is to show how the use of particular metamaterials allows to increase the performances of coupled microstrips in terms of obtainable coupling values.

Metamaterials are artificial materials obtained, generally, through the inclusion of resonant metallic particles in an host dielectric medium [2]. Since, by definition, the linear dimensions of the inclusions and the separation between them must be much smaller than the operating wavelength, it is possible to describe the electromagnetic behavior of these materials through effective macroscopic constitutive parameters [3]. In particular, the constitutive parameters necessarily change with the frequency (i.e. metamaterials are dispersive materials) and are complex-valued (i.e. metamaterials are characterized by losses at given frequencies) [3]. Around the resonant frequency of the inclusions it is also possible to obtain negative values of the real part of permeability and/or permittivity.

Negative constitutive parameters at given frequencies are not necessarily obtained by including resonant particles in a host dielectric. Some natural materials, in fact, may exhibit anomalous values of permittivity or permeability in a given frequency range. For instance, a properly excited plasma behaves as a medium with a negative real part of the permittivity at given frequencies [4]. In this particular case, losses are much smaller than in the case of artificial Epsilon NeGative (ENG) materials made by resonant wire inclusions. In addition, the material can be regarded as actually isotropic, since its polarizability does not depend on the shape and symmetry of resonant inclusions.

In this work, we investigate the effects of an ENG thin slab placed between two metallic strips in a coupled microstripline layout in order to increase the coupling values. An heuristic interpretation of the physical phenomenon is firstly proposed. Then, a new quasi-static model of the structure, based on an extension of the Garg-Bahl model for coupled microstriplines [5], is presented. A conformal mapping technique is used, then, to derive closed-form design formulas for the analysis and synthesis of coupled microstrips with an ENG loading. The validity of the design formulas has been verified comparing the results with those obtained with the full-wave numerical solver CST Microwave Studio®. Finally, the fabricated sample using plasma tube technology and the experimental setup used for the excitation of the plasma and measuring the coupler characteristics is also presented. The experimental part of the work is currently in progress and we hope to have the measured date ready for the conference.

2. Microstrip coupler with ENG metamaterial loading

The layout we propose here to overcome the limitation in the coupling values achievable in regular coupled microstrip lines is shown in Figure 1. An isotropic and homogenous ENG thin slab is placed between the two strips inside the homogenous and isotropic dielectric substrate. In the frequency band of operation, the metamaterial slab presents negative values of the real part of the permittivity, while the substrate is assumed to be made by a high-index material (i.e. alumina). The negative permittivity of the ENG slab is assumed to be, as absolute value, much smaller than the substrate permittivity.

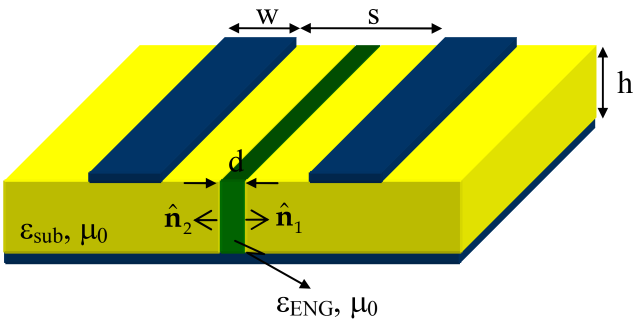


Figure 1 – Proposed setup consisting of a pair of coupled metallic microstrip lines printed on a high-index grounded substrate. An electrically thin metamaterials ENG slab is placed between the two coupled lines.

a) Physical insight

Since the normal component of the electric displacement is continuous at the interfaces, the choice of a low absolute value of the permittivity for the ENG slab allows to obtain a rather strong amplitude of the electric field in the slab. If we apply the boundary condition for the electric displacement, in fact, we obtain:

$$\mathbf{E}_{1,2}^{ENG} \cdot \hat{\mathbf{n}}_{1,2} = \frac{\varepsilon_{sub}}{\varepsilon_{ENG}} \mathbf{E}_{1,2}^{sub} \cdot \hat{\mathbf{n}}_{1,2} \quad \overset{|\varepsilon_{sub}/\varepsilon_{ENG}|>>1}{\Rightarrow} \quad \left|E_{n_{1,2}}^{ENG}\right| >> \left|E_{n_{1,2}}^{sub}\right|$$

The principal effect of the anomalous permittivity of the ENG slab is, thus, to force in the slab itself an electric field normally directed with respect to the interfaces. Examining the field lines of the odd and even TEM modes of a regular microstrip line on a transverse section of the coupler [1], it is evident that the presence of the ENG slab affects, prevalently, the field distribution of the odd mode, which is the one satisfying the PEC symmetry condition. The effect of the ENG slab on the odd mode, therefore, is to increase the equivalent capacitance of the odd mode, reducing, thus, its characteristic impedance. On the other hand the capacitance of the even mode is almost unchanged and, thus, also the characteristic impedance of the even mode does not change very much when placing the ENG slab in the middle of the coupler.

Therefore, the final result is a reduction of the characteristic impedance of the odd mode, increasing, thus, the mismatch of the characteristic impedances of the two TEM modes, which results in the increase of the maximum allowable coupling values. Changing the negative permittivity value of the ENG slab, we expect to change also the maximum coupling value.

b) Conformal mapping and design formula

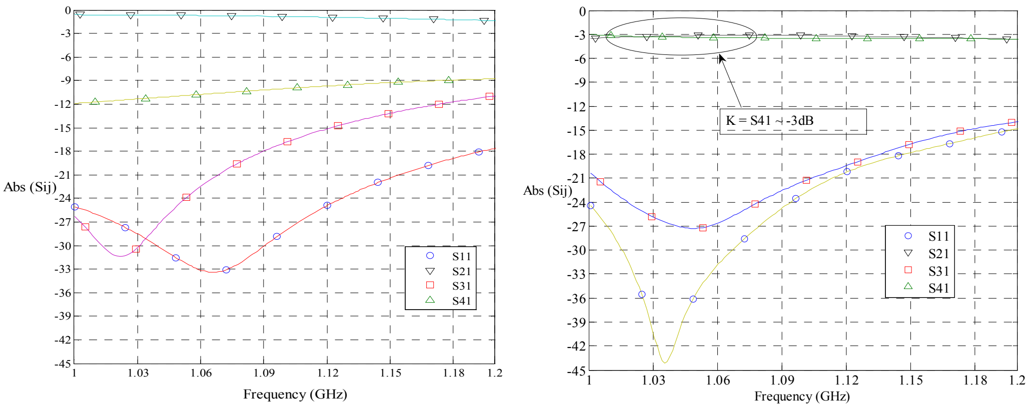
In order to derive suitable design formulas for the coupler in Figure 1, we have analyzed the structure through a conformal mapping technique, extending the formulation presented in [5]. Some details about the application of the conformal mapping and the derivation of the design formulas will be given at the conference. Here we just present the expression of the design formula, which relates the needed permittivity of the slab with the geometrical and electrical parameters of the coupler of Figure 1 and the desired coupling value *K*:

$$\varepsilon_{\text{eng}} = -\varepsilon_{\text{sub}} \frac{d}{h\,h_o} \left\{ 1 + \frac{\varepsilon_{\text{sub}}}{\dfrac{h_o^2}{l_o l_o^{eng}} \dfrac{Z_0^2}{Z_{0\text{e}}^2} \left(\dfrac{K+1}{K-1} \right)^2 - \left[\dfrac{l_o}{l_o^{eng}} + (\varepsilon_{\text{sub}} - 1) \right]} \right\}$$

For the meaning of the symbols, please, refer to [6].

c) Full-wave numerical results

Using the formula now presented, we have designed the microstrip coupler of Figure 1 in order to provide a – 3 dB coupling value around 1 GHz. The geometrical and electrical parameters of the coupler (see Figure 1) are chosen as: d = 1.1 mm, s = 3.2 mm, w = 9.8 mm, h = 10 mm, ϵ_{sub} = 8.9. For this set of coupling value and geometrical/electrical parameters, the resulting value of the relative permittivity of the ENG slab is – 0.70. The structure has been simulated using CST Microwave Studio® and the results are presented in Figure 2, showing the comparison between the proposed setup and the regular microstrip coupler without the ENG metamaterial slab. The ENG slab has been modeled as an isotropic, homogeneous slab characterized by the vacuum permeability and a permittivity following the Drude dispersion model, such that at the design frequency (1 GHz in this case) the corresponding value is – 0.70.



a) b)

Figure 2 – Amplitude of the scattering parameters of the coupler in Figure 1 without a) and with b) the ENG slab. The input port is labeled as port 1. Port 2 is the output port along the input line. Port 3 and 4 are the ports of the second microstrip line.

The results presented in Figure 2 show that the ENG slab placed between the two lines is capable to increase the coupling values between two microstrip lines beyond what is possible with standard layouts and confirm the effectiveness of the proposed design.

d) Experimental setup

The circuit that is proposed for the experiment is shown in Figure 3. In [7], miniature tubes are excited with a microstrip line so that plasma is formed in the tube. The microstrip coupler is formed by ports: (1) input; (2) through; (3) coupled; and (4) terminated. The input and termination for two symmetric high-power lines, used to excite the plasma tube, are formed by ports: (5)-(8). The two high-power lines (ports 5&6 and ports 7&8) will likely not both be needed unless the plasma is asymmetric along the length of the coupler junction. The coupler is designed for 1.5 GHz while the high-power line will be energized at 2.54 GHz. The quartz tube is placed under the high-power microstrip, so that the strong normal fields under the microstrip can ignite the plasma. It is then placed between the low-power microstrip lines in a groove milled into the substrate. Note that care must be taken so that the high-power lines do not coupled strongly to the low-power lines, thus endangering the test equipment. Analysis indicates that at 2.54 GHz, the coupling between port 5 and the low-power ports is -30 dB or better. Nevertheless, during experimentation, the coupling between those lines will be monitored carefully prior to igniting the plasma. The circuit shown in Figure 3 will be fabricated and measured results will be shown at the conference.

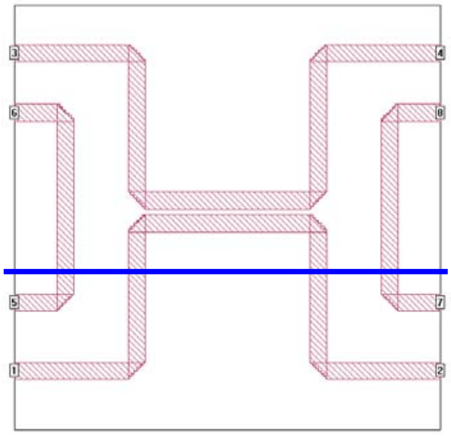


Figure 3 – Proposed experimental circuit lay-out. The ports 1-4 shown correspond to Figure 2 while ports 5-8 are used for two symmetric high-power plasma ignition lines. The plasma tube is shown being excited by a high-power line an running along the junction between the two low-power lines.

3. Conclusion

In this contribution, we have presented the theoretical and a proposed experimental demonstration of a single layer microstrip coupler with enhanced coupling values. The enhancement has been obtained by using an ENG metamaterial slab placed between the two strips. The theoretical formulation, design formulas and full-wave numerical simulations of this new component have been presented in the paper. Finally, the experimental implementation of the ENG slab through the plasma tube technology will be presented at the conference. Some details about the experimental setup have been already given, while we the measurements are in still progress.

4. Acknowledgments

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