EXPERIMENTAL DETERMINATION OF THE PERMITTIVITY AND PERMEABILITY OF AN ARRAY OF SPLIT-RING RESONANTORS IN A X-BAND WAVEGUIDE

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1 Introduction

Experiments on the propagation and transmission of electromagnetic waves in waveguides loaded with anisotropic magnetic metamaterials (as for example, periodic arrangements of split-ring resonators, called SRRs) have enabled the development of waveguides of subwavelength, resonators, filters, etc. [1-5]. In this work, we use magnetic probes to excite the loaded waveguide and to study the effects of weak and strong coupling between the SRR array and the probe through a retrieval procedure of constitutive parameters ε and μ, as well as the transmission parameters, namely, the refractive index and the wave impedance. Detailed knowledge of the constitutive properties of such artificial materials becomes relevant for microwave applications, as for instance, antennas, dephasers, and absorbers. All experiments were implemented by loading a rectangular waveguide with a periodic arrangement of six SRRs, with dimensions and physical features detailed in [6]. The array is placed in the plane of symmetry of a X-band waveguide (WR90) having a cross-sectional area 2.29 x 1.02 cm^2 and cutoff frequency 6.55 GHz (Fig. 1).

Fig. 1. (a) *WR90 waveguide loaded with six SRRs. (b) Set-up to measure scattering parameters in the X-band waveguide loaded with the SRR array using waveguide coaxial adapters.*

2. Experimental Results and Discussion

First the waveguide loaded with the SRR array is symmetrically connected on both ends to identical X-band waveguide-to-coaxial adapters, by means of which the input and output signals have been injected and detected by an Agilent N5230C vector network analyzer [6]. The results presented in Fig. 2(a) show that the first passband is left-handed in nature and occurs around f ~ 3.45 GHz, but the transmission is very weak ($S_{21} \sim -45$ dB).

Fig. 2 **(a)** *The transmission band for the waveguide loaded with a periodic array of six SRRs measured with coaxial-waveguide adapters.* ***(b)*** *Magnitudes of reflection (S_{11}) and transmission (S_{21}) scattering parameters. Measurements were made by using magnetic probes.*

To enhance the transmission band resulting from the effect of magnetic resonance, a pair of magnetic probes is used to excite and detect the propagating signal, as described in [6]. The magnitudes and phases of reflection and transmission coefficients, respectively, S_{11} and S_{21}, are obtained for two cases: a) weak coupling between the probe and the SRRs; b) strong coupling between the probe and the SRRs, as displayed in Fig. 2(b).

It is observed that in the case of weak coupling, the maximum transmission intensity (S_{21} ~ 0,22) is obtained at f ~ 3.32 GHz, while in the case of strong coupling the resonant frequency is slightly reduced (f ~ 3.28 GHz) and the transmission band is wider, with S_{21} reaching ~ 0.56.The refractive index retrieved, according to a method described in [7], is shown in Fig. 3(a). In the case of strong coupling the real part of the index is negative in all the range studied (f ~ 3.0 − 3.8 GHz), indicating negative refraction, with values varying in the range $-1.3 \lesssim n_r \lesssim -0.25$, whereas in the weak-coupling case the real part of the refractive index is negative only for frequencies $f \lesssim 3.32$ GHz and takes values in the range $-1.25 \lesssim n_r \lesssim 0.67$. The imaginary parts of the refractive index show that the strong coupling leads to a much lower energy dissipation level. In Fig. 3(b) the retrieved magnetic permeability shows a real part which is negative in almost all the range of frequencies, in both cases of weak and strong couplings. Although in the case of weak coupling, Re{μ} has larger negative values in the frequency range between 3.0 and 3.2 GHz, in practice it means nothing since the transmission in this frequency range is negligible (see fig. 2(b)). Note that in the region of stronger transmission, between 3.2 and 3.4 GHz, both permeabilities are approximately the same, indicating that the permeability nearly independent of the incident magnetic field. The electric permittivity ε_r of the SRR periodic array is negative only in the region around the magnetic resonance frequency ($f \sim 3.2 - 3.3$) GHz and is larger in the case of weak coupling, as shown in Fig. 3(c). In the frequency range $3.3 \leq f \leq 3.65$ GHz we have obtained $\varepsilon_r > 0$ for both the strong and weak coupling cases.

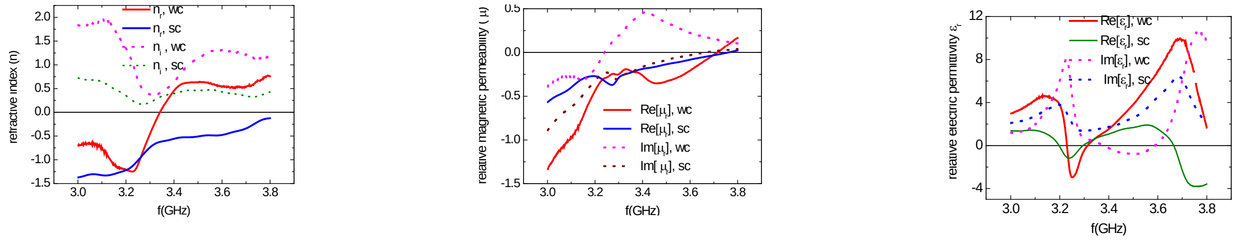

Fig. 3. *(a)Refractive index extracted from scattering parameters S measured in loaded waveguide. The solid lines refer to the real part n_r and the dotted lines to imaginary part n_i. The minima of n_i spectrum correspond to largest transmission, as would be hoped. (b) Magnetic permeability extracted from measured S -parameters. The solid lines refer to the real part and the dotted lines to imaginary part. (c) Relative Electric permittivity extracted from scattering parameters (S) measured. (sc=strong coupling, wc= weak coupling)*

The permeability and permittivity of an arrangement of resonant rings inserted in a X-band rectangular waveguide have been experimentally determined in the range of frequencies 3.0 ~ 3.8 GHz, which exhibits magnetic resonance below the cutoff frequency of the empty waveguide (6.55 GHz). It was noted that the excitation by using magnetic probe has intensified the transmission LH (left-handed) and that, depending on the intensity of the coupling, transmission can be equivalent to that of a balanced CRLH line (weak coupling) or a purely LH line (strong coupling). We also observed a negative refraction even in the range of frequencies over which the electric permittivity is positive. A reverse procedure (not explained in the text), retrieves all the original parameters (S parameters) using the permeability and permittivity extracted, fully validating the accuracy of the retrieved constitutive parameters.

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