Refractive Properties of Artificial Dielectrics Consisting of a Periodic Wire Medium

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***Abstract*—This paper examines the refractive properties of a wire medium designed to operate in the X-band for directive antenna application. The periodic structure is implemented using 0.5-mm-diameter copper wires arranged on a square lattice with spacing of 10 mm, yielding a cutoff frequency of 7.7 GHz. Through numerical experiments, the refractive index is calculated as $n = \lambda_0/\lambda_g$, where λ_0 and λ_g are the free-space and guided wavelengths, giving an average value of n = 0.6 over the 8-12 GHz frequency range.**

I. INTRODUCTION

The wire medium structure is used to synthesize artificial dielectrics for applications in different microwave designs, with the main purpose of providing a relative electric permittivity less than unity, or even negative. The realization of artificial dielectrics from an array of metallic wires has found application in the control and enhancement of beam directivity for a variety of antennas [1-3]. In this case, the electric permittivity should present a near zero value (ENZ) making the refractive index of the homogenized structure, $n = \sqrt{\varepsilon\mu}$, less than one, as the magnetic permeability of such a non-magnetic structure is unity. Then, $n = \sqrt{\varepsilon}$, where the electric permittivity can be calculated by.

$$\varepsilon = \varepsilon_h\left(1 - \frac{f_c^2}{\varepsilon_h f^2}\right) \qquad (1)$$

where the ε_h is the permittivity of the host material where the wire is allocated, f_c is the cutoff frequency of the structure and f the frequency of the incident wave. A typical periodic wire medium is displayed in Fig. 1, where d is the diameter of the wire and a is the periodic distance between wires. The corresponding cutoff frequency of the wire medium can be calculated by [4].

$$f_c = c\left[a\sqrt{2\pi\left(\ell n\frac{a}{\pi d} + 0.5275\right)}\right]^{-1} \qquad (2)$$

where c is the speed of light in vacuum. Details of the wire medium construction and its characterization are given in [4].

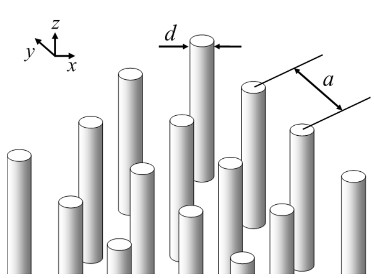


Figure 1. The wire medium structure.

II. WIRE MEDIUM DESIGN

The wire medium is designed to operate in the X- band (8.2 – 12.4 GHz), and for achieving optimum frequency response the geometrical parameters should be properly chosen while taking into account commercially available diameters for the metallic wire. The lattice constant and the wire diameter were chosen as a = 10.0 mm d = 0.5 mm, yielding a cutoff frequency of 7.7 GHz calculated from (2). For other values of d and a, the corresponding cutoff frequencies are shown in Fig. 2. We see that f_c is very sensitive to the lattice constant since, at d=0.5 mm, f_c increases from 7.7 GHz to 10.0 GHz when a decreased from 10.0 mm to 8.1 mm.

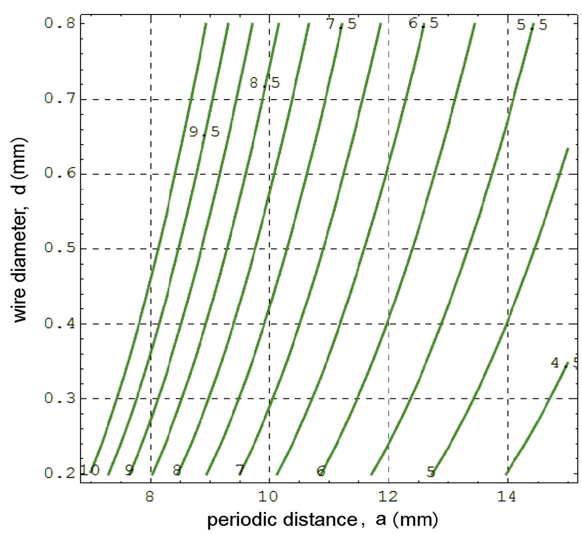
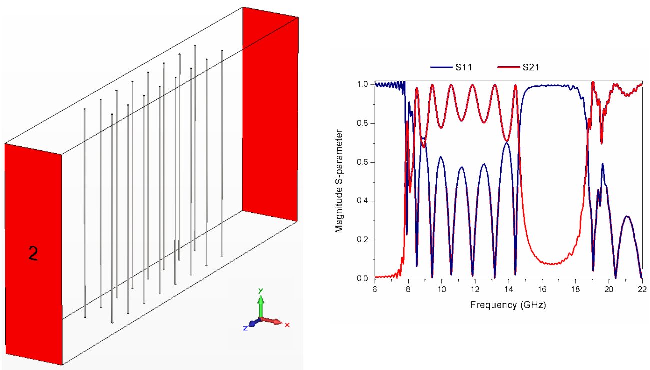


Figure 2. Curves of constant cutoff frequencies on the plane of parameters a-d.

III. NUMERICAL RESULTS

With air being the host material, the refractive properties of the wire medium so designed have been studied on the basis of analytical and numerical considerations. Then using the CST MWS software [5], electromagnetic simulations have been performed on a structure consisting of two rows of eight parallel metallic wires as illustrated in Fig. 3. In the simulations, electric and magnetic boundary conditions were applied on the transverse surfaces (planes y-z) and two open ports were used to simulate the S-parameter response to a normally incident plane wave with the electric field parallel to the wires.



(a) (b)

Figure 3. (a) Wire medium and (b) simulated S-parameters

The response of the structure exhibits two band gaps, with the first one starting from 0 to f_c=7.7 GHz. The second band gap extends from 14.5 GHz to 19.0 GHz, where the lower end is identified as the Bragg cutoff frequency $f_B=c/2a$ =15.0 GHz. Here we note that increasing the number of layers in each row would give the simulated lower end frequency closer to f_B. Between the two gaps, there appear seven resonant dips, which is just the number of layers, 8, minus 1. This is because eight adjacent layers form seven coupled resonators.

By measuring the simulated wavelength we can estimate the refractive index of the homogenized medium using the relation

$$n = \frac{\lambda_0}{\lambda_g} \tag{3}$$

where λ_0 and λ_g are the free-space and guided wavelengths, respectively. An example of this approach is given in Fig. 4, where at the incident wave frequency of 10.56 GHz, with λ_0=28.5 mm, the measured λ_g=39.5 mm yields a refractive index of 0.66. Additional measurements have been made for other frequencies for which the resulting refractive indexes are compared in Fig. 5 with those from the analytical model described by (1)-(2). It is apparent from Fig. 5 that the refractive index values determined from numerical simulation are in good agreement with the analytical curve.

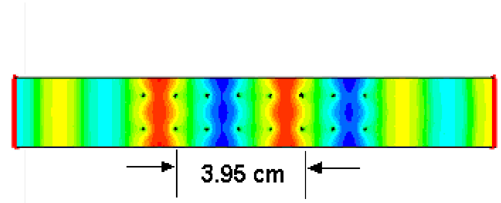


Figure 4. Electric field pattern showing the guided wavelength at 10.56 GHz.

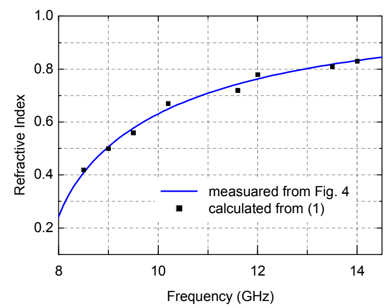


Figure 5. Analytical and numerically simulated refractive index for the proposed wire medium.

IV. CONCLUSION

An X-band example with square-cell arrays has shown the feasibility of the wire medium to the realization of artificial dielectrics with required permittivity aiming at a wide range of applications, namely microwave focusing lens and directive antennas. It is possible to obtain near-zero refractive index in other frequency ranges by properly selecting the geometrical parameters (lattice constant, wire diameter) that characterize the periodic array. The present study has also shown analytical and numerical details for wire medium design.

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