Wave Propagation in a Waveguide Loaded with an Array of Nonconnected Wires

Joaquim J. Barroso[1], A. Tomaz[1], J. P. Leite Neto[2], José Edimar B. Oliveira[2], and Ugur C. Hasar[3]
[1]Instituto Tecnológico de Aeronáutica (ITA), São José dos Campos , SP Brazil
[2]National Institute for Space Research, São José dos Campos, SP, Brazil
[3]Gaziantep University, Gaziantep 27310, Turkey

***Abstract*—Artificial dielectrics composed of periodically conducting straight wires were proposed in the 1950s as a low cost and light beam shaping element in microwave lens antenna application as an option for replacing bulky and heavy dielectrics. Renewed interest in wire media was sparkled with the advent of metamaterials in the 2000s, leading to a range of new applications such as subwavelength imaging, directive emission, and broadband absorbers. Concerned with waveguide applications, the present paper examines analytically and numerically mode propagation in waveguide filled with a double array of nonconnected wires perpendicular to the waveguide walls. The presence of the loading wire medium gives rise to new eigenmodes in the transmission spectrum where a low-frequency passband emerges below the cutoff frequency of the dominant mode, and also allows for the occurrence of backward-wave modes nonexistent in the otherwise unloaded waveguide. This kind of guiding structure can find application in delay lines, phase shifters, and the miniaturization of waveguide devices supporting backward waves.**

***Keywords* — metamaterials; wire media; nonconnected wires; backward waves; periodic structures**

I. Introduction

Owing to their unusual electromagnetic properties, metamaterials have received considerable scientific and technological interest since a negative index material was first demonstrated nearly two decades ago [1]-[4]. Generally consisting of a periodic array of subwavelength split-ring resonators (SRR) and wires, and engineered with properties not found in nature, these materials have demonstrated an unprecedented skill in controlling the propagation of electromagnetic waves and enabled the creation of novel devices, namely perfect absorbers, invisibility cloaks, directive antennas, and metasurfaces [5]. Further experiments on materials made up with periodically arranged metallo-dielectric scatterers (SRRs and wires) have demonstrated the property of negative refraction of electromagnetic waves and left-handed wave propagation [6]-[9], giving support that these metamaterials can be adequately described by simultaneously negative permeability, μ, and permittivity, ε, whereby negative μ is provided by the split-rings and negative ε is achieved by the array of wires, which acts like an artificial dielectric.

In an early application of SSRs, it was demonstrated below-cutoff wave propagation in a waveguide filled with an array of SRRs [6]. To explain backward-wave propagation in the SRR-loaded guide, it has been asserted that negative permittivity is set up by the waveguide operating below cutoff while negative permeability is provided by the array of SRSs, such that the coexistence of negative permeability with negative permittivity produces a negative-refractive-index medium [6]-[7]. This phenomenon has been discussed [7]-[9] as an approach for the miniaturization of waveguide components, wherein the transversal dimension of the waveguide can be smaller than the propagation wavelength in the loaded guide provided that the transverse permeability of the anisotropic material is negative.

Besides its interesting properties, a waveguide filled with wires also supports propagation below cutoff, but with negligible losses due to the non-resonant nature of the wire medium [9]-[11]. Based on this approach, here we report on the propagation properties of a wire-loaded rectangular waveguide where a low-loss forward-wave mode is located below the cutoff frequency of the empty waveguide. In addition, such wire-loaded waveguide shows isolated transmission peaks in the transmission spectrum, which can be useful as a narrow transmission filter for channel selection in communication systems.

II. Waveguide Loaded with an Array of Nonconnected Wires

We consider a waveguide with square cross section of side 23.0 mm and length 50.0 mm, as among rectangular waveguides with cross-sectional aspect ratio other than unity the square waveguide has the lowest attenuation due to ohmic losses above cutoff frequency. The guide is filled with three layers of nonconnected double wires of diameter 0.5 mm and separated by periodic distances as indicated in Fig. 1. This arrangement supports propagation below cutoff and is devised as a miniaturization approach for waveguide components. In comparison with SRR-loaded waveguides, the wire-loaded waveguide has lower losses due to the nonresonant nature of the wire medium [10]-[12].

The system is excited by a coaxial probe connected to the first horizontal wire by driving an electric current through the input-port wire, while the transmitted signal is detected by the receiving probe in direct contact with the third horizontal wire. We verified that another excitation scheme with the probes placed on the end faces of the waveguide was unable to excite TE-like modes.

III. Simulation Results and Discussion

Full-wave electromagnetic simulations using the 3D simulator CST Microwave Studio [12] were performed to calculate the S-parameters of the wire-medium loaded waveguide. The mode spectrum for the unloaded guide is shown Fig. 2, where the vertical lines above the horizontal scale indicate the cutoff frequencies (6.52, 9.22, 11.29, and 13.04 GHz) corresponding, respectively, to modes TE_{10}, TM_{11} (degenerate with TE_{11}), TE_{12} (degenerate with TE_{21}, TM_{12}, and TM_{12}), and TE_{02} (degenerate with TE_{20}) of the square waveguide.

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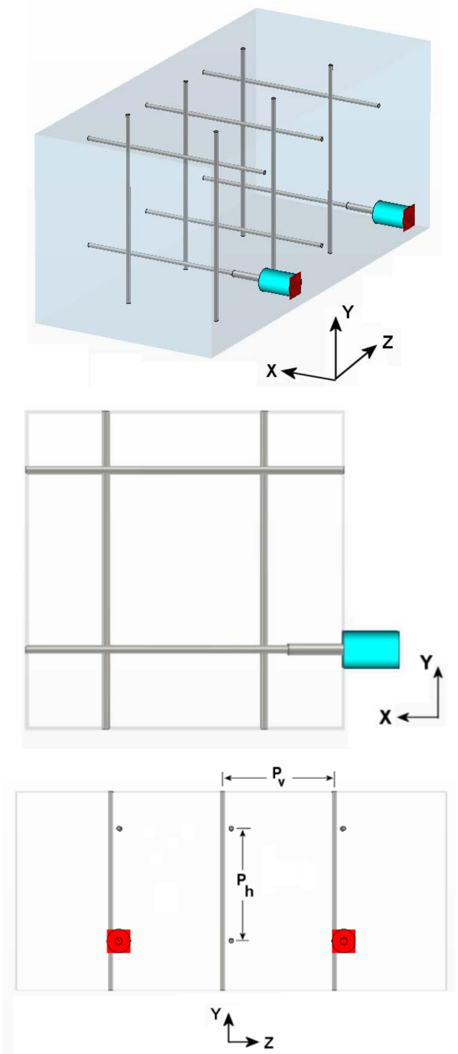

Fig.1 From top to bottom: perspective, side, and front views of the wire-loaded square waveguide with side a=23.0 mm. In the bottom panel, the vertical and horizontal wires are periodically spaced by $P_h = 11.5$ mm and $P_V = 13.0$ mm; the coaxial probes are placed 12.0 mm from the lateral walls.

On the other hand, for the loaded waveguide, the associated spectrum is more densely populated, as given in Fig. 3, where the following distinguishing features are noticed. First, below-cutoff propagation occurs in a 4.40-5.57 GHz band with a sharp peak at 4.94 GHz and with $|S_{21}| = 1.0$. Second, and not predicted by the homogenized model in Sec. III, there appears an isolated mode at 5.93 GHz. Such a mode is likely to be due to multiple interference mediated by the wire layers and the reflecting end walls, by noting that the transmission coefficient attains $|S_{21}| \sim 0.5$. Also, it is seen that the transmission band centered about 7.58 GHz is widened. Third, and to be discussed later, a mode with $|S_{21}| = 1.0$ which appears at 8.85 GHz in the otherwise 8.0-9.2 GHz band gap of the unloaded waveguide (Fig. 2).

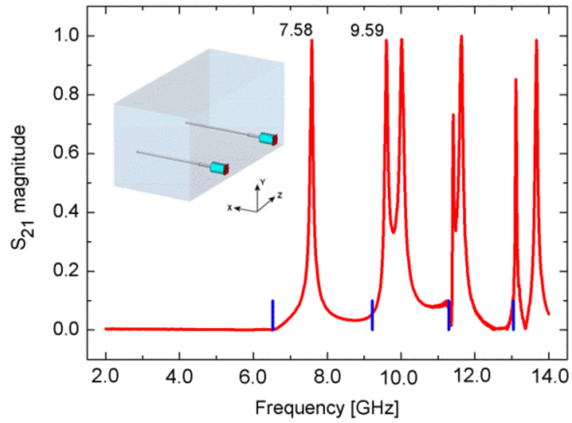

Fig. 2 Transmission coefficient for the unloaded waveguide. The vertical lines above the horizontal scale indicate cutoff frequencies of 6.52, 9.22, 11.29, and 13.04 GHz.

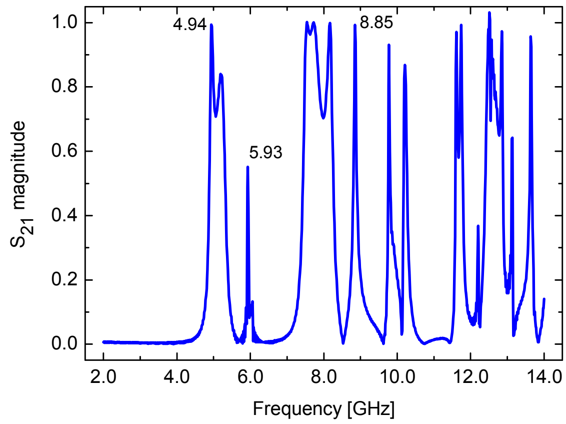

Fig. 3 Transmission coefficient for the loaded waveguide, with new transmission modes at 4.94, 5.93, and 8.85 GHz.

Therefore the presence of the wires completely changes the original spectrum, allowing for lower-frequency modes and giving rise to new features in the transmission properties of the square waveguide. To illustrate these findings, H_X magnetic field intensity patterns in both waveguides at 7.58 GHz (the first transmission peak in Fig. 2) are displayed in Figs. 4 and 5. The mode in the unloaded waveguide (Fig. 4) shows a non-propagating structure resembling an oscillating trapped mode, whereas its counterpart (Fig. 5) in the loaded waveguide is identified as a backward-wave mode (blue and red spots move to the left).

We notice that the transmission spectrum (Fig. 3) shows a 4.4-5.6 GHz passband, where the lower frequency bound is not predicted by a continuous model [6]-[8]. Such a behavior is due to the discrete character of the periodic structure which gives rise to a lower cutoff (Bragg) frequency, where half the guided wavelength (k) is equal to the periodic distance (p) such that $kp = \pi$. This is shown in Fig. 6, where the Bragg cutoff frequency corresponds to a transmission phase of π.

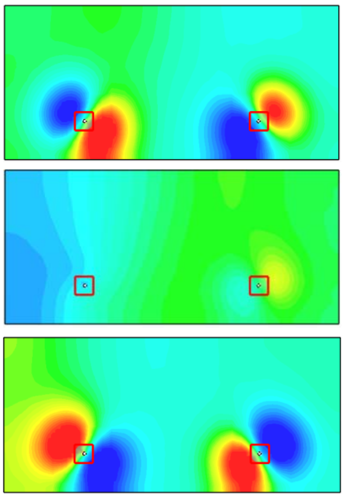

Fig. 4 H_x magnetic-field intensity patterns for the 7.58-GHz mode in the unloaded waveguide. From top to bottom, the panels show contour plots at propagation phases of 0º, 120º, and 240º degrees. The intensity scale varies from -2.1×10^{-3} A/m (red) to $+2.1 \times 10^{-3}$ A/m (blue), with zero intensity represented by green. The input port is on the left.

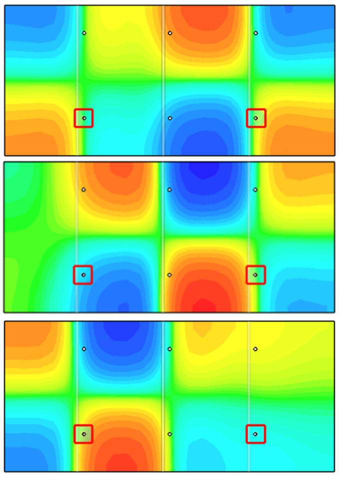

Fig. 5 H_x magnetic-field intensity patterns for the 7.58-GHz mode in the loaded waveguide. From top to bottom, the panels show contour plots at propagation phases of 0º, 120º, and 240º degrees. The intensity scale varies from -0.9 A/m (red) to +0.9 A/m (blue), with zero intensity represented by green.

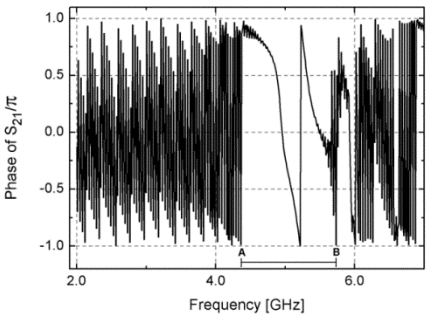

Fig. 6 Transmission phase (normalized to π) of the loaded waveguide, where the low-frequency passband is indicated by $\overline{AB}$, with $A(4.40\ \text{GHz}, 0.94)$ and $B(5.57\ \text{GHz}, -0.2)$.

IV. Conclusion

The cutoff frequency of a square waveguide has been decreased by introducing into the guide a few thin conducting wires, which has caused the occurrence of a low-frequency passband from 4.4 to 5.7 GHz below the cutoff frequency (6.52 GHz) of the dominant TE_{10} mode. In addition to sharpening the transmission bands, the wire medium drastically changes the character of the propagating modes. In fact, the primary forward-wave mode at 7.58 GHz turns into a backward-wave mode in the loaded waveguide. An interesting feature not addressed in previous works, is that due to the discrete nature of the periodic wire layers an isolated peak emerges at 5.93 GHz in the 5.7-7.0 GHz bandgap, which allows the wire-loaded waveguide to act as a narrowband reflection filter.

Finally, we mention that the above features have been observed by using excitation and detection coaxial probes directly connected to the input and output wires. Were the probes attached to the end walls, TE modes could not have been excited. Increasing the numbers of layers sharpens the passbands and decreases the height of the isolated peak at 5.93 GHz; for instance, upon using ten layers the peak vanishes.

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