Equivalent material parameter extraction of double strip loaded waveguide

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Abstract: Equivalent material parameters of a periodic waveguide structure loaded with double strips printed on dielectric has been extracted. It shows a passband where the relative permittivity and permeability are simultaneously negative also called as double negative (DNG) passband. Full-wave Hybrid MoM-Immittance Approach is employed for the material parameter extraction validated by independent Ansoft High Frequency Structure Simulator (HFSS) extracted results.

Keywords: DNG passband, metamaterials, periodic waveguide structures

Classification: New functional devices and materials

References

1 Introduction

Metamaterials (meta means ‘beyond’ in Greek) are new artificial materials with unusual electromagnetic properties that are not found in naturally occurring materials. All ‘natural’ materials have positive electrical permittivity and magnetic permeability. In these new artificially fabricated materials, these material parameters are negative. Metamaterials with simultaneously negative $\varepsilon$ and $\mu$ were theoretically proposed by Russian physicist V. Veselago in 1968 [1]. However, experimental verifications of such materials with simultaneously negative $\varepsilon$ and $\mu$ did not occur until recently. In April 2001, D. Smith and his colleagues [2] at the University of California at San Diego (UCSD) announced the first experimental verification of existence of metamaterials. Science magazine even named metamaterials as one of the top ten scientific breakthroughs of 2003 [3]. Due to both the material parameters $\varepsilon$ and $\mu$ are negative, such artificially made materials are also called as double negative (DNG) materials [4]. Here we report the first observation of metamaterials like behavior in double strip loaded periodic waveguide structures. Material parameters are extracted using the Hybrid MoM-Immittance Approach (HMIA) [5] which has been developed for efficient and accurate full-wave analysis of such printed strips in layered waveguide. Ansoft High Frequency Structure Simulator version 9 (HFSS v 9) is widely accepted as one of the accurate commercial softwares available for full-wave characterization of such waveguide based structures [6]. The HMIA extracted material parameters are validated by independent HFSS v 9 simulation results.

2 Proposed periodic waveguide structure acting as DNG metamaterials

Figure 1 (a) illustrates 3-D geometry of rectangular waveguide loaded with double strips printed on a dielectric layer. The dimensions for the periodic waveguide structure depicted in Figure 1 (a) are chosen as $w = 8.00 \text{ mm}$, $l = 6.00 \text{ mm}$, $h = 1.00 \text{ mm}$, $p = 3.00 \text{ mm}$ and $\varepsilon_r = 7.00$. We will consider the two-port network representation of a lossless transmission line (waveguide) of length $p$ as depicted in Figure 1 (b) to extract the various material parameters. Full-wave Hybrid MoM-Immittance Approach [5] and HFSS have been used for extraction of material parameters like effective electric permittivity and magnetic permeability. The scattering parameters obtained for a unit cell of the proposed DNG metamaterial architecture are transformed to ABCD parameters and then effective electric permittivity, magnetic permeability are extracted from the ABCD parameters similar to the method for material parameter extraction which has been developed in [4].

3 Extraction of material parameters

Figure 2 illustrates the DNG passband of an unit cell of the periodic waveguide structure. The $-5 \text{ dB}$ insertion loss bandwidth is 8.3-8.7 GHz. It would be good to see the difference between this novel periodic waveguide structure with the general periodic waveguide structure loaded with the single printed
Fig. 1. (a) Proposed architecture for waveguide based DNG Metamaterials (b) Two-port network representation of a lossless transmission line (waveguide) of length p of a periodic cell

![Diagram](image)

**Fig. 2.** Scattering parameters showing the DNG passband

Single printed strips periodic waveguide structures are totally reflecting at the resonant frequency of strip thereby there is no transmission at the resonant frequency unlike this particular double strips printed periodic waveguide structure which has a DNG passband.
3.1 Extracted Relative Permittivity

In practice, if the unit cell is smaller than the guided wavelength $p < \lambda_g/4$, then the electrical length of the unit cell is smaller than $\pi/2$ and the periodic structure is seen as effectively homogeneous by electromagnetic waves [7]. Then, we may obtain relative permittivity from the ABCD parameters of a unit cell using the following equations [4].

$$\varepsilon = \frac{C}{j\omega\varepsilon_0 pA}$$

The material parameters are extracted from the ABCD-parameters using the full-wave Hybrid MoM-Immittance Approach (HMIA) and HFSS. The real parts of extracted relative permittivity vs frequency are plotted in Figure 3 (a). The amplitude of real part of relative permittivity $\varepsilon_r$ reaches its most positive value, i.e., 500 at 8.2 GHz, passes through zero at 8.2 GHz and then reaches its most negative value, i.e., $-230$ at 8.3 GHz. The large values of extracted material parameters are due to resonant nature of the response. There is also slight shift in the HMIA and HFSS extracted material parameters. This may be due to HFSS usually do single mode analysis. Although, only dominant TE_{10} mode is propagating in the X-band waveguide in this frequency range. But the effect of higher order evanescent modes is also more pronounced for such kinds of periodic waveguide structures. Here, the double strips printed on two sides of dielectric layer for a unit cell of the periodic waveguide structure mainly produce effective permeability whereas dielectric layer inside multilayered waveguide environment gives main contribution to effective permittivity.

3.2 Extracted Relative Permeability

For $p < \lambda_g/4$, we may obtain the relative permeability from ABCD parameters using the following equations [4].

$$\mu = \frac{B}{j\omega\mu_0 pA}$$

The amplitude of real part of the relative permeability $\mu_r$ reaches its most positive value, i.e., 11 at 8.2 GHz, passes through zero at 8.27 GHz and then reaches its most negative value, i.e., $-7$ at 8.3 GHz as shown in Figure 3 (b).

4 Conclusion

In this short letter, the material parameters of a periodic waveguide structure loaded with double printed strips on dielectric substrate have been extracted. It is observed for the first time the properties of metamaterials viz., negative permittivity, negative permeability are exhibited in DNG passband region of such printed periodic waveguide structures. The immediate possible applications of such waveguide based novel artificial DNG metamaterials are in meta-interface (phase conjugation devices), symmetrical scanning leaky wave antenna (fast wave), etc.
Fig. 3. (a) Extracted Effective Relative Permittivity and (b) Extracted Effective Relative Permeability