BEAM-SQUINT MINIMIZATION IN SERIES-SLOTTED WAVEGUIDE ARRAY ANTENNAS USING DOUBLE NEGATIVE MATERIALS

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1. Introduction

The concept of meta-materials, with both negative relative permittivity and permeability , so called as double negative (DNG) materials, was proposed by Veselago in 1968 [1]. Their existence has been confirmed, showing unusual characteristics, not common in nature, such as a negative refractive index (NRI), negative wave vector *k*, negative phase velocity v_p, left-handed set (*k*, *E*, *H*), backward-wave (*k* is anti-parallel to Poynting vector *S*), and negative group velocity v_g. Recently, for their practical realization, periodic structures comprising of split-ring resonators and conductive strips have been developed [2], and the *C*-*L* configurations have been extensively studied [3]-[4]. On the other hand, while a combination of the *C*-*L* configuration and *RLC* resonator circuits has been shown satisfying both NRI and negative group velocity, but being heavily mismatched and lossy because of its embedded resistor [5]. To remedy, an amplifier and properly selected matching circuits was implemented, by the authors, to simulate a lossless double negative material [6].

In this paper, a lossless ideal double negative material was used in a 5×1 series-slotted waveguide array antenna. The negative wave vector and negative group velocity can make the DNG materials to act as a phase compensator in series-fed arrays. This concept is investigated and full-wave simulated results show that the beam-squint angle and gain variation are made much smaller than those of a corresponding conventional array.

2. Design of array antennas

In order to understand clearly the influence of DPS and DNG materials on the waveguide array performance, their transmission coefficient in the waveguide were investigated in [6]. From the results, an interesting phenomenon was observed. It is the fact that the phase curve for the DPS material has a negative slope, while that for the DNG material has a positive slope. Another interesting fact is the equality of the guided wavelengths for DPS and DNG materials at the same frequency. These properties is used here to design a phase compensated waveguide.

In this study, the phase compensating characteristic is applied to the slotted waveguide

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antenna. Initially, a simple air-filled waveguide with shorted end as shown in Fig. 1(a) is investigated, which generates a standing wave. The voltage calculated from the E-field is plotted for three frequencies. When the distance is zero from the short, all voltages are zero. But their difference increases with distance from the short, which results in a frequency-dependant main-beam direction in large series-fed slotted waveguide arrays. Fig. 1(b) shows the waveguide filled alternatively with air and DNG materials of ε_r = –1 and μ_r = –1, and the length of each section is half guided-wavelength. As shown in Fig. 1(b), at the shorted end, all voltages are zero. After travelling through air medium by 0.5 $\lambda_{g,f0}$, three curves have different phases at *A*-*A*' plane. Between *A*-*A*' and *B*-*B*', there is a DNG material, with backward phase. Since the guided wavelength for the DNG and DPS materials are the same, each backward phase amount will be exactly the same as the forward one in the air medium. At *B*-*B*', the voltages of all three curves become zero again. Therefore, contrary to the air-filled waveguide, the voltage curves for three different frequencies are not different after a DPS-DNG pair, and large series-fed arrays can be made with small or no radiating phase variations.

Base on the investigation in Fig. 1(a) and (b), two arrays having five longitudinal slots were designed on a X-band waveguide of width = 22.86 mm and height = 10.16mm. The center frequency is 10 GHz. The conventional array is shown in Fig. 2(a), which is filled with only DPS materials of ε_r = +1.35 and μ_r = +1.0. Slot length, width, and thickness are 13.2 mm, 2 mm, and 1 mm, respectively. Slots are also offset by 5 mm from the center line of the waveguide, and are spaced by 31.26 mm, which is one-guided wavelength. These specific parameters were determined to act as a reference for the array of Fig. 2(b), which is filled successively with DPS and DNG materials. It is known that simple lumped DNG materials do not exit in nature. Practically, lossless double negative materials could be implemented using its equivalent structures, such as a combination of microstrip line and amplifier [6]. Therefore, it is difficult to place a radiating slot on top plate of a waveguide loaded with this alternative to DNG materials. Slots can be placed only in DPS materials as illustrated in Fig. 2(b). In order to decrease the inter-element spacing, the ε_r and μ_r of DPS and DNG materials were adjusted to ε_r = +1.35, μ_r = +1.0 and ε_r = –2.35, μ_r = –2.35, respectively. When determining the values of ε_r and μ_r, the wave impedances of TE_{10} mode, $Z_{TE} = k\eta/\beta$, where η is the intrinsic impedance and β is a propagation constant, should agree for the two waveguides to avoid reflections. In this study, Z_{TE} was set as 393 Ω. In Fig. 2(b), the slot length and offset are 13.4 mm and 4.5 mm, respectively. The slot spacing is 31.26 mm, which is larger than one free-space wavelength, and, however, it can be decreased by more adjustment of ε_r and μ_r. The length of the DNG material section is 9.32 mm so that the guided wavelength is equal to that of the DPS material.

3. Results

The full-wave analysis of the two arrays of Fig. 2 were performed using Ansoft HFSS. Fig.

3(a) shows the radiation patterns including the return loss for the slotted waveguide array illustrated in Fig. 2(a). As expected, the main beam is tilted depending on the frequency. Within the 10 % frequency band, the main beam is tilted by 5° and the boresight gain is reduced by 3.3 dB. These variations will be severer in case of large arrays having many slots.

The Gain patterns for the array using both DPS and DNG materials, as shown in Fig. 2(b), are plotted in Fig. 3(b). As can be seen, the main beam directions are –0.5°, –0.5°, and 0°, nearly the same for 9.5, 10.0 and 10.5 GHz, respectively. The beam tilt variation is only 0.5° within the 10 % bandwidth. The boresight gain variation is reduced to 0.8 dB from 12.6 dBi at 10 GHz to 11.8 dBi at 9.5 GHz. Non-zero beam and gain variations are due to finite bandwidth of the radiation element, the longitudinal slot and not the array. There are high sidelobes around theta = ± 60°, which are caused by the large inter-element spacing, and could be decreased by optimizing the material parameters.

4. Conclusions

In this paper, a 5 × 1 slotted waveguide array antenna using ideal lossless double negative materials was designed and rigorously investigated. For comparison, a conventional slotted waveguide array was also designed. Its simulated radiation patterns showed a negligible beam squint of 0.5° and boresight gain variation of 0.8 dB, within a 10%. These are considerably smaller than the corresponding values of 5° and 3.3 dB, for the conventional array. It should be noted that, these simulated small beam squint and boresight gain variation were generated by the array elements, the waveguide slots. Thus, the above array parameters are not expected to change significantly for large arrays.

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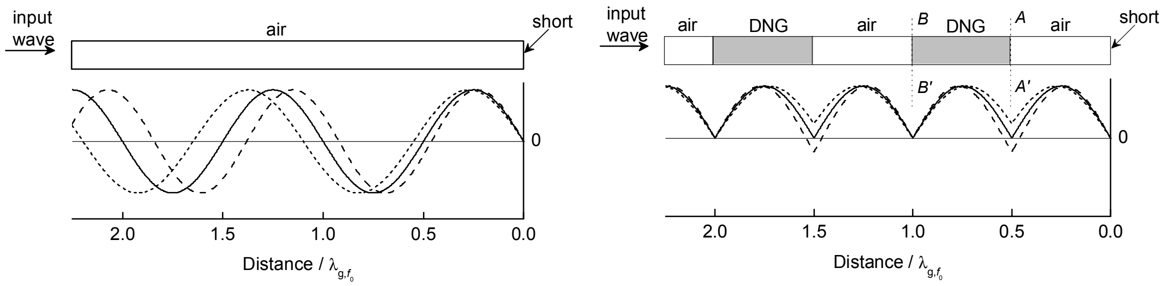
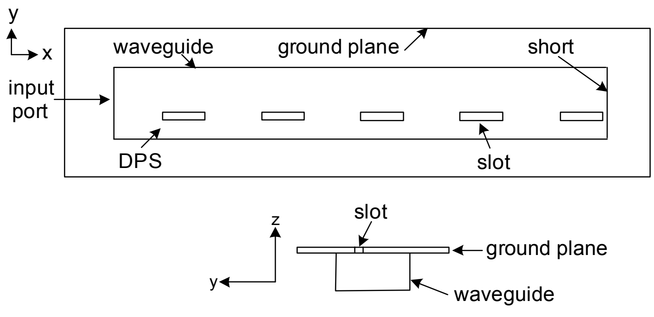
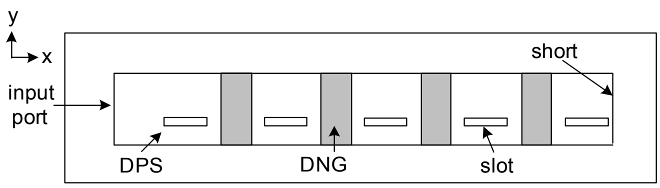


(a) (b)

Fig. 1. Voltage waves in a shorted waveguide filled with (a) air only, and (b) cascaded air and DNG materials, solid line —— at the centre frequency f_0, broken line ------- at f_0–Δf, and dashed line - - - - at f_0+Δf .

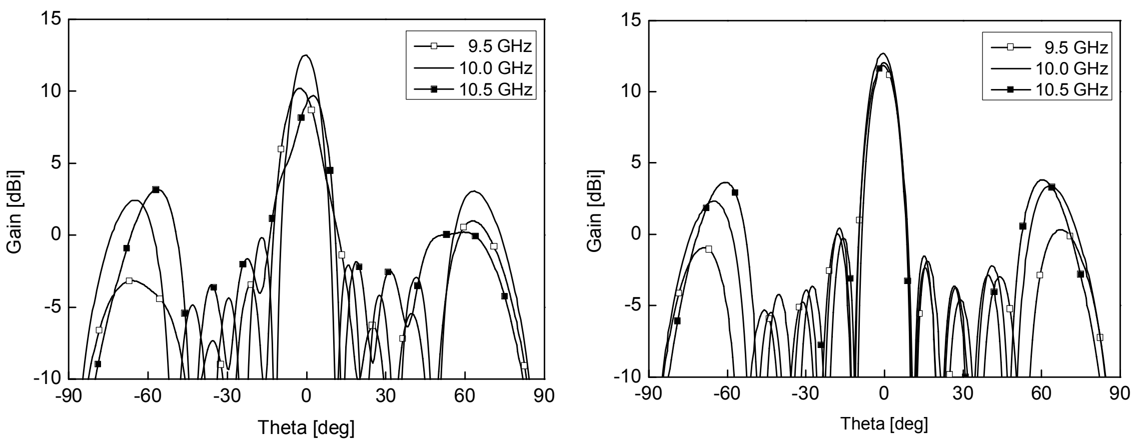


(a)



(b)

Fig. 2. Geometry of the slotted waveguide array antenna filled with: (a) Only DPS material, (b) Cascaded DPS and DNG materials.



(a) (b)

Fig. 3. Gain patterns for two arrays of Fig.2 at 9.5, 10.0, and 10.5 GHz.