Waveguide Miniaturization utilizing Broad Side Coupled Metamaterial structures

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Abstract — Extracted results of open-end loaded X-band BJ-100 waveguide antenna with proposed broad Side Coupled structures, radiating below the cut-off frequency was fulfilled. According to results, the antenna operates about 6GHz. it maneuvers 600MHz below the cut off frequency of the waveguide. The antenna has an impedance bandwidth of 900 MHz from 5.5 GHz to 6.4 GHz. The objective of the research was to miniaturization of antenna using novel electromagnetic metamaterial. The radiation attributes of the antenna does not affect by the cross section of the waveguide and backward wave propagation is possible below the waveguide cutoff frequency. Transverse width of such a waveguide can be arbitrarily small hence the miniaturization property is dictated by metamaterial implementation at the interest frequency. Finally a smaller, compact, and low profile antenna with appropriate bandwidth and relatively good radiation characteristics is fabricated.

Index Terms— Antenna, Metamaterial, Split ring resonator, waveguide.

I. INTRODUCTION

Electromagnetic rules state that for propagation of waves through the waveguide, it cross section width must be at least one of half wavelength [1]. Waveguides with smaller dimensions for high power transition is the need of communication industry. Recently, there have been several new ideas which causes to the waveguides miniaturization [1-2]. A very unusual waveguide was proposed in [2] and then fully researched by [3]. Ref. [3] proposes a rectangular waveguide periodically loaded with resonant magnetic structures, called ring resonators. Metamaterial are artificial materials that cannot be found normally in nature. They are combination of periodic metallic structure and dielectric substrates. They have outstanding properties for instance; negative refraction and supporting back ward wave propagations in the waveguides. The implementation of resonator is very vital to construct a new type of metamaterial. Numerous types of different ring and ring-like structures such as Ω-shaped, U-shaped, S-shaped and others are used to create new structures [4-6]. In the light of the known structures we decided to use a modified and novel structure which consists of a proposed broad side coupled split resonator. We use this structure in an open ended waveguide antenna and do simulation in the frequency range of 5-9 GHz. Simulation results are presented below. This kind of metamaterial has negative permeability and permittivity in the operating frequency band. Standard X-band (BJ-100), open ended waveguide antenna loaded with unitcells which is radiating below the cutoff frequency with a good bandwidth, better impedance matching and good radiating performance, is realized and simulated.

II. THEORETICAL ANALYSIS AND SIMULATION

In this section, first composition of ring resonator (RR) and Wire Strip (WS) structures are utilized to fabricate artificial material called metamaterial. Figure 1 illustrates the geometry of the unitcell comprised of RR and WS.
A FR4 epoxy substrate of 1mm thickness with relative permittivity 4.4 is used for this configuration. RR and WS are produced of copper with conductivity of $6 \times 10^7$ S/m. The width of unitcell is 0.6 mm. RRs are inserted on top layer of FR4 and WSs are placed on its bottom layer. HFSS 15 software Based on finite-element method (FEM) is used for parametric study. The width of WS is chosen 0.4 mm. The RR inner and out radios are 7mm and 8mm respectively. The gap in each SRR is 0.44 mm and space between SRRs centers are is 8.5 mm. Left hand medium is simulated by a array of twelve RR-WS placed in the symmetry plane of 110 mm long. In a lossless case, the longitudinal propagation factor of this waveguide is given by the simple set of equations [4]:

$$k_z = \pm k_0 \sqrt{\varepsilon_r \mu_r \left[1 - \left(\frac{f}{f_c}\right)^2\right]}, f_c = \frac{f_{c0}}{\sqrt{\varepsilon_r \mu}}; f_{c0} = \frac{mc}{2a}, m = 1,2,3,\ldots$$

(1)

Here, $k_z$ stands for waveguide propagation factor, $k_0$ is a free space propagation factor, $\varepsilon_r$ is relative permittivity and $\mu_r$ and $\mu$ stand for relative permeability in transversal(x) and longitudinal (z) directions of the waveguide, respectively. $f_{c0}$ and $f_c$ are the cut-off frequency of an empty waveguide and the filled waveguide with material respectively. The X-band waveguide (cross-section of 22.86mm×10.16mm) loaded with RR-WS is excited by a C-band waveguide-to-coaxial transition. To ensure the excitation of the first RR in the array, the first ring was partly located in the X-band waveguide; and to enhance the radiation, the last ring was placed out from the open-end of the waveguide along with an extra ring as illustrated in figure 2.

Return loss curve at the input port for antenna is depicted in figure 3. From the figure, it can be understood that the antenna has two separate operation bands from 5.5-6.4 GHz and 7.8-8.4 GHz. it is clear that the first propagation pass band is located well below the cut of frequency of X-band waveguide with the bandwidth 900 MHz. Return loss minimum point is -17 dB. At 5.5 GHz. Comparing this to previous works of miniaturization of waveguides in [2], [3], a larger bandwidth achieved with small size and the less number of cells with unique radiation characteristics.
Achieving pass-band below the cutoff frequency of the waveguide is not proof of a backward wave. In figure 4, which shows the phase of return loss, it is clearly seen that in the first pass-band (backward wave region), the phase of the wave increases unlike an ordinary waveguides where phase reduces. So, physically longer waveguides exhibit larger phase of $S_{11}$. This is due to the orientation of the phase velocity and the energy flows are opposite. It can be deduced, physically longer backward wave waveguide acts electrically shorter with phase improvement.

Figure 4. Phase of return loss plot for Antenna with 12 unit cells

III. PARAMETRIC ANALYSIS

There are parameters that affect on the antenna characteristics such as radiation performance and impedance bandwidth. Results demonstrate that the bandwidth is related to methods utilized in the antenna design. It is obvious a larger bandwidth with the respect to cut-off frequency is resulted when proposed metamaterial structure is used in the antenna scheme. Impact of using different dielectric substrates in the waveguide antenna structure is studied in figure 5. Rogers RT/duroid 5870 with relative permittivity of 2.2 and loss tangent of 0.0009 and Roger RO4003 with $\varepsilon_r = 3.55$ and $\tan\delta = 0.0027$ are employed. As it is evident from this figure, deviation from optimum value of design leads to loss the backward wave propagation region. So choosing FR4 as a proper dielectric substrate to have a larger bandwidth and less return loss is suitable. Fabricated prototype is inserted in Figure 6. This figure shows extracted results of return loss for ten & twelve arrays of proposed metamaterial unitcell. Figure 7 illustrates E-plane and H-plane patterns of the antenna in resonance frequency. The patterns display that the antenna works similar to unidirectional antenna on resonance frequency.

Figure 5. Return loss plot for Antenna with two different Substrates
Figure 6. $S_{11}$ return loss of fabricated results

Figure 7. Measured radiation patterns of antenna with 12 unit cells in 6 GHz (blue solid-line: $\phi = 0$ & black solid-line: $\phi = 90$). a) E-plane b) H-plane

IV. CONCLUSION

Unique method was employed to miniaturize the open-ended radiator by electromagnetic metamaterial. In this manuscript, an open-ended standard rectangular waveguide filled with broad side coupled metamaterial split resonator is presented. This study focus on design, simulation, miniaturization and realization. Extracted results show that the antenna is capable to behave below the cut-off frequency of waveguide by supporting backward waves. This type of waveguide has low pass performance and can be assumed as dual of popular waveguide with high pass performance. Miniaturized waveguide have an impedance bandwidth about 900 MHz below the cut-off frequency, dual band functionality which makes it perfect candidate for microwave high power transition.

REFERENCES