RADIO SCIENCE, VOL. 38, NO. 3, 1041, doi:10.1029/2002RS002697, 2003

A microstrip Yagi antenna using EBG structure

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Received 15 April 2002; revised 20 February 2003; accepted 25 March 2003; published 22 May 2003.

[1] In this paper a detailed design, development and performances of a 5 GHz microstrip Yagi antenna, which uses a two-dimensional (2-D) electromagnetic band gap (EBG) structure in the ground plane, are presented. The results indicate that the use of the EBG structure improves the radiation pattern of the antenna. The cross polarization is suppressed by properly choosing the period and dimensions of EBGs. Also, the broadside gain is improved in comparison with the analogous antenna without the EBGs. *INDEX TERMS:* 0609 Electromagnetics: Antennas; 0624 Electromagnetics: Guided waves; 0619 Electromagnetics: Electromagnetic theory; 0689 Electromagnetics: Wave propagation (4275); *KEYWORDS:* electromagnetic band gap, EBG antenna, microstrip Yagi antenna, wireless LAN, antennas for wireless LAN

Citation: Padhi, S. K., and M. E. Bialkowski, A microstrip Yagi antenna using EBG structure, *Radio Sci.*, *38*(3), 1041, doi:10.1029/2002RS002697, 2003.

1. Introduction

[2] An electromagnetic band gap (EBG) structure is a periodic structure, which exhibits a band gap over a certain frequency range over which the propagation of electromagnetic waves is prohibited. The term band gap is well known in the semiconductor physics in relation to the propagation of optical waves [*Yablonovitch*, 1993; *Joannopolous et al.*, 1999; *Brown et al.*, 1993]. The photonic structures associated with this phenomenon are named Photonic Band Gap structures (PBGs). Recently, this concept has been scaled down to microwave and millimeter-wave frequency bands resulting in a more appropriate term EBG. A periodic structure (EBGs) applied to microwave planar waveguides can produce passband or stopband characteristics [*Yang et al.*, 1999; *Fu et al.*, 2001; *Lopetegi et al.*, 2000]. By proper selection of dimensions and periods certain waves are allowed to propagate through, while the other waves, such as surface waves, can be suppressed. Due to such properties, EBGs have potential to improve performances of planar antennas in terms of their radiation pattern and gain [*Gonzalo et al.*, 1999; *Coccioli et al.*, 1998].

[3] Microstrip antennas have been used widely and continue to be popular in commercial applications due to their light weight, low profile, low cost and ease of integration with MMIC fabrication technology. In particular, the ease of integration with MMIC leads to low cost manufacturing. The particular role of an electromagnetic band gap (EBG) technique is that it can be applied to improve performances of a planar antenna designed on a high dielectric material. By loading the EBGs periodically on substrate, a band gap can be created for frequencies around the operating frequency of antenna. Such structure can stop the propagation of surface waves, which can be excited along the high dielectric substrate material supporting MMIC components. By doing this, more power can couple to a space wave instead of being wasted in the substrate.

[4] In general, EBGs can be realized as 1-D (one-dimensional), 2-D or 3-D structures [*Pozar*, 1983; *Coccioli et al.*, 1999]. With respect to microwave planar circuits they can be obtained as 1-D or 2-D structures by creating holes in the dielectric substrate or by etching them in the conducting ground plane.

[5] The present paper demonstrates the use of EBG in the design a microstrip Yagi antenna. This antenna is aimed for possible use in a Wireless LAN at 5.2 GHz (such as is offered by the IEEE 802.11a standard). Its performance is compared with a Yagi antenna, which is developed using conventional microwave substrates without EBGs.

[6] The paper is organized as follows. Section 2 describes the theoretical fundamentals concerning EBGs

0048-6604/03/2002RS002697$11.00

and antenna design. Section 3 reports on a complete parametric study of the antenna with different EBGs sizes. Simulated and experimental results are presented. In Section 4, conclusions are drawn.

2. Design

[7] A microstrip Yagi antenna is a planar array antenna, which consists of a driven element and a few parasitic elements in the form of conducting patches. Its interesting property is that due to the electromagnetic coupling between adjacent patches (which introduces suitable phase shift) it is able to provide beam squint in elevation plane while offering directional radiation pattern in azimuth. Using conventional substrate materials, its design, development and testing for possible application with Wireless LAN at 5.2 GHz were presented by *Padhi and Bialkowski* [2000, 1998]. The Yagi antenna developed by *Padhi and Bialkowski* [2000, 1998] was to achieve communications between peripheral computers and a base station.

[8] The present article describes the design of an aperture-coupled microstrip Yagi antenna, which uses EBGs to enhance its performance. Here, a two-dimensional (2-D) EBGs in the ground plane is selected to improve the radiation properties of a planar Yagi antenna.

2.1. EBGs Design

[9] The EBG structure is basically a periodic structure defined by the following equation:

$$k = \frac{\pi}{d} \quad (1)$$

where k and d are the wave number at a stop band frequency and the period or cell spacing, respectively.

[10] When the EBGs is formed by periodically spaced circular holes, the ripples and the suppression of harmonics depend primarily on the cell period (d) and the filling factor (r/d), which is defined as a ratio of the radius of the circular hole and the cell spacing. In order to get an optimum performance in the rejection band, the filling factor in the range of 0.24 to 0.3 is suggested [*Fu et al.*, 2001; *Lopetegi et al.*, 2000].

2.2. Antenna Design

[11] For the planar Yagi antenna considered here, the radiating elements consisting of a driven element, reflector and two directors, are printed on top surface of the upper dielectric substrate of material permittivity of ε_{r1} and thickness h_1. The feed line is printed on the lower substrate of material permittivity of ε_{r3} and thickness h_3. The third dielectric layer of material permittivity of ε_{r2} and thickness h_2, is placed in between the upper and lower dielectric substrates to increase the electrical height of the structure and the level of coupling. The material properties and dimensions of the radiator, parasitic elements and the feed network are given in Figure 1, where a, a_r and a_d are the sizes of (square in shape) patch, reflector and directors respectively and d_r and d_d are the interelement spacing between reflector and the driven element, and the driven element and director, respectively. The characteristic impedance of the feed line is chosen as 50-Ω. The EBG holes are etched in the ground plane except the region underneath the driven patch and the parasitic elements. The holes in these regions are purposely eliminated to avoid an excessive perturbation of the operation of the feed line and the radiating element. A 4-mm (h_2) air gap (layer II) is maintained in between the top patch layer (layer I) and the metallic ground plane containing the aperture and EBGs to achieve suitable coupling over the required bandwidth. The initially proposed EBG structure consists of a regular (5 × 5) lattice of holes etched in the ground plane. However, to avoid disrupting of the radiating modes and the fringing field generated underneath the patch, some of the holes underneath the patch and the feed line in the patch regions, are not included. In this way, the created lattice becomes irregular. To investigate the implication of removing the holes from the lattice, a detailed parametric study is performed.

[12] The analysis of the proposed antenna structures (with and without EBGs) was carried out using the commercially available full-wave EM CAD tool IE3D

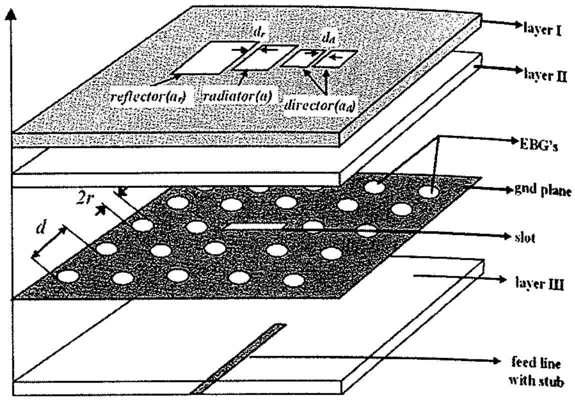
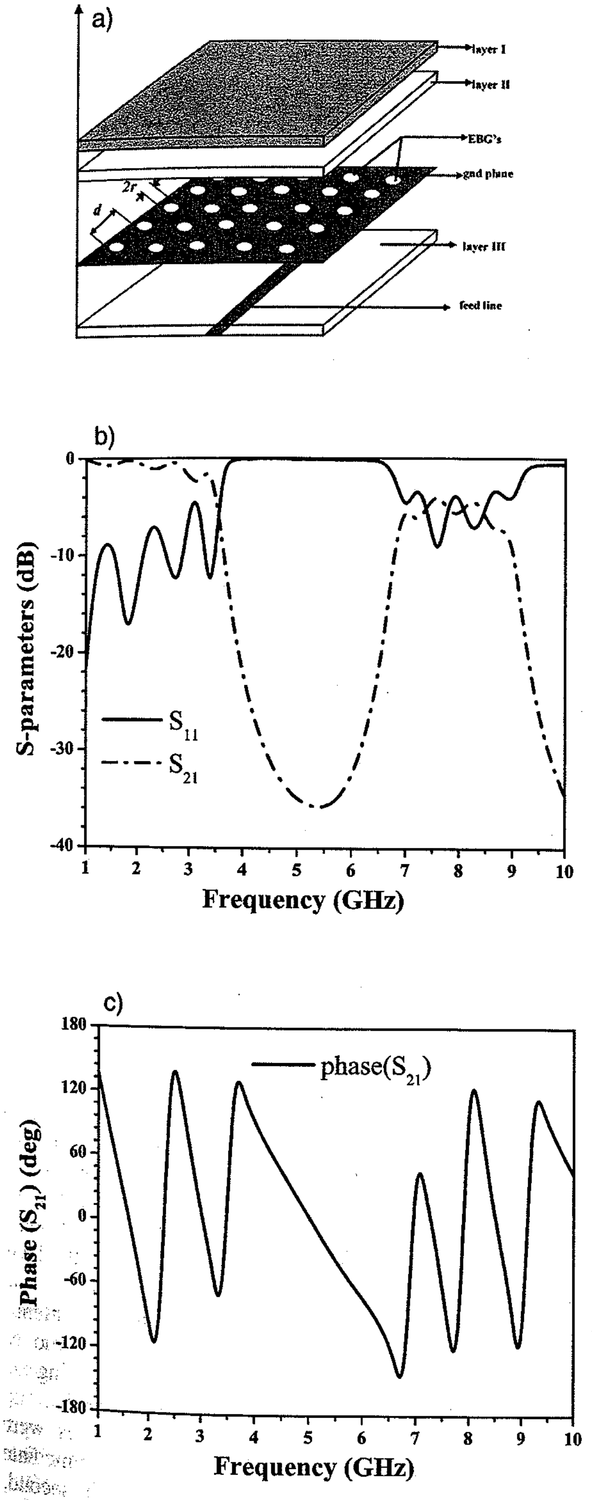


Figure 1. Configuration of microstrip Yagi antenna (3-D view). Parameters for layer I (patch layer): ε_{r1} = 2.43, h_1 = 0.79 mm, layer II: ε_{r2} = 1.06, h_2 = 4.00 mm, layer III (feed layer): ε_{r3} = 2.43, h_3 = 0.79 mm. Other dimensions: reflector: a_r = 25.00 mm, radiator: a = 20.0 mm, director: a_d = 17.0 mm, d_r = 2.0 mm and d_d = 2.0 mm; coupling aperture (slot): (14 × 2) mm^2, feed line: (2.27 × 50) mm^2, stub: (2.27 × 5.0) mm^2, EBGs: period: d = 20 mm, filling factor (r/d): 0.3.



of Zeland. The method of analysis is based on a method of moments (MoM). The software is able to predict the antenna performance in terms of return loss, broadside radiation pattern and directivity. A detailed parametric study of the microstrip line with EBGs is carried out and the calculated results are presented in the next section. The antenna prototypes with and without EBGs were developed on PCB board by using a milling machine as an etching tool.

2.3. Measurement Setup

[13] The input impedance of the antenna was measured with HP8510C Vector Network Analyzer. Here, the antenna impedance bandwidth is defined as the frequency range over which the VSWR observed at the antenna feed port is less than 2 or return loss is not less than 10 dB. The far field radiation patterns and gain of the antenna were measured in an anechoic chamber equipped with an HP8530-A Microwave Receiver. Absorbers were used in the antenna holding fixture to suppress the unwanted radiation from edges and back holding. The gain was determined by using the standard gain transfer technique. The maximum power level at transmitting and receiving antennas and the losses due to cable and connectors were measured and then using the Friis transmission formula, the gain was determined.

3. Results and Discussion

3.1. Dispersion Characteristics of Microstrip Line With EBG

[14] In order to understand the bandstop behavior, first, a detailed parametric study of a separate microstrip line with EBGs, the same as it was used in the Yagi antenna, was undertaken. In this case, the radiating layers and the coupling aperture were removed from the antenna structure without making any change to the remaining layers. The stop band was selected near the frequency of 5.2 GHz. This choice led to the period of the EBGs (d) of 20 mm. The filling factor was chosen of 0.3. As can be seen in Figure 1, the material permittivity of top and bottom layer is $\varepsilon_{r1} = 2.43$ and thickness 0.79 mm. A 4-mm (h_2) air gap (layer II) is maintained in between the top patch layer (layer I) and the metallic ground plane containing the EBGs. A microstrip line of center conductor width of 2.27 mm and length of 120 mm is etched on the bottom side of feed layer. The EBG structure is

Figure 2. (opposite) (a) The geometry of microstrip transmission line with EBG holes in the ground plane. Feed line: (2.27 × 120) mm^2. Other dimensions are as for Figure 1. (b) Calculated S-parameters of the microstrip transmission line with EBGs. (c) Calculated phase of S_{21}.

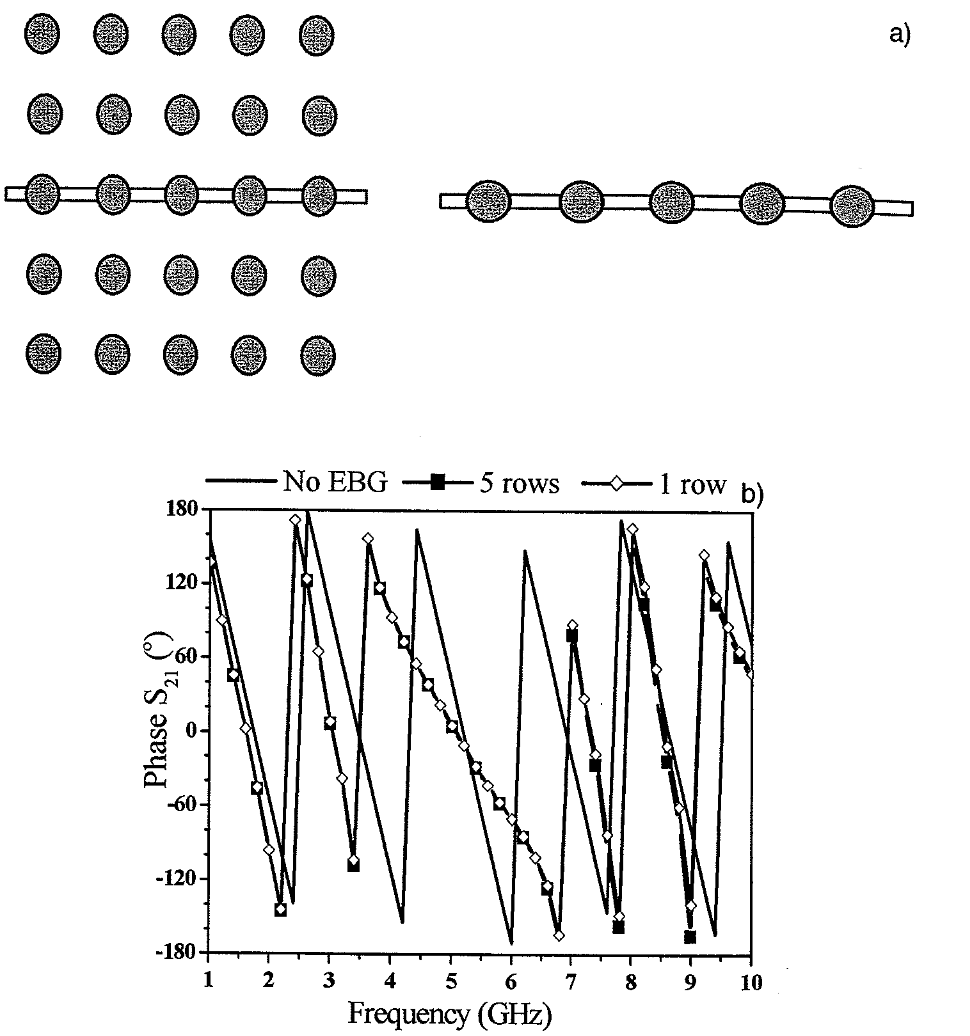


Figure 3. (a) The geometry of transmission line with different EBGs lattice structures. (b) Calculated phase of transmission coefficient (S_{21}) of the line.

realized by using a 5 × 5 lattice of holes etched on the ground plane. The calculated results of the microstrip line with different periods are presented in the following section. We keep the period and the filling factor the same in the parametric study and in the antenna design.

[15] The first simulations were concerned with a microstrip line employing an EBG structure. The calculated magnitude of scattering parameters (S_{11}, S_{21}) and the transmission phase of the microstrip line with EBGs are shown in Figures 2b and 2c. As can be seen, the level of rejection band (value of S_{21}) at the harmonics of design frequency is below −30 dB. The −20 dB rejection bandwidth extends from 4 to 6.6 GHz, and from Figure 2c the bandstop occurrence is quite prominent in the designed frequency range. To verify the band gap feature, the transmission phase of the line with 1 row (1 × 5) and 5 rows (5 × 5) of EBGs are plotted in Figure 3. As can be seen, the bandstop phenomenon is still distinct with one row (1 × 5) of EBG lattice. There is no significant difference in the slopes of transmission phase of the line. As the period increases to 9 (1 × 9), the level of rejection band increases to 53 dB.

[16] As mentioned above, while designing the antenna some of the holes from the lattice structure were removed so that fringing field was uninterrupted. By doing so, some deflection in the lattice structure was made.

[17] In the present study, two different cases were considered. In the first case, (Case-A) two immediate holes (2nd and 3rd holes from 4th row) and in second, (Case-B) two holes from either side of the microstrip line

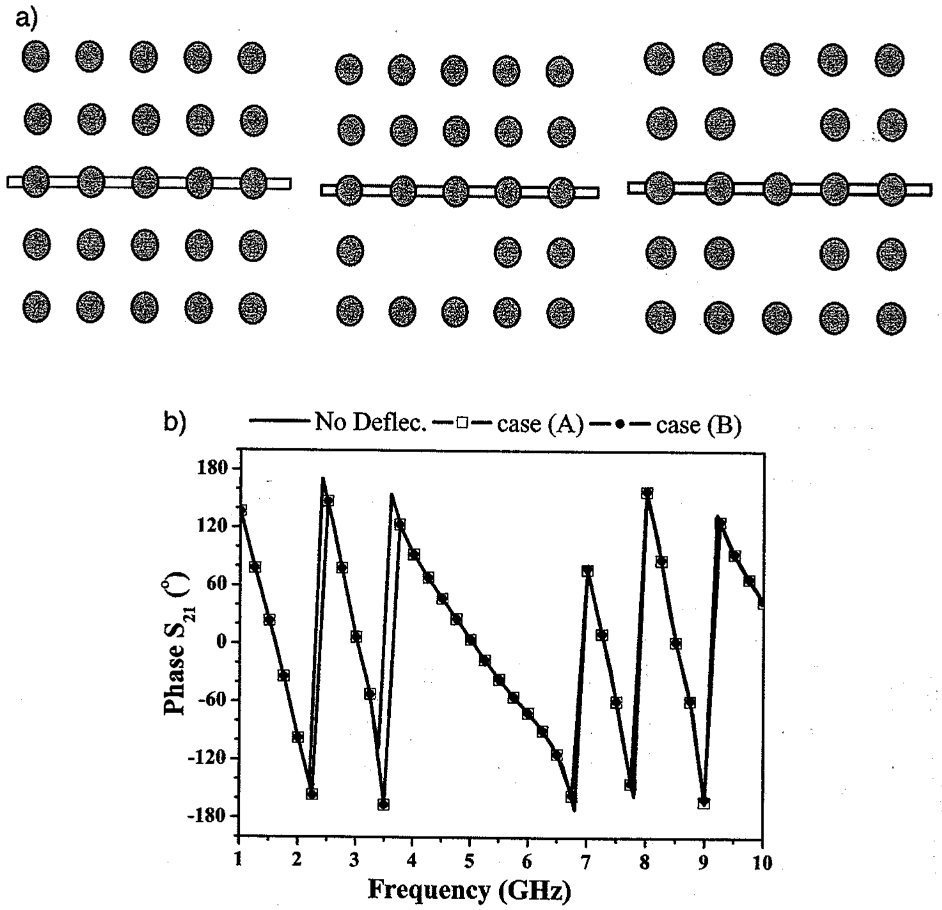


Figure 4. (a) Geometry of transmission line with removed holes. (b) Calculated transmission phase S_{21} of the line.

(3rd holes from 2nd and 4th row) were removed. These configurations are shown in Figure 4a. The results of simulations are presented in Figure 4b. The results obtained are compared with those that were obtained for the lattice structure with no deflection. The variation in phase value is very small. In addition, no variation in the slopes of S_{21} (phase) in band gap region was found. This result shows that the structure still exhibits the forbidden band gap even if some of the holes are removed from the lattice structure.

[18] Having achieved satisfactory performance of the microstrip line with EBGs, in the next step, the Yagi antennas were designed. This process was aided with IE3D. The design concerned including the radiating elements on top layer and the coupling aperture on the ground plane containing the EBGs. In order to investigate the band gap phenomenon, the performance of the antenna was evaluated in terms of its return loss and reflection phase with different matrices of periodic structures and the results are shown in Figures 5a and 5b.

[19] As can be seen in Figure 5a, for a single row of periods (1 × 5), the return loss of the antenna degrades. This is due to the blockage of a fringing field as the holes are lying underneath the feed line. While calculating the return loss of all other cases (except the case of the 1 × 5 lattice), the holes underneath the feed line were removed to avoid the fringing field blockage. As can be seen, a marginal change in return loss is seen in the figure due to an increase of lattice structure. The corresponding reflective phases are shown in Figure 5b. The variation in slope stabilizes for the lattice structure with four or more rows of periods. These results show that obtaining the band gap is possible with a single row of EBGs underneath the antenna.

[20] Etching holes underneath the transmission line causes degradation of the return loss, as the fringing field is blocked. To avoid such blockage, two alternative actions can be undertaken. In one, some of the holes underneath the transmission line can be removed. In two, the lattice can be offset to provide clearance so that the

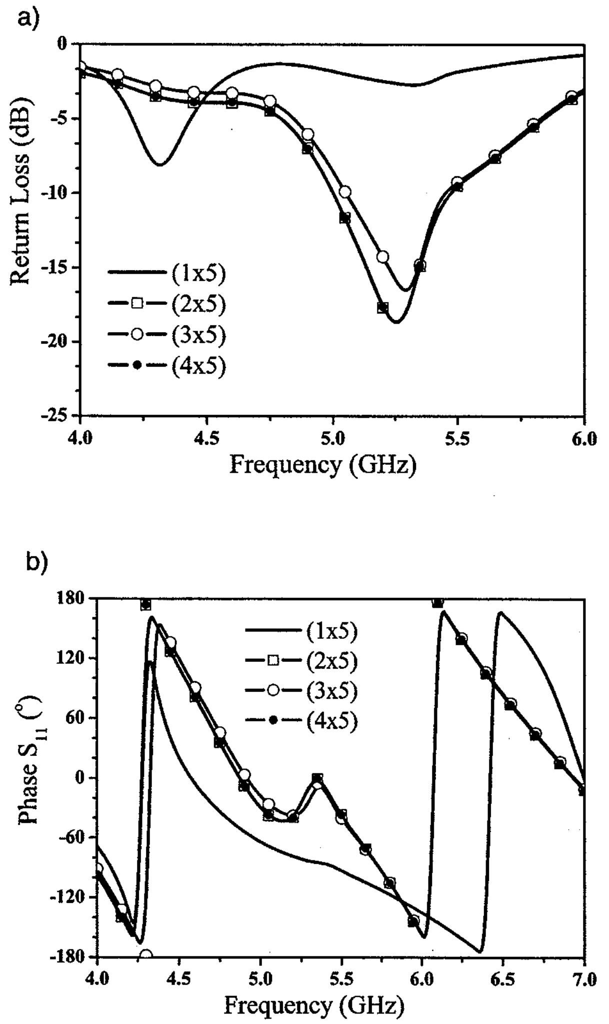


Figure 5. Calculated (a) return loss of and (b) reflective phase of Yagi antenna with various lattice structures.

holes are not located underneath the microstrip line. We did the simulation for both cases, where 10 mm offset was assumed in the second case, and the magnitude of return loss and the reflective phases were compared. However, we did not find any change in the slope of reflective phase or in magnitude of return loss of the antenna.

3.2. Return Loss

[21] Having achieved the satisfactory simulation results, the Yagi antennas with EBGs different layers were etched using a milling machine and then assembled. A reference (conventional) antenna structure without EBGs in the ground plane was also developed. The measured and calculated return loss of the antennas with and without EBGs is shown in Figures 6a and 6b. The best return loss of the antenna without EBG is measured at 5.00 GHz compared with the simulated one at 5.2 GHz. The calculated impedance bandwidth (10 dB return loss (RL)) is from 5 GHz to 5.4 GHz (400 MHz) or 7.5% of bandwidth compared to measured impedance bandwidth range (10 dB RL) of 300 MHz or 5.8%. The discrepancies found in the simulated and experimental resonant frequencies may be due to the tolerance of the milling machine and an incorrectly assumed value of permittivity. In the experiment, the material permittivity

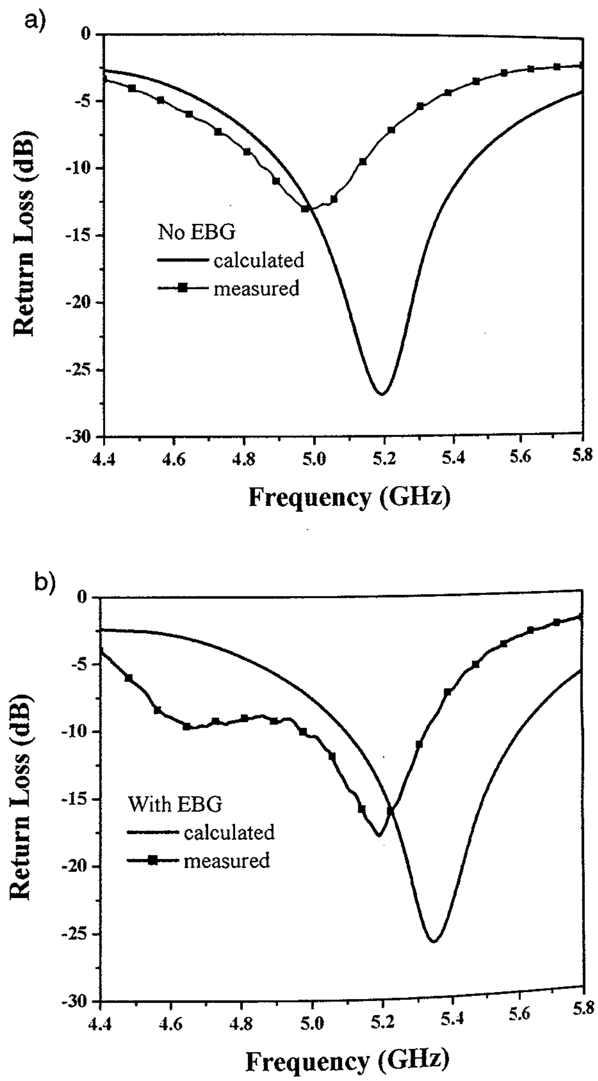


Figure 6. Calculated and measured return loss of Yagi antenna (a) without EBGs and (b) with EBGs.

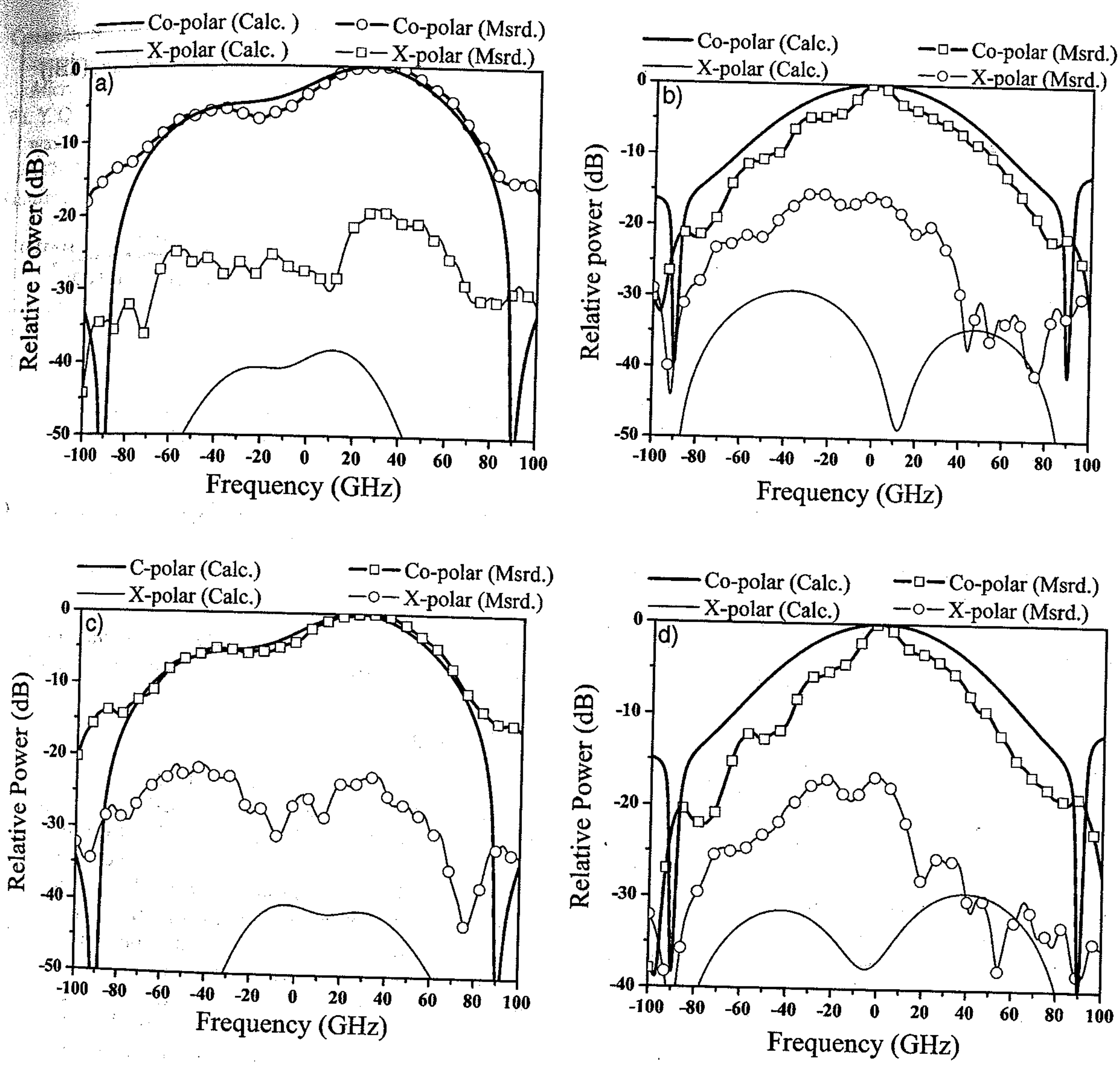


Figure 7. Calculated and measured copolar and cross-polar radiation patterns of Yagi antenna without EBGs in (a) elevation plane, (b) azimuth plane, and with EBGs, in (c) elevation plane, (d) azimuth plane.

of the substrate was found to be $\varepsilon_r = 2.2$ which was slightly smaller than $\varepsilon_r = 2.43$ assumed in simulations. The slight difference in the measured permittivity affects the impedance match conditions and results in a reduced impedance bandwidth. For the antenna with the EBG structure, the measured resonant frequency is 5.18 GHz compared to the simulated one of 5.33 GHz. The calculated and measured bandwidths (10 dB RL) are 650 MHz (>11%) and 350 MHz (7%) respectively. The discrepancy in the calculated and measured resonant frequencies may be attributed to the material properties and the tolerance of the milling machine.

3.3. Radiation Pattern

[22] The simulated and measured copolar (thick line) and cross-polar (thin line) radiation patterns in azimuth and elevation planes at the respective resonant frequencies for antennas with and without EBGs are shown in Figures 7a–7d. In Figure 7a, measured radiation pattern

of the main beam is pointed at an angle of 28° from the broadside direction and agrees well with the calculated radiation pattern. The calculated cross-pol levels are on average 35 dB below the maximum copolar level. The average measured cross-pol levels are at 18 dB below the maximum copolar level.

[23] For the EBG structure the main beam position is 31° from the broadside direction and the radiation pattern is found to be similar to the measured pattern of the antenna without EBGs. The measured radiation pattern of the antenna with EBGs agrees well with the simulated radiation pattern within the angular range of ±80°. The average measured cross-pol levels are improved by 4 dB compared to the antenna without EBG holes. Back lobe radiation pattern also improves compared to the antenna without EBGs. However, in both cases discrepancies in the radiation pattern are found for angles around ±90°. These discrepancies could be due to the fact that in simulations IE3D assumes the substrate and ground plane to be infinite while the developed antennas use a finite ground plane. The observed back lobes are mainly due to the radiation from slot and not from the diffracted surface waves. They can be suppressed by using a metallic shield at a distance of λo/4 from the microstrip feed line at the back of the antenna structure.

[24] The calculated and measured E-plane radiation patterns are presented in Figures 7c and 7d. The calculated radiation pattern is broadside and the cross polar level is below 30 dB with respect to the peak in the copolar pattern. The simulated cross-polar level is lower (−20 dB on average) than the measured one. The ripples found in the measured radiation pattern may be due to the finite ground plane size. There is no improvement in measured cross-pol levels in E-plane compared to cross-pol response in H-plane radiation patter.

3.4. Gain Enhancement

[25] In the next step, the effect of different lattice size of the EBGs on the antenna gain was studied. In all the undertaken simulations a fixed value filling factor of 0.3 was used. The maximum gain of 11.2 dB was obtained with the lattice size of 8 × 5. The study was restricted to the largest lattice size of 14 × 14. This restriction came to avoid an excessive computational time for large size lattice structures. The calculated gain versus the number of EBG holes (lattice size) is shown in Figure 8. As can be seen in Figure 8, the gain increases with the lattice size and reaches maximum value of 11.2 dB when the size becomes (8 × 5). After that the gain starts decreasing as the size increases. The observed increase in the value of gain is likely due to suppression of surface waves. The measured gains of the antenna at their resonant frequencies (of 5.18 GHz and 5.0 GHz) are

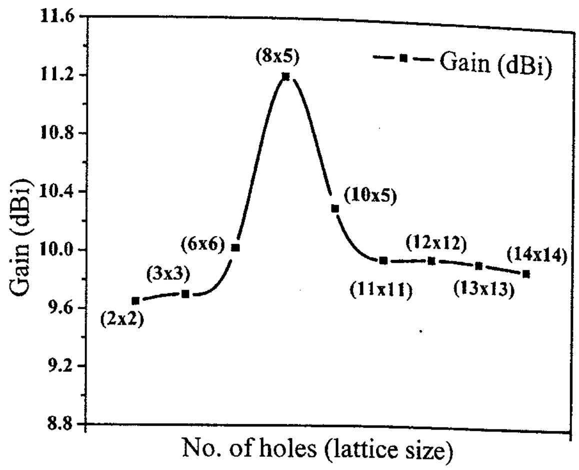


Figure 8. Calculated gain of Yagi antenna with EBG holes etched in the ground plane.

10.8 dBi and 9.6 dBi, respectively, for the antenna with and without EBGs. The gain improvement is 1.2 dB.

4. Conclusion

[26] In this paper, a detailed theoretical and experimental study of an aperture coupled microstrip Yagi antenna with and without EBG structure has been presented. The theoretical study has been performed using an EM field simulator while the experimental study has been achieved through a number of measurements on the developed antenna prototypes. In particular, a parametric study concerning the effect of various EBG lattice structures for the feed line and the entire antenna has been undertaken. It has been found that by using a suitably chosen EBG structure, the antenna performances with respect to gain and cross-pol level can significantly be improved. These findings can be of special importance while designing a microstrip Yagi antenna on a high dielectric constant substrate, such as is required in MMIC applications. In this case, the use of EBGs can suppress propagation of surface waves and at the same time improve the radiation pattern and gain of the antenna integrated with the MMIC module.

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