Application of Defect Induced Microwave Band Gap Structure for Non-destructive Evaluation and the Construction of a Frequency Selector Switch

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Abstract — The use of microwave band gap structures for the non-destructive evaluation of material property is being probed in this paper. As a first step, we studied numerically, the appearance of a point defect mode within the band gap of a microwave band gap structure for the use as a tool to evaluate the dielectric constant of the material at the defect site. The simulations were carried out using the FEMLAB software. In a pure $10 \times 10$ square lattice constructed with a material of dielectric constant ($\varepsilon$) 5.5 (in the form of a right circular cylinder), a point defect is created by replacing one of the rods with a geometrically similar but with different dielectric constant material. The appearance of the defect mode is governed by the refractive index contrast (defined as the ratio between the refractive index of the material at the defect site ($n_d$) and the material of the lattice ($n_l$)). In this case, the refractive index contrast ($n_d/n_l$) was found to be between 0.85 and 1.28. Simulations were also done with the lattice material of dielectric constant 10 and the defect mode appeared for $1.18 < n_d/n_l < 0.84$. For the contrast less than 1, defect creates the fundamental mode similar to TE$_{01}$ mode whereas for the contrast greater than 1, next higher mode similar to TE$_{11}$ appears. Once a defect mode appears, it moves towards lower frequency as the dielectric constant of the defect site is increased. In this paper, we propose to evaluate the dielectric constant of a material using the above procedure. This paper also proposes the construction of a novel frequency selector switch that has two line defects in a $10 \times 20$ square lattice structure constructed with material of dielectric constant 10.

1. INTRODUCTION

The electromagnetic propagation through periodic structures, also called photonic crystals has attracted attention over the years [1–3] because of their potential applications [4, 5]. The periodic sites can be occupied by either dielectric and/or magnetic materials depending on the application. This is analogous to the electronic case where the propagation is because of electrons compared to photons in photonic crystals. The dielectric constant/magnetic permeability of the material at the defect site is responsible for the scattering of electromagnetic waves resulting in band gaps over a range of frequencies. In order to achieve this, the periodicity should be of the order of wavelength of source. Thus, in microwave frequencies, the periodicity will be of the order of centimeters and is of the order of micrometer in the optical frequency region. Defects can also be created in these structures and are of two types viz; acceptor type and donor type [6]. The creation of defect makes the structure acts like a resonator locally resulting in an extra mode within the band gap. The position and nature of the defect mode depends on the position as well as the dielectric constant of the material at the defect site. Similarly, line defects created in the structure act as either Fabry-Perot resonator or waveguide depending on the direction of propagation [7]. The use of these structures allows one to have control over photons in their own fashion similar to the electronic case. Since photons travel much faster than that of electrons, these structures can be exploited for communications where a faster transmission can be achieved. The applications of such structures include resonators, filters, antennas, polarizers, optical switches [8] etc. In this paper, we propose the use of these structures for non-destructive evaluation of a material property such as dielectric constant (or refractive index) and also as a frequency selective switch in the microwave frequency region. The results were based on the simulations performed using FEMLAB and few experimental results were also presented. The structure chosen was a $10 \times 10$ square lattice constructed with a material of dielectric constant 5.5 and the length and diameter of the rods were 10 and 0.414 cm respectively. The lattice spacing was chosen to be 0.9 cm. Point defect was introduced at the center of the structure in all the cases. Line defects were created at two different positions in order to demonstrate the frequency selector switch. In this case, the $10 \times 20$ lattice structure was chosen with the same set of parameters for convenience.
2. EXPERIMENTAL ARRANGEMENT

A microwave vector network analyzer (N5230A) was used to obtain the $S_{21}$ parameter in the frequency region between 10 and 20 GHz with the help of two horn antennas kept on either side of the structure. The antennas were separated by a distance of 50 cm. The fringe effects of the electric field were assumed to be minimum. Initially, the $S_{12}$ parameter was normalized without any structure between the antennas. For all the experiments, only $E$-polarized beam (with electric field parallel to the length of the rod) was used. For convenience, only the normal direction ($\Gamma$-$X$) was considered in the present case. In case of frequency selector switch also, the experiment was performed in a similar manner but with horn antennas placed according to the structure.

3. RESULTS AND DISCUSSION

Figure 1(a) shows the transmission spectrum obtained numerically for a square lattice without any defects. It can be observed that there exists a band gap from 10.06 to 15.27 GHz with a mid-gap frequency of 12.67 GHz. The experimentally observed value was 13.30 GHz as shown in Fig. 1(b). Simulations were carried out with a point defect at the center of the structure (by inserting a geometrically similar object), but with varied dielectric constant. The dielectric constant at this particular site ($\varepsilon_d$) was varied from 1 to 20 in steps of 1. It was found that the resonant frequency moves towards lower frequency side as the dielectric constant at the defect site is increased from 1 to 4 indicating the resonance effect. The defect mode was again observed for a dielectric constant of 9 at the defect site. This shows that, in order for a defect structure to act as a resonator, one should have a minimum value of refractive index contrast, defined as the ratio between refractive index of the material at the defect site ($n_d$) and the refractive index of the material of the lattice ($n_l$). In the present case it was found to be 0.85 if $\varepsilon_d < \varepsilon_l$ and 1.28 if $\varepsilon_d > \varepsilon_l$. Simulations were also performed for a square lattice constructed with a material of dielectric constant 10 and the dielectric constant at the defect site was varied from 1 to 20. In this case also, the minimum refractive index contrast was observed to be 0.84 if $\varepsilon_d < \varepsilon_l$ and 1.18 if $\varepsilon_d > \varepsilon_l$. The obtained results are shown in Fig. 2. For $\varepsilon_d < \varepsilon_l$, the mode is like a fundamental mode and for $\varepsilon_d > \varepsilon_l$, it is the next higher order mode. This particular method is useful in the evaluation of dielectric constant. Suppose we have a material whose dielectric constant (or refractive index) is not known, we can insert that material at a particular defect site and observe the resonant frequency from which the dielectric constant can be found. If one couldn’t observe the defect mode, it means that the refractive index contrast is not sufficient to support a resonant mode inside the band gap, in such case, changing the lattice material might help in observing a resonant mode. Thus, one can use this method effectively for non-destructive evaluation. Experiment performed by inserting a Poly Tetra Fluoro Ethylene (PTFE) sample at the center of the structure shows the resonant frequency to be 12.54 GHz as in Fig. 1(b) whereas the simulated results show a defect mode at 13.33 GHz as in Fig. 1(a). It can be observed that the position of the defect mode is towards the positive side of the mid-gap frequency.
frequency in simulated results whereas it is towards negative side of the mid-gap frequency in the experimental results.

![Figure 2: The shift in resonant frequency with change in refractive index of a material at the defect site.](image)

Photonic crystals can be used for a variety of applications such as antennas, filters, switches etc. In this paper we demonstrate the frequency selector switch in which we have a $10 \times 20$ (rows $\times$ columns) square lattice constructed with a material of dielectric constant 5.5. The lattice spacing was chosen to be 0.9 cm. Line defects were created at two different positions. Along the direction of propagation, 5th and 6th columns till 5th row were removed from the structure and for convenience we labeled port 1, port 2 and port 3 at windows of the structure as shown in Figs. 3(a) to 3(c). The excitation field was at port 1 in between 5th and 6th rows of the structure and the frequency span was from 8 to 20 GHz. It was observed that for majority of the frequencies, there was output at port 2 and port 3 simultaneously as shown in Fig. 3(a). However, at 11.03 GHz, there was output only at port 3 and at 13.45 GHz there was output only at port 2 as shown in Fig. 3(b) and 3(c) respectively. This was confirmed with the experiment which was performed to obtain $S_{21}$ and $S_{31}$ at port 2 and port 3 respectively for the frequency range of 10–20 GHz. The parameters $S_{21}$ and $S_{31}$ were normalized with the background data (without structure) at port 2 and port 3. Fig. 4(a) indicates that at 14.95 GHz, $S_{31}$ is more by 43.20 dB compared to $S_{21}$, whereas Fig. 4(b) indicates that at around 17.3 GHz, $S_{21}$ is more by 26.71 dB compared to $S_{31}$. This gives the confirmation that line defect based photonic crystals can be used as a frequency selective switch.

![Figure 3: (a) Photonic crystal as a frequency selector switch with the input at port 1 and the output at the ports 2 and 3; (b) Photonic crystal as a frequency selector switch with the input at port 1 and the output at the port 3 but not at port 2; (c) Photonic crystal as a frequency selector switch with the input at port 1 and the output at the port 2 but not at port 3.](image)
Figure 4: (a) The transmission spectra obtained experimentally demonstrating frequency selection among port 2 and port 3. It can be observed that at 14.95 GHz, the output at port 3 is more by 43.20 dB compared to port 2; (b) The transmission spectra obtained experimentally demonstrating frequency selection among port 2 and port 3. It can be observed that at 17.30 GHz, the output at port 2 is more by 26.7 dB compared to port 3.

4. CONCLUSIONS

The effect of point defect in the form of varying dielectric constant shows that one can extend this to evaluate non-destructively the dielectric constant of the material at the defect site. It may be noted that to observe a defect mode, there should be some refractive index contrast depending on the lattice structure and host material. The efficient use of these structures as a frequency selector switch was also demonstrated.

REFERENCES