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Two-dimensional microwave band-gap structures of different dielectric materials

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Abstract. We report the use of low dielectric constant materials to form two-dimensional microwave band-gap structures for achieving high gap-to-midgap ratio. The variable parameters chosen are the lattice spacing and the geometric structure. The selected geometries are square and triangular and the materials chosen are PTFE ($\varepsilon = 2.1$), PVC ($\varepsilon = 2.38$) and glass ($\varepsilon = 5.5$). Using the plane-wave expansion method, proper lattice spacing is selected for each structure and material. The observed experimental results are analyzed with the help of the theoretical prediction.

Keywords. Band gaps; gap-to-midgap ratio; dielectric constant.

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1. Introduction

There has been a growing interest in the field of photonic crystals (PCs) both theoretically and experimentally over the past fifteen years [1–4] and many structures that can exhibit photonic band gaps (PBGs) were investigated [5–8]. Photonic crystals or photonic band-gap structures are structures in which the dielectric constant and/or magnetic permeability (or in particular impedance) are periodic and the propagation of electromagnetic waves is forbidden at certain frequencies when allowed to pass through these structures. This is similar to the electronic band gaps in the case of crystals where the propagation of electron is forbidden in certain energy regions and is known as a band gap. The photonic band gap is exact as there is no possibility of electron–electron interactions as in the electronic case [9]. Yablonovitch [10] was the first to show that spontaneous emission can be suppressed by using these types of periodic structures. The appearance of the band gaps can be explained based on the concepts of interference and dielectric potential. The incoming waves undergo Bragg diffraction and because of destructive interference, we will get a band gap. Also, the samples that are used for creating the structures

act as dielectric potential and if the dielectric constant is greater than one, we can expect a band gap. Photonic band-gap structures are constructed artificially in one, two and three dimensions with unit cell dimensions compared to that of the wavelength of the source used. These structures make good reflectors since photons with energies within the band gap are not allowed to propagate inside the crystal. Since the dimensions should be comparable to that of the wavelength of the source used, in optical region, the lattice spacing should be of the order of micrometers and in the microwave region it should be of the order of centimeters.

The formation and the width of the band gaps mainly depend on the geometric structure, filling fraction (fractional volume occupied by the samples within a unit cell) and the dielectric contrast (ratio of the dielectric constant of the sample to that of the background). As the filling fraction is increased, the width of the band gaps starts increasing and becomes maximum at a certain value of filling fraction known as optimum filling fraction. A further increase in the filling fraction results in the decrease in the width of the band gap.

In general, the use of low dielectric constant materials in the band-gap structure results in the formation of low gap width. Hickmann *et al* [11] used acrylic rods of dielectric constant 2.59 to construct band-gap structures. They reported a maximum gap width of 1.5 GHz. Therefore, one uses a material with high dielectric constant to achieve a higher gap width. For the first time, in this paper, we report the formation of higher bandwidth using materials with low dielectric constant. The materials chosen for this work are polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC) and glass rods. The parameters that are varied to obtain higher bandwidth are the lattice spacing and geometric structure. The selected geometric structures are square and triangular. Using the plane-wave methodology, suitable lattice spacing for each material and geometric structure is selected.

2. Experimental arrangement

The structures considered in the present case are square and triangular lattices consisting of 100 samples in all the cases. A microwave vector network analyzer (HP 8720A) was used to obtain the scattering parameter S_{12} for the frequency region between 7 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 vector of the electromagnetic wave parallel to the length of the rod) was used. The experimental arrangement was given in figure 1. The experiments were done only in normal direction (Γ–X for square lattice and Γ–M for triangular lattice) in such a way that the gap-to-midgap ratio would be maximum.

3. Results and discussion

The radius and the dielectric constant of the materials used are given in table 1. In all the cases, the length of the rods was taken as 10 cm. The dielectric constants

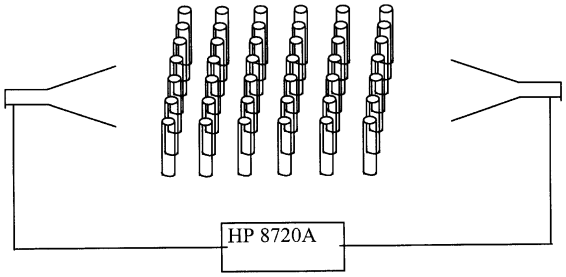

Figure 1. The experimental arrangement.

listed in the table were measured at 10 GHz using cavity perturbation technique. Both square and triangular lattices were constructed with all the three samples. Using plane-wave expansion method [12,13], the lattice constants were chosen in such a way that the gap-to-midgap ratio is always maximum. Thus the lattice constants were chosen as 1.0 cm in the case of PTFE rods for both square and triangular lattices, 1.0 cm for square lattice and 1.1 cm for triangular lattice in the case of PVC rods and 0.9 cm for both the lattices in the case of glass rods.

3.1 *PTFE rods*

As mentioned earlier, the lattice spacing was chosen as 1.0 cm for square and triangular lattices. For the square lattice, the plane-wave method predicts a gap width of 2.04 GHz with a midgap at 13.14 GHz (figure 2a). This corresponds to the gap-to-midgap ratio of 0.15. The experimentally observed transmission spectrum (figure 2b) indicates a gap width of 2.68 GHz with a midgap frequency of 13.48 GHz which corresponds to a gap-to-midgap ratio of 0.20. It is to be noted that the value of gap width obtained is higher than the values reported elsewhere for still higher dielectric constant materials [11]. Similarly, the band structure for a triangular lattice predicts a band gap at 14.84 GHz with a gap width of 2.20 GHz which corresponds to a gap-to-midgap ratio of 0.15. The transmission spectrum shows a band gap at 14.49 GHz with a gap width of 3.20 GHz. This corresponds to a gap-to-midgap ratio of 0.22. From the above values it can also be observed that the gap width for triangular lattice is more than that for the square lattice.

Table 1. The radius and the dielectric constant of the samples under consideration.

Material	Radius (cm)	Dielectric constant
PTFE	0.300	2.10
PVC	0.320	2.38
Glass	0.207	5.50

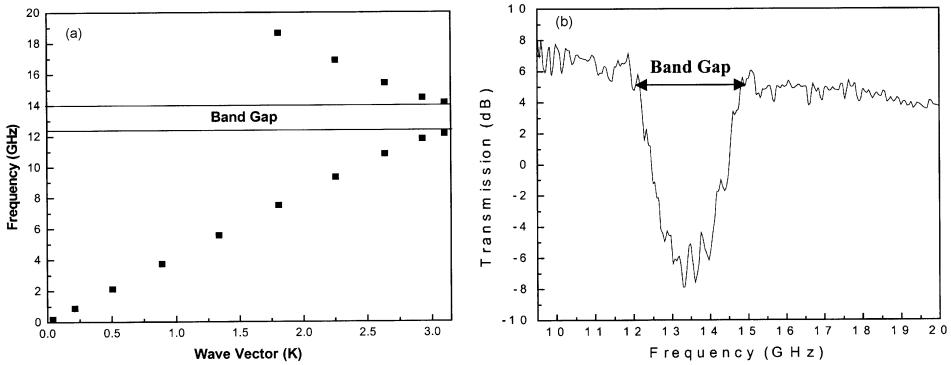

Figure 2. (**a**) The band structure for a square lattice of PTFE rods of lattice spacing 1.0 cm. (**b**) The transmission spectrum for the above structure.

3.2 *PVC rods*

The lattice constant chosen for square lattice is 1.0 cm. The plane-wave method predicts a band gap centered at 12.54 GHz with a gap width of 2.32 GHz. This corresponds to a gap-to-midgap ratio of 0.19. The corresponding transmission spectrum indicates a band gap centered at 11.65 GHz with a gap width of 3.16 GHz resulting in a gap-to-midgap ratio of 0.27. Similarly, for the triangular lattice (where the lattice spacing is 1.1 cm), the plane-wave method predicts a band gap at 13.18 GHz with a gap width of 2.31 GHz corresponding to a gap-to-midgap ratio of 0.18. Experimentally, there exists a band gap at 11.91 GHz with a gap width of 3.22 GHz resulting in a gap-to-midgap ratio of 0.27. In this case also, there is an increase in the gap width for the triangular lattice when compared to that of square lattice. Also, when compared to PTFE case, there is an increase in the gap width as well as the gap-to-midgap ratio.

3.3 *Glass rods*

For a square lattice of lattice spacing 0.9 cm of glass rods, plane-wave method predicts a band gap centered at 12.87 GHz with a gap width of 4.64 GHz. This corresponds to a gap-to-midgap ratio of 0.36. Experimentally, the gap is observed to be at 13.40 GHz with a gap width of 4.28 GHz resulting in a gap-to-midgap ratio of 0.32. Similarly for the triangular lattice, plane-wave method predicts a band gap at 14.18 GHz with a gap width of 5.15 GHz corresponding to a gap-to-midgap ratio of 0.36. The transmission spectrum shows a band gap centered at 14.56 GHz with a gap width of 4.32 GHz resulting in a gap-to-midgap ratio of 0.30. It can be observed that the gap width is more for triangular lattice in this case also and the gap width as well as gap-to-midgap ratio increases as the dielectric constant is increased.

Table 2 summarizes the results obtained theoretically as well as experimentally for all the samples. In general, the discrepancy between the theoretically calculated

Table 2. Comparison between the theoretical and experimental results for all the samples under consideration.

Sample		Theoretical			Experimental		
		Mid-gap (GHz)	Gap width (GHz)	Gap/midgap	Midgap (GHz)	Gap width (GHz)	Gap/midgap
PTFE	Square	13.14	2.04	0.15	13.48	2.68	0.20
	Triangular	14.84	2.20	0.15	14.49	3.20	0.22
PVC	Square	12.54	2.32	0.19	11.65	3.16	0.27
	Triangular	13.18	2.31	0.18	11.91	3.22	0.27
Glass	Square	12.87	4.64	0.36	13.40	4.28	0.32
	Triangular	14.18	5.15	0.36	14.56	4.32	0.30

and the experimentally observed values may be due to the finiteness of the structure whereas the band structure calculations apply for an infinite structure. The dielectric samples that were used in the structure act as a dielectric potential and if the dielectric contrast is greater than one, one will get a band gap. But as the dielectric contrast is increased, the potential that is created by the samples increases and so the degeneracy will be further lifted resulting in a larger band gap. This is also similar to the electronic case in which the crystal potential plays a crucial role and the appearance of the band gaps and their width (energy) purely depend on the potential that is created by the ion cores. The present results indicate that one can still use low dielectric constant materials to obtain wide band gaps around 4 to 5 GHz by properly adjusting the lattice spacing and selecting appropriate lattice geometry.

It is observed that the triangular lattice results in a larger gap width when compared to that of the square lattice. This is because triangular lattice has six-fold symmetry whereas square lattice has only four-fold symmetry. It may also be noted that for two-dimensional structures, triangular lattice possesses the highest symmetry. Therefore, one can infer that apart from the lattice spacing and dielectric constant, symmetry of the structure also plays a role in deciding the width of the band gap.

Keeping the dimensions of the samples to be same, increase in the dielectric constant will result in a lower value of midgap frequency and an increase in the gap width. Figures 3a and 3b show the variation in gap width and the midgap frequency obtained theoretically for a square lattice with the dielectric constant (radius 0.207 cm) and for a lattice spacing of 1.0 cm. The shift in the midgap frequency towards lower frequency side is expected because of the increase in total electric length by increasing the dielectric constant. Thus the gap-to-midgap ratio also increases with increase in the dielectric constant. It is also suggested that smaller structures are possible to construct in the following way. Consider a structure, which shows a band gap with a midgap frequency at 10 GHz. Using a material of higher dielectric constant in the structure (for the same lattice spacing), brings down the midgap frequency. Then by decreasing the lattice spacing accordingly we can match the frequency to 10 GHz. Thus, we can attain a smaller structure with a high dielectric constant material.

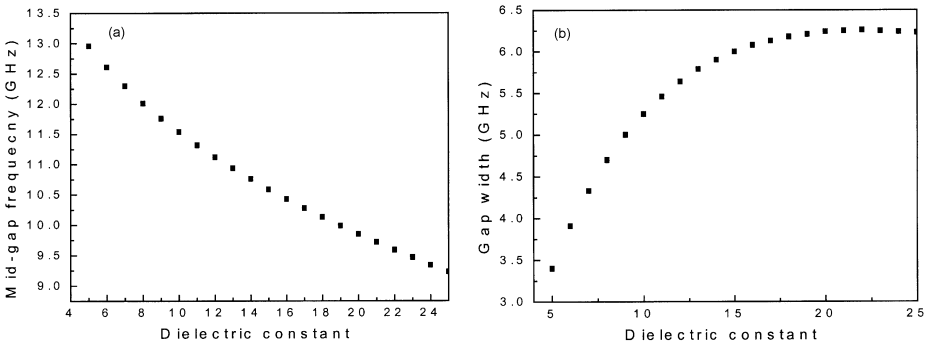

Figure 3. (**a**) The variation in the mid-gap frequency with dielectric constant. The lattice spacing was chosen as 1.0 cm and the radius of the sample was taken as 0.207 cm. (**b**) The variation in the gap width with dielectric constant. The lattice spacing was chosen as 1.0 cm and the radius of the sample was taken as 0.207 cm.

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