

Experimental investigation of layer-by-layer metallic photonic crystals

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Abstract: The authors have investigated the transmission properties and defect characteristics of layer-by-layer metallic photonic crystals. They have demonstrated experimentally that the metallicity gap of these crystals extends to an upper band-edge frequency, and no lower edge was detected down to 2GHz. The defect structures built around these crystals exhibited high transmission peak amplitudes (100%) and high Q factors (2250). The crystals with low filling ratios (around 1–2%) were tested and were still found to possess metallic photonic crystal properties. These crystals exhibited high reflection rates within the metallicity gap and reasonable defect mode characteristics. A power enhancement factor of 190 was measured for the electromagnetic (EM) wave within planar cavity structures, by placing a monopole antenna inside the defect volume. These measurements show that detectors embedded inside a metallic photonic crystal can be used as frequency selective resonant cavity enhanced (RCE) detectors with increased sensitivity and efficiency when compared to conventional detectors.

1 Introduction

Photonic crystals are periodic structures having the property of reflecting the EM waves in all directions for a certain range of frequencies [1–6]. Earlier investigations were mainly concentrated on dielectric based photonic crystals, and were successful in various applications [7–10] but some of their properties restrict the wide usage of these materials. First, dielectric based photonic crystals have low rejection rates per layer, so a large number of layers are needed for applications requiring high isolation purposes [11]. Second, for applications around the 1–10GHz range, these crystals become impractical due to their relatively large dimensions. As an example, for a 2GHz application, the dielectric based photonic crystal will have a typical size of $100 \times 100 \times 20$ cm, which will be an important limiting

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factor for many applications. These problems can be solved by introducing metals to photonic crystals [12–21].

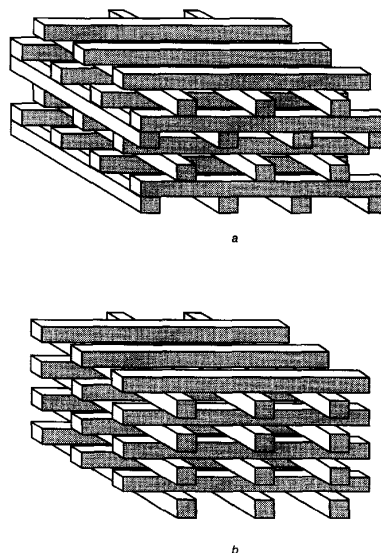


Fig. 1 Schematic diagrams of fct and st based photonic crystals
a fct; b st based crystals

2 Crystal structure

In this paper, we have investigated the properties of two types of layer-by-layer metallic photonic crystals. The first structure, in which the stacking sequence repeats every four layers, is the equivalent of a face centred tetragonal (fct) lattice as shown in Fig. 1a. Fig. 1b shows the other structure similar to the first, but with a repeating sequence of two layers, which is the analogue of a simple tetragonal (st) lattice. The metallic rods used in these crystals were 0.8mm wide, 2.5mm thick and 120mm long, and were placed with a centre to centre separation of 7.6mm. The rods were obtained by machining $150 \times 150 \times 5$ mm aluminium blocks. These blocks were then stacked together to form either fct or st structures depicted in Fig. 1.

3 Transmission properties of metallic photonic crystals

We first measured the transmission properties of both structures using a Hewlett-Packard 8510C network analyser, and standard-gain microwave antennas. Fig. 2a compares the transmission properties of 6-layer

fect and st based crystal structures where the propagation direction of the EM wave is along the stacking direction. Both crystals yielded bandgaps with upper edges ~ 20 GHz, and no lower edge exists down to 10 GHz. Fig. 2a shows the rejection ratios for two different crystal structures at 12GHz, as the number of layers are increased. The typical rejection factors of 7–8dB per layer are observed at 10GHz, which is significantly superior to dielectric-based photonic crystals having a maximum rejection of 3–4dB per layer at midgap frequencies.

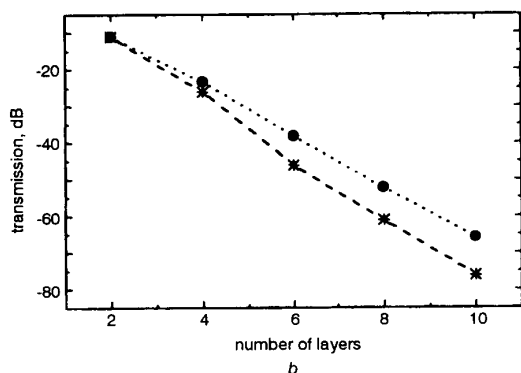
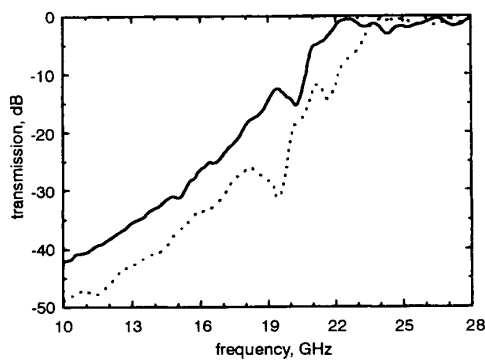


Fig. 2 Transmission characteristics of 6-layer fct and st based metallic photonic crystals, and change in rejection rates of these crystal structures as number of layers is increased
a fct ——— st; b ••• st —*—*— fct

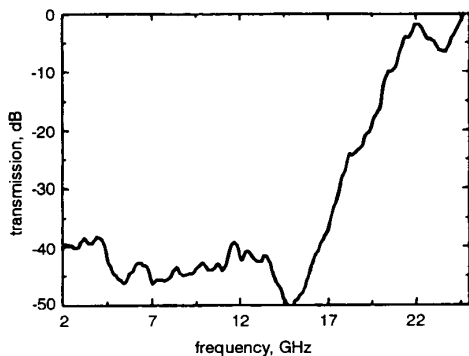


Fig. 3 Transmission measurement performed by monopole antennas show that metallicity gap extends down to lower frequencies

The metals are perfect reflectors at microwave frequencies, and EM waves cannot penetrate into these materials. This property results in the metallicity gap which is expected to extend down to 0GHz [19]. In

order to verify this, we measured the transmission properties of a 10-layer st based metallic crystal using two monopole antennas, instead of standard gain horn antennas. The monopole antennas, which were constructed by removing the shield around one end of a microwave coaxial cable, were used to transmit and receive the EM wave radiation. As seen in Fig. 3, the bandgap still exists even at frequencies as low as 2GHz. Since the monopole antenna radiates in all directions, these measurements also reveal the fact that the metallicity gap conserves its property of reflecting the EM wave in all directions. The relatively low rejection ratio observed, which is still higher than its dielectric equivalent, is mainly due to the following two reasons: first, the finite size of our crystal compared to large wavelengths at which the measurement is made was a limiting factor. Secondly, the radiation efficiencies of the monopole antennas used were relatively poor.

As we mentioned earlier, if dielectric materials were used, the crystal dimensions will be in the metre scale in order to have a bandgap at 2GHz. The dimensions of the metallic crystal we investigated, which is suitable for applications at these frequencies, is about an order of magnitude smaller than its dielectric counterpart. The three orders of magnitude reduction in the structure volume makes the usage of metallic photonic crystals feasible for low frequency applications.

4 Defect structures in metallic photonic crystals

It was previously shown in dielectric based layer-by-layer photonic crystals that defect structures around this geometry can be built by means of adding or

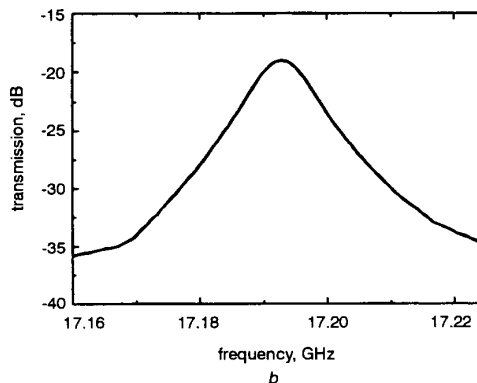
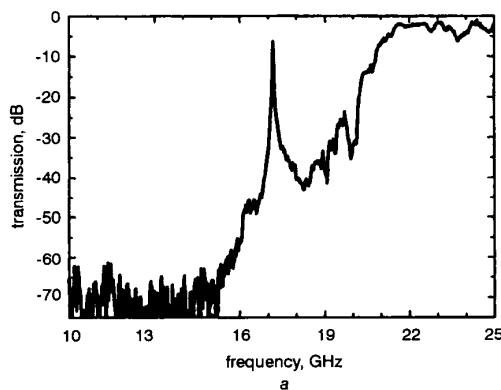


Fig. 4 Transmission characteristics of 14-layer st based crystal with a single rod removed defect structure, and expanded frequency scale of a similar defect structure built around 18-layer crystal

removing rods from an otherwise perfect crystal [11]. The same idea was used to investigate the defect characteristics of these metallic photonic crystals [12]. Fig. 4a shows the transmission properties of 14-layer st type photonic crystals where the 7th layer is the defect layer with a single missing rod. The defect mode was only observed when the electric field polarisation vector of the incident EM wave e was parallel to the rods of the defect layer. The defect mode was observed at 17.2GHz with a peak transmission amplitude of -7dB, and a Q factor (quality factor, defined as the centre frequency divided by the peak's full width at half maximum) of 750. Increasing the number of layers to 18 (where the 9th layer was chosen as the defect layer) yielded a defect mode with an increased Q factor of 1740 and a peak transmission of -19dB (Fig. 4b).

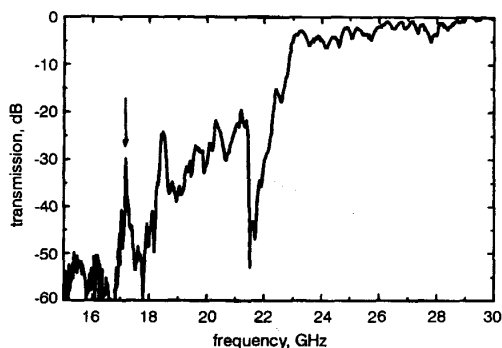


Fig. 5 Defect characteristics of a 14-layer fct based crystal with a single rod removed defect structure

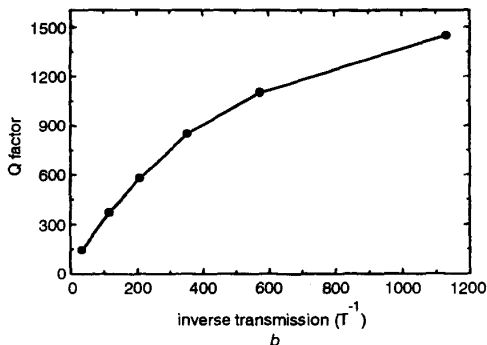
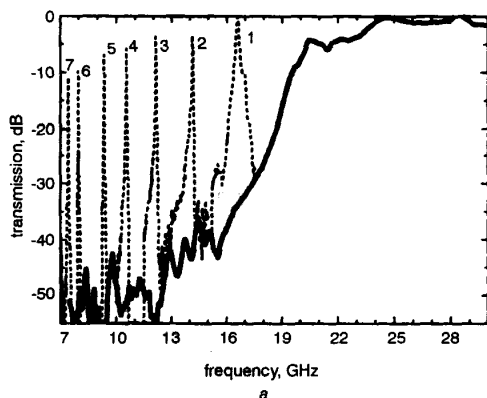


Fig. 6 Transmission characteristics of 8-layer st based photonic crystal with no gap (solid line), and with planar defects with separation widths of (i) 3mm, (ii) 5mm, (iii) 7mm, (iv) 9mm, (v) 11mm, (vi) 14mm and (vii) 15.5mm (dotted lines), and change in Q factor of defect modes as a function of inverse mirror transmission of cavity at defect frequency

A similar defect structure built around fct based photonic crystal gave a higher Q factor of 950, but with a low peak transmission amplitude of -30dB (Fig. 5). This put a limit to achieve a higher Q factor by increasing the number of layers, where the peak transmission dropped below the noise level. In the following investigations, we concentrated on st based metallic photonic crystals, which are superior to fct based photonic crystals considering the advantages of the higher peak amplitude and maximum achievable Q factors.

We then investigated the planar type of defect structures, built around an 8-layer st based photonic crystal. The planar defect was obtained by separating the 4th and 5th layers of the crystal. This resulted in a planar airgap between the two photonic mirrors, each formed of a 4-layer (2-unit cell) crystal. Fig. 6a shows the transmitted EM wave, along the stacking direction, through the planar defect structure with separation widths of 3, 5, 7, 9, 11, 14 and 15.5mm (with corresponding labels 1, 2, 3, 4, 5, 6 and 7, dotted lines), and with no gap (solid line). Although the transmitted peak amplitude drops from 100% transmission at 17GHz to -11.3dB at 7.4GHz, there exists a significant increase in the Q factor from 115 to 1450. Both of these observations can be explained by considering our structure as a Fabry-Perot cavity. The increase in the reflectivities of the mirrors of a Fabry-Perot cavity results in a lower transmitted peak amplitude and a higher Q factor [22]. In order to see this effect, we plotted the Q factors of the defect modes as a function of inverse transmission of the mirrors (4-layer crystal) of the cavity at the corresponding defect frequency (Fig. 6b). The curve is expected to be linear if the mirrors of the cavity were large compared to the resonant wavelength of the cavity [22]. As the resonant wavelength and the cavity width increases, due to the finite size of our crystal mirrors, the curve deviates from linearity and flattens. These results show that this structure can be used to create defect modes with high Q factors at frequencies as low as a few GHz, which is nearly impossible for dielectric based photonic crystals.

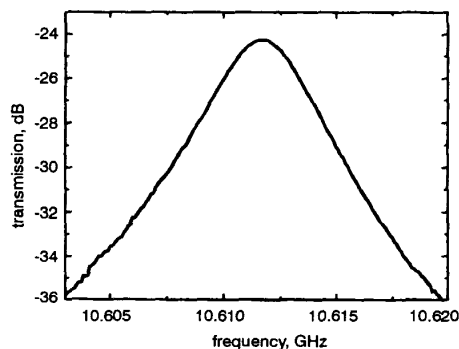


Fig. 7 Transmission characteristics of a planar defect mode with a Q factor of 2250, in an expanded frequency scale

Another way to increase the Q factors of these planar defect structures is to increase the rejection ratio of photonic mirrors of the cavity by increasing the number of layers. As shown in Fig. 7, a 12-layer photonic crystal separated from the middle with a separation width of 10mm resulted in a Q factor of 2250, with a peak transmission amplitude of -25dB at 10.6GHz.

We continued to explore the properties of the planar defects in metallic structures by changing the angle of incidence of the EM wave. Increasing the angle of incidence, peaks other than the main peak at $\theta = 0^\circ$ (where θ is the angle between the surface normal of the crystal and the incident EM wave) came into view. If we continue to increase the angle further, we observe that a number of peaks appearing at higher frequencies dominate, while the peak transmission amplitudes of lower

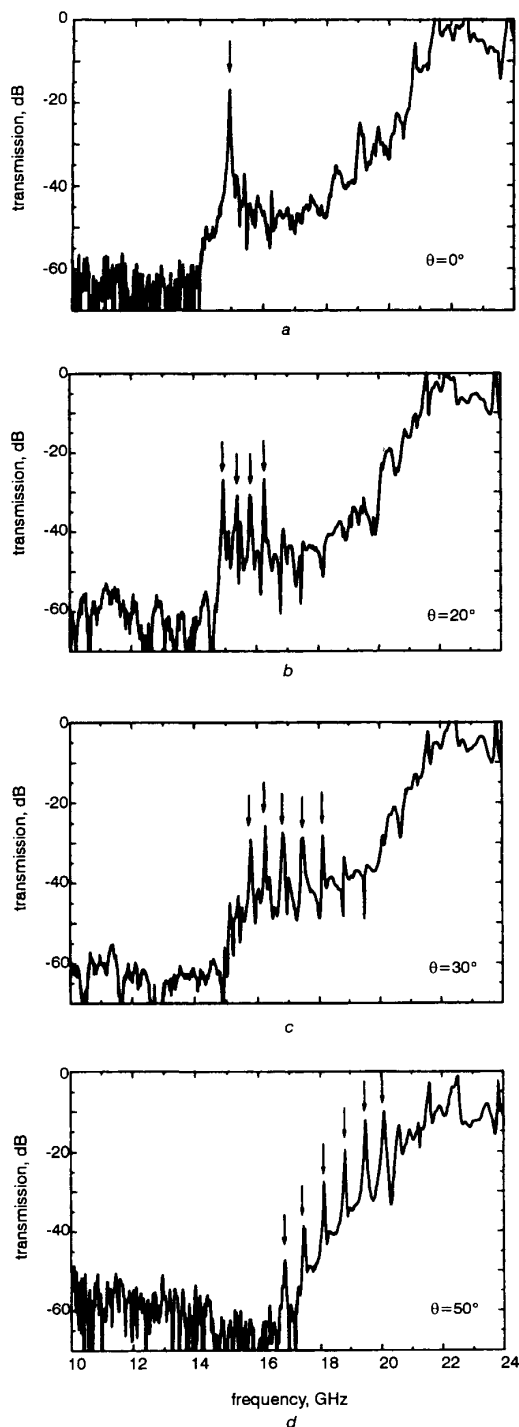


Fig. 8 Additional defect modes observed for planar defect structures with increasing angle of incidence

frequency modes diminish, disappearing at the noise level. The frequencies of the defect modes do not shift with the changing angle of incidence, but dominate at certain fixed frequencies for certain angles. These observations are demonstrated in Fig. 8, where the angle of incidence is changed from 0° to 50° , measured from a 12-layer photonic crystal separated from the middle by a 5mm gap. These defects cannot be explained by a simple Fabry–Perot model [11, 13], since the next resonance is around 7–8GHz away from the observed one, while the consecutive peaks appear with a separation < 1 GHz. An explanation can be made using the theory of resonant cavities, where the reflecting mirrors are considered to be curved. The solution for this structure is a combination of Hermite Polynomials, which results in additional peaks other than the main resonance. This unexpected phenomenon is under further theoretical and experimental investigation.

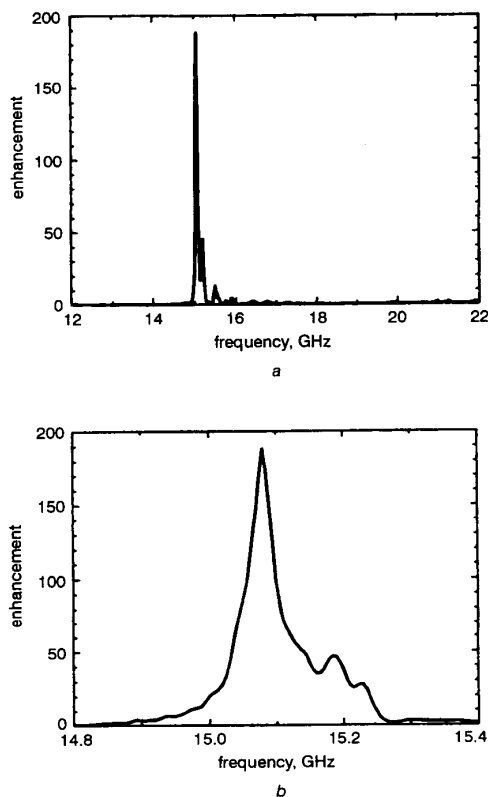


Fig. 9 Enhancement characteristics of a planar defect structure within 8-layer *st* based metallic photonic crystal

5 Resonant cavity enhancement

The electric fields in cavities are usually enhanced, and by placing active devices in such cavities, one can make the device benefit from the wavelength selectivity and the large enhancement of the resonant EM field within the cavity [22]. This effect has already been used to achieve novel devices such as resonant cavity enhanced (RCE) photodetectors and light emitting diodes [23, 24]. In order to demonstrate this effect, we placed a monopole antenna inside the defect volume of planar defect structures described above. We used the network analyser and the standard gain horn to obtain EM waves, and the monopole antenna, which is also connected to the network analyser, as a receiver. The sin-

gle pass absorption data of the probe was used to calibrate the measured enhancements.

Our previous investigations on dielectric photonic crystals show that asymmetric planar cavities result in higher enhancement factors when compared to symmetric ones [25]. Fig. 9 shows the enhancement characteristics of a planar type of defect structure, with a 4-layer thick front mirror and a 6-layer thick back mirror. At a 5mm separation width of the cavity, the defect frequency was observed to be at 15.08GHz. We observed a power enhancement factor of 190 at the defect frequency, with a Q factor of 335. When compared with enhancement factors obtained in cavity structures built around dielectric photonic crystals, this value is rather small. This may be the result of small but finite absorption coefficients of metals, which exist even at microwave frequencies. This absorption becomes significant when we consider the high number of times the field circulates inside the cavity and experiences a loss in each cycle. Still these investigations suggest the possibility of using an embedded detector inside a metallic photonic crystal, as a frequency selective RCE detector with an increased sensitivity and efficiency. As an example, detectors based on photonic crystals will be more efficient than a typical frequency selective LC resonant circuit detector as the EM field does not recycle in such detectors. The RCE detectors based on photonic crystals are also superior to other types of resonant cavity antennas such as patch antennas. The ultra-high EM wave rejection properties of photonic crystals result in better and more controlled confinement of the resonant EM field in all directions. This means photonic crystal based RCE detectors will have higher quality factors and better frequency selective properties when compared to conventional RCE detectors.

6 Towards lower filling ratios

Although the filling ratio of the metallic crystal we have investigated has quite a lower filling ratio (11%) when compared with its dielectric equivalent (30%), considering the high rejection ratio property of metals, it is possible to lower the filling ratio further. Therefore, we constructed and tested a new layer-by-layer structure, with cylindrical metallic rods which are 0.7mm in radius, 150mm long, and with centre to centre separation of 6mm. The rods of the consecutive layers are placed perpendicular to each other, along the stacking direction, and are touching in couples. These touching couples of layers form a square mesh surface, and are separated from each other by 6mm in st and 3mm in fct based crystals. This structure results in a filling ratio of 1.1% in st and 2.2% in fct crystals.

Fig. 10 shows the transmission properties of 7-mesh layer fct (a) and st (b) based photonic crystals. The upper band-edge is at 24GHz in fct based crystal, and shifts to 15GHz in st based crystal. The metallicity gap extends to lower frequencies as expected. The average rejection rate per mesh layer of these crystals is ~ 8 – 10 dB, which is superior to that of the dielectric based photonic crystals.

Defects created by removing rods in this structure resulted in similar defect modes observed in other photonic crystals, but with lower peak transmission amplitudes and lower Q factors. Fig. 11 shows the transmission properties of a 7-mesh layer fct (a) and st (b) based crystals with a defect introduced by removing

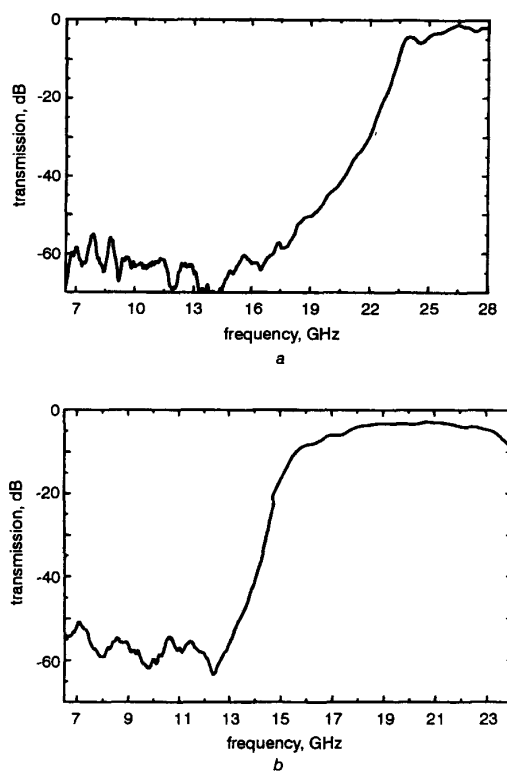


Fig. 10 Transmission properties of low filling ratio fct and st based layer-by-layer metallic photonic crystals
a fct ; b st based crystals

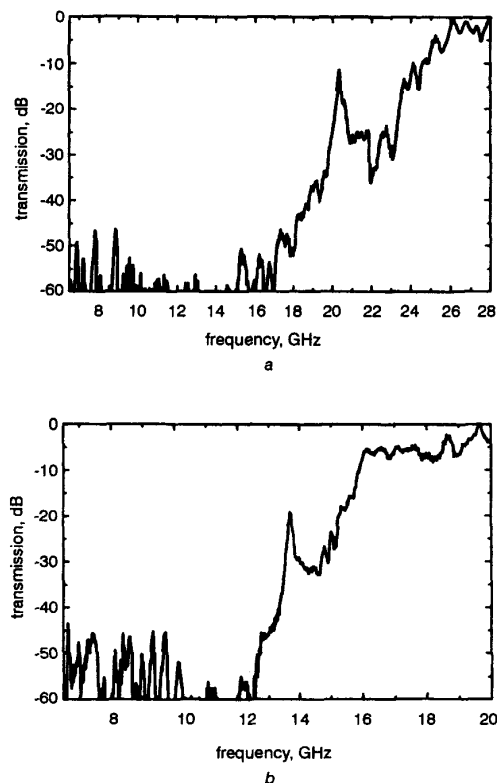


Fig. 11 Characteristics defect structures built around fct and st based low filling ratio photonic crystals
a fct ; b st based crystals

a single rod from the 4th layer. This time, contradictory to the other type of crystal, fct based crystal is superior to st based one considering the higher peak transmission amplitudes (-11.2dB in fct and -18.4dB in st) along with the same Q factors (150 in both). The relatively poor defect characteristics of st based crystals may be assigned to the leakage of the EM waves from the sides of the separation planes of the consecutive touching couples of layers, which is lower (but still significant) in fct based crystals.

These results, although not as good as the previous type of crystal, are of great importance considering applications which require crystals that are light and that have low filling ratios. Also, since metals exhibit high absorption at optical frequencies, these crystals with their minimised metal contents, when compared to the other metallic crystals we investigated, will be quite useful at optical frequencies if built in sufficiently small dimensions.

7 Conclusion

We have investigated the properties of metallic layer-by-layer photonic crystals. An average rejection rate of 8dB per layer was measured. We have observed that the metallicity gap extends down to frequencies as low as 2GHz without any lower band-edge. Defect modes created by removing rods resulted in high peak transmission (80%) and high Q factors (1740). Planar type defect structures exhibited 100% peak transmission amplitudes, and higher Q factors (2250), and existed at low frequency values (~ 7GHz). We also demonstrated the RCE effect in planar cavities built around metallic photonic crystals. A new type of crystal with very low filling ratio is tested and the existence of the metallicity gap and the defect modes were observed. With all these advantages, metallic photonic crystals are suitable for various applications at microwave, millimetre wave and submillimetre wave frequencies. Considering the second type of crystal (with low filling ratio), these applications may also be extended to optical frequencies.

8 Acknowledgments

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