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Cotton-yarn/TiO_2 dispersed resin photonic crystals with straight and wavy structures

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Abstract. The feasibility of three-dimensional (3-D) photonic crystals made using textile technology was investigated. Three different textures consisting of the cotton-yarn and TiO_2 dispersed resin; a crossed linear-yarn laminated fabric, a multi layered woven fabric, and a 3-D woven fabric, were fabricated. The microwave attenuation of the transmission amplitude through these photonic crystals was measured. The straight cotton-yarn as well as the wavy cotton-yarn/TiO_2 dispersed resin photonic crystals exhibited band gaps in the 6 to 15 GHz range. Thus, we could fabricate successfully 3-D photonic crystals using textile technology.

PACS. 42.70.Qs Photonic bandgap materials – 84.40.-x Radiowave and microwave (including millimeter wave) technology

1 Introduction

A photonic crystal is a new type of optical material in which a refractive index or dielectric constant is periodically changed [1–5]. A photonic band gap is formed in this artificial crystal analogous to the band gap in semiconductors. It is shown that the propagation of electromagnetic waves is prohibited for all wave vectors in the photonic band gap and an allowed level is formed in the band gap when the periodicity of the crystal is disturbed.

The photonic crystal has potential applications such as new wave guides, filters, high-efficiency single-mode light-emitting diodes and so on. There have been several studies in the literature, which deal with the fabrication methods of photonic crystals. Yablonovitch fabricated a three-dimensional (3-D) photonic crystal with a complete photonic band gap [1,4]. A slab of material is covered by a mask, which consists of a triangular array of holes. Each hole is drilled through three times at an angle 35.26° away from normal and a spread of 120° in the azimuth. The resulting crisscross of holes below the surface of the slab produces a fully 3-D periodic fcc structure. The drilling can be done by a real drill bit for microwave work or by reactive ion etching to create an fcc structure at optical wavelengths. A layer by layer formation method to obtain a woodpile structure was proposed by Ho et al. [6]. Noda et al. [7,8] have proposed a fabrication method for 3-D photonic crystals by stacking a striped structure with a wafer fusion technique. Spectral properties of opal-based photonic crystals having a SiO_2 matrix were studied by Reynolds et al. [9]. Kirihara et al. [10,11] have developed 3-D photonic crystals composed of millimeter order epoxy lattices including TiO_2 particles by a stereolithographic rapid prototyping method. However, most of these processing methods are based on new technologies and fabrication facilities are expensive. In addition, it is difficult to obtain relatively large three-dimensional (3-D) photonic crystals.

While, it is easy to fabricate 3-D periodic structures using textile technology. Straight cotton-yarn/TiO_2 dispersed resin photonic crystals with different periods, yarn diameter and dielectric constant were fabricated, and the microwave attenuations of the transmission amplitude through these photonic crystals was measured. The electromagnetic band profiles were calculated along the symmetry lines in the Brillioiun zone by using the plane wave expansion method. In addition, wavy cotton-yarn/TiO_2 dispersed resin photonic crystals were also fabricated. Based on the experimental results, the advantage of woven photonic crystals made using textile technology will be discussed.

2 Experimental procedure

100% purity cotton-yarn with 1 mm and 2 mm diameters, which has low dielectric constant near 1, were used

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Table 1. Structure parameters and dielectric constants of the matrix for different textured photonic crystal samples.

	Cotton-yarn diameter	Period	Dielectric constant of matrix
Sample A	2 mm	8 mm	10
Sample B	2 mm	8 mm	7
Sample C	1 mm	8 mm	10
Sample D	1 mm	4 mm	10

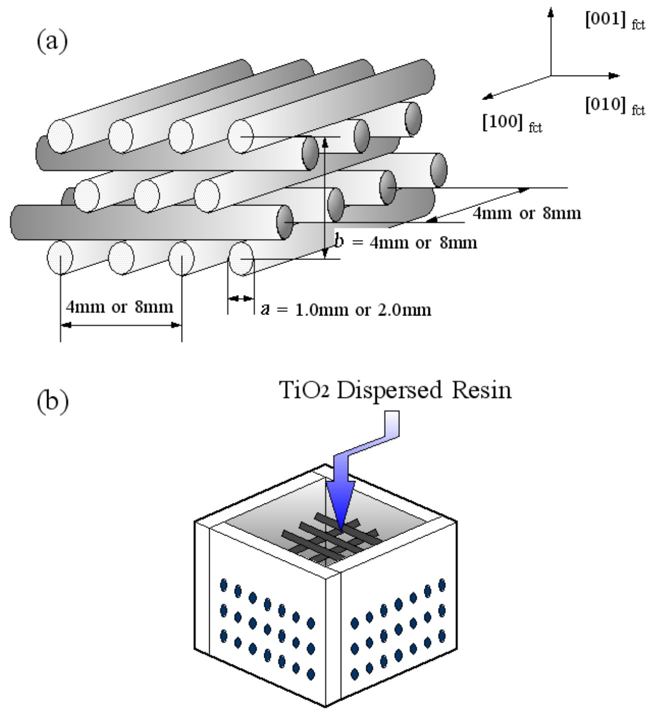

Fig. 1. Schematic illustrations of the crossed linear-yarn laminated fabric (a) and the molding jig (b).

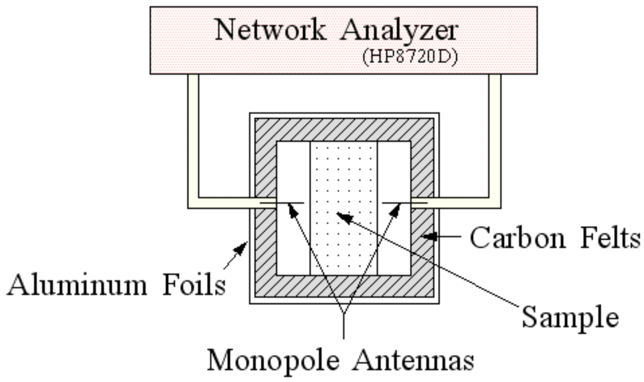

Fig. 2. An experimental configuration to measure the transmission attenuation in the millimeter-wave range through a photonic crystal.

to weave a 3-D periodic structure. The yarn structure is a crossed linear-yarn laminated fabric as shown in Figure 1a. The lattice symmetry of the crossed linear-yarn laminated fabric is face centered tetragonal (fct). This structure resembles the so-called woodpile structure [10,12] which is a popular structure for 3-D photonic crystals. The standard lattice period of the woven structures was 8mm, however, a 4 mm lattice period structure was also made. The dimensions of these structures are shown in Figure 1a.

The TiO_2 particles, which have a high dielectric constant, were dispersed into a polyester resin and provided the matrix material. The particle size is about 10 μm. The resin with TiO_2 particles was impregnated into the array of the cotton-yarn (Fig. 1b).

The attenuation of the transmission amplitude through a photonic crystal was measured along the [001] direction of the structure using a network analyzer (HP-8720D). Figure 2 shows the experimental set up. Monopole antennas for emission and reception were attached to a sample. The dielectric constant of the bulk samples of TiO_2 particles dispersed in the resin matrix was also measured using a dielectric probe kit (HP-85070B).

3 Results and discussion

The diameters of the cotton-yarn, lattice periods, and dielectric constants of the matrix for four different samples prepared are listed in Table 1. The optical length of the photonic band gap; L, along Γ-Z [001] directions, is roughly estimated by the following equation,

$$L/2 = a\sqrt{\varepsilon}_c + b\sqrt{\varepsilon}_m. \tag{1}$$

where a and b are the diameter of the cotton-yarn and the width of matrix in one period along the microwave direction [001], respectively. ε_c and ε_m are the dielectric constants of the cotton yarn and the TiO_2 dispersed resin matrix, respectively. The dielectric constant of the TiO_2 dispersed resin matrix can be estimated by applying a simple rule of mixtures as follows

$$\varepsilon_m = \varepsilon_t f + \varepsilon_r(1 - f) \tag{2}$$

where f is the volume fraction of TiO_2. ε_t and ε_r are the dielectric constants of TiO_2 and the polyester resin, respectively. In the cases of samples A, C, and D with the same dielectric constant of the matrix of 10, the volume fraction of TiO_2 can be estimated to be $f = 8.2$ vol.% from equation (2). While, it is calculated to be 5.1 vol% for sample B which has a different matrix composition with a dielectric constant of 7.

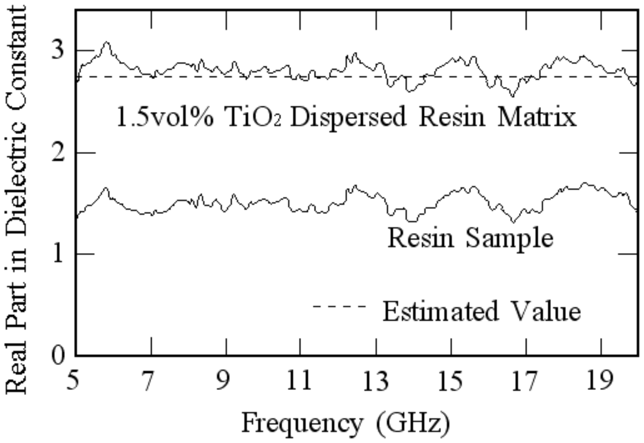

Fig. 3. The measured and estimated values of the dielectric constant for 1.5 vol% TiO_2 dispersed resin matrix.

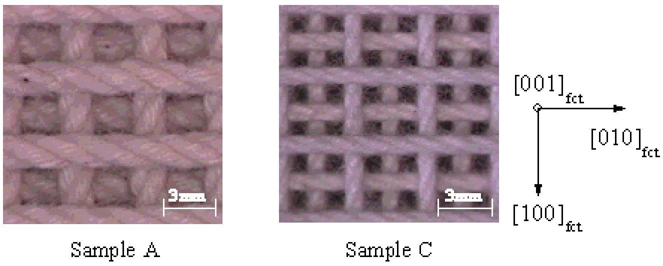

Fig. 4. Photographs of the cotton-yarn/TiO_2 dispersed resin photonic crystal with a crossed linear-yarn laminated fabric structure.

Figure 3 shows the experimental and estimated values of the dielectric constant for a bulk sample of 1.5 vol% TiO_2 dispersed resin matrix as a function of microwave frequency. The dielectric constant of the resin is also shown in this figure. It is seen that the dielectric constants do not change and almost no absorption was observed in the measured frequency range. The estimated dielectric constant agreed with the measured one.

Photographs of the cotton-yarn structure consisting of the crossed linear-yarn laminated fabric are shown in Figure 4. These photographs were taken along the [001] direction of the yarn structure. Millimeter order lattice structures could be formed by impregnating the resin and including TiO_2 particles into the cotton-yarn structure.

The attenuations of the transmission amplitude though samples A and B along the [001] direction and the bulk sample are shown in Figure 5. The solid and dashed lines show the attenuations of the photonic crystals and the bulk sample, respectively. Almost no attenuation was observed for the bulk sample.

Samples A and B exhibited band gaps at 9.0 GHz and 9.4 GHz, respectively. The maximum attenuation in the band gap was about 20 dB. In the case of sample A, the lower edge of the gap starts at 8.2 GHz, while the upper edge is around 9.7 GHz. On the other hand, sample B exhibits a band gap in the 9.0 to 9.7 GHz range. A narrower band gap was formed in sample B, which has a smaller contrast of dielectric constant between the fiber and matrix. It is known that the smaller the dielectric constants contrast, the smaller the band gaps [13], which could explain our experimental result.

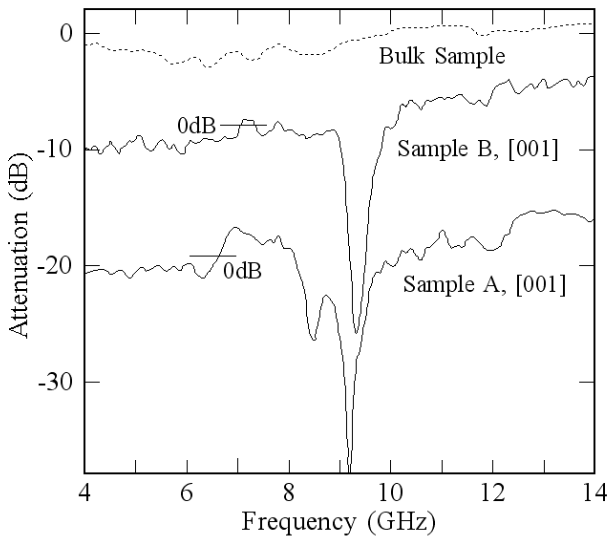

Fig. 5. The attenuations of the transmission amplitude though samples A, B, and the bulk sample. The dielectric constants of matrices for samples A, and B are 10 and 7, respectively. The zero-attenuation line of each sample is shifted for clarity.

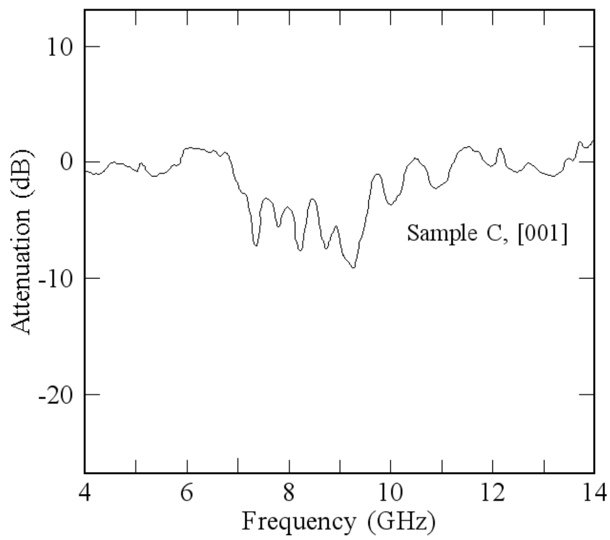

Fig. 6. The attenuations of the transmission amplitude though sample C. The cotton-yarn diameter is 1 mm.

Figure 6 shows the attenuation of transmission amplitude for sample C with the same lattice period and dielectric constant of matrix of sample A, but with the thin cotton-yarn diameter of 1 mm. The band gap was wider, but more shallow and shifted toward lower frequencies when compared to sample A. The oscillations observed in the gap could be caused by an inadequate number of lattice numbers to reflect the microwaves better. We can expect the formation of sharp and deep gaps without oscillations when such a sample with more lattices can be

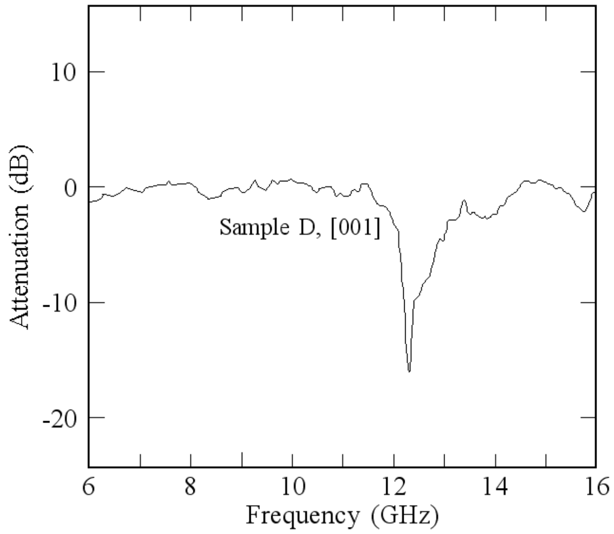

Fig. 7. The attenuations of the transmission amplitude though sample D. The cotton-yarn diameter and the lattice period are 1 mm and 4 mm, respectively.

prepared. In such ideal samples, the lower volume fraction of thin fiber lattices may extend the band gap and shift it towards lower frequencies though it must be confirmed by the band calculation.

Figure 7 shows the attenuation of the transmission amplitude for sample D with a cotton-yarn diameter and period; 1 mm and 4 mm, respectively. As the lattice period decreases, the band gap position was shifted to higher frequency, but the maximum attenuation did not change so much. Thus the desired band gap shows up at a different position due to the change in the period. The band gap position shift could be explained by equation (1). Namely, if the diameter of the cotton-yarn and the period of the structure became half of their actual values, the wavelength of the photonic band gap would also take half the value.

3.1 Electromagnetic band profiles

The cotton-yarn/TiO_2 dispersed resin photonic crystals with a crossed linear-yarn laminated fabric structure exhibit band gaps in the 6 to 15 GHz range. The electromagnetic band profile was calculated along the symmetry lines in the Brillouin zone for the woodpile structure of fct lattice, which resembles the crossed linear-yarn laminated fabric, by using the plane wave expansion method [11] with 1986 plane waves.

Figure 8 shows the calculated band profile of sample A where the dielectric constants for the cotton-yarn and the matrix are adopted to be 1 and 10, respectively. The Brillouin zone of the fct lattice is also shown in this figure. Note that the band gap opens in the [001] direction, and the band gap for the [001] direction ranges from 8.1 to 10.3 GHz. The experimental data in Figure 5, for sample A exhibits a band gap in the 8.2 to 9.7 GHz range, fits well with the band calculation.

3.2 Wavy cotton-yarn/TiO_2 dispersed resin photonic crystals

The observed band gaps in the straight cotton-yarn/TiO_2 dispersed resin photonic crystals showed that a photonic band gap can be formed in the woven structures by textile technology. If the wavy yarn-fiber/TiO_2 dispersed resin can have a photonic band gap, flexible and/or wearable photonic crystals could be realized. We have fabricated two other textures of wavy cotton-yarn/TiO_2 dispersed resin photonic crystals on the basis of their yarn structures, namely, multi layered woven fabric and 3-D woven fabric, as shown in Figure 9. 100% pure cotton-yarn with 1 mm diameter was used, and the dimensions of these structures are shown in this figure.

Figures 10a and b show photographs of the fabricated wavy cotton-yarn/TiO_2 dispersed resin photonic crystals, multi-layered woven fabric, and 3-D woven fabric, respectively. The corresponding attenuation of the transmission amplitude through the wavy photonic crystals is shown in Figure 11. Both of the wavy photonic crystals exhibit band gaps in the range of 7 and 15 GHz, although the observed band gaps are wide and shallow. The wavy cotton-yarn/TiO_2 dispersed resin photonic crystals reflected the microwaves because of the formation of photonic band gaps.

3.3 Advantages of cotton-yarn/TiO_2 dispersed resin photonic crystals

A lot of fabrication methods have been proposed to fabricate 3-D photonic crystals [1–11]. However, these processing methods are based on new technologies and fabrication facilities are expensive. In addition, it is difficult to obtain large 3-D photonic crystals. As an alternative, we propose a new fabrication method, which is an application of textile technology, and demonstrate this for the cotton-yarn/TiO_2 dispersed resin system. Since the fabrication facilities for the proposed method are inexpensive, the textile technology can be applied to the mass-production of large 3-D photonic crystals at low cost. Moreover, since the fabricated 3-D photonic crystal is a kind of composite material reinforced by a fiber shaped material, its mechanical properties should be stronger than those of other photonic crystals. These new photonic crystals could be used as flexible wave-guides and filters.

4 Conclusions

In this study, we have investigated the feasibility of fabricating 3-D photonic crystals by the applying textile technology. Cotton-yarn/TiO_2 dispersed resin photonic crystals, and crossed linear-yarn laminated fabric are fabricated with different cotton-yarn diameters, lattice periods and dielectric constants of the matrix. The attenuations of the transmission amplitude through these photonic crystals are measured. The straight cotton-yarn/TiO_2 dispersed resin photonic crystals with a crossed linear-yarn laminated fabric structure exhibit band gaps in the range of 6 to 15 GHz. A narrower band gap was found for smaller dielectric constants of the fiber and matrix.

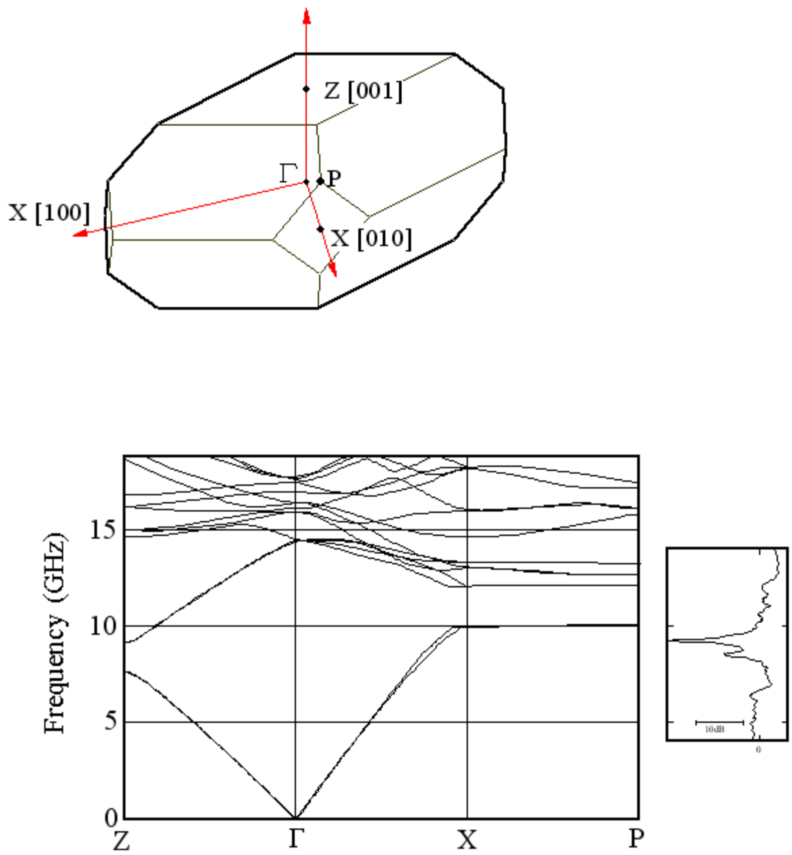

Fig. 8. Calculated electromagnetic band profile of sample A, where the dielectric constants for the cotton-yarn and the matrix are adopted to be 1 and 10, respectively. The Brillouin zone of the fct lattice is also shown in this figure.

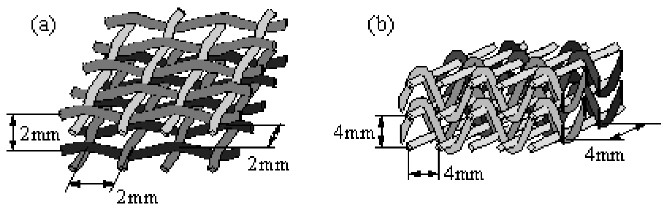

Fig. 9. Schematic illustrations of the wavy cotton-yarn/TiO_2 dispersed resin photonic crystals. (a) multi-layered woven fabric; (b) 3-D woven fabric.

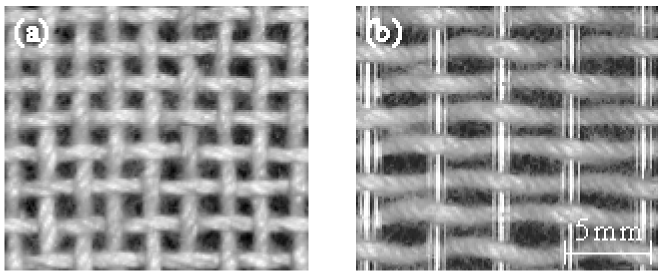

Fig. 10. Photographs of the fabricated wavy cotton-yarn/TiO_2 dispersed resin photonic crystals. (a) multi-layered woven fabric; (b) 3-D woven fabric.

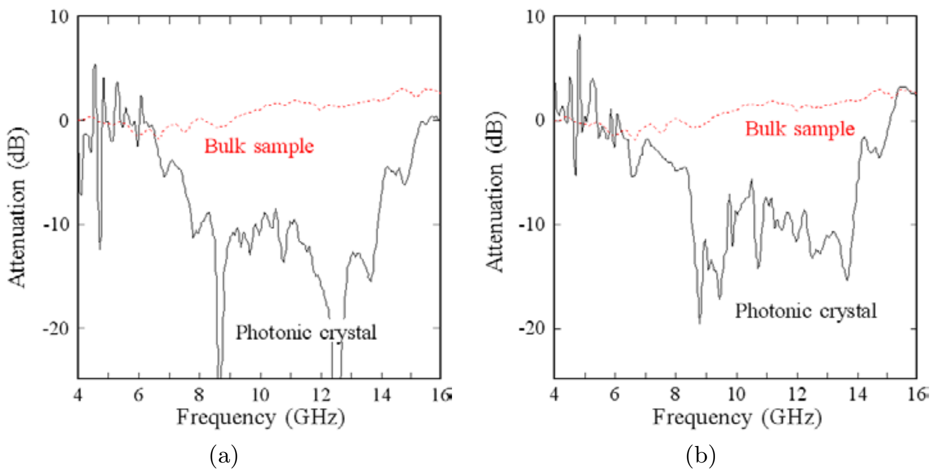

Fig. 11. Attenuation of the transmission amplitude through the wavy photonic crystals. (a) multi-layered woven fabric and (b) 3-D woven fabric.

As the lattice period decreases, the band gap position is shifted to higher frequency. The position of band gap agreed with the band calculation made using the plane wave expansion method. The wavy photonic crystals, multi layered woven fabric, and 3-D woven fabric exhibited a band gap in the range of 7 to 15 GHz. The proposed method can be applied to the mass production of large 3-D photonic crystals at low cost.

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