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Microwave measurements of stub tuners in two-dimensional photonic crystal waveguides

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The transmission spectra of photonic crystal stub-tuned waveguides created in the microwave region are measured. The photonic crystal is a two-dimensional square lattice of dielectric rods. The waveguides are formed by removing rods along a line or by creating a line of coupled cavities. Additional stub-tuning cavities are formed by removing rods or by replacing them with different diameter rods to stub tune the transmission properties of the waveguides. Depending on the cavity geometry, certain wavelengths can be reflected from the stub tuner creating a notch in the waveguide transmission with measured quality factors as high as 488.

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I. INTRODUCTION

Photonic crystals are artificially fabricated structures that have the ability to control and manipulate the propagation of electromagnetic (EM) waves. For high refractive index contrast and specific structures, photonic crystals can prohibit the propagation of light within the photonic band-gap region, or localize light in specified areas around defects.[1,2] Clearly, such materials would be very useful for applications requiring the spatial localization of light. Efficient guiding and bending of EM waves in photonic crystals have been studied both theoretically[3,4] and experimentally.[5–7] Photonic crystal based add-drop filters have been also proposed recently.[8,9]

It is well known in the microwave regime that it is possible to affect the transmission characteristics of a microwave waveguide using stub tuners. A typical microwave guide can consist of a hollow metal pipe with the appropriate dimensions for having confined propagating modes in the frequency range of interest. Addition of a segment, or stub, to the sidewall of the waveguide can dramatically alter the spectrum of transmission properties. It has been shown that resonance modes in the stub can generate spectrally sharp zeros in the transmission properties of the waveguide. Calculations show that for frequencies close to the stub resonance frequencies, the stub modes are excited and subsequently leak energy back to the waveguide to precisely cancel the transmission of the incident waveguide mode, generating total reflection of the incident wave. More recently, Noda, Chutinan, and Imada[10] have studied waveguide structures in a two-dimensional slab photonic crystal. In this study,[10] photons propagating along the photonic crystal waveguide are trapped by neighboring defects and then emitted perpendicular to the plane of the slab into free space.

This paper presents the results of an experimental study of stub-tuned waveguides in two-dimensional photonic crystals in the microwave region. The two-dimensional (2D) photonic crystals in this study consist of alumina rods forming a square lattice. The rods are supported on both sides by an aluminum plate sandwiched by absorbing foam. Waveguides are created by removing alumina rods [Figs. 1(a) and 1(b)]. The 3.18-mm diameter alumina rods, making up the square lattice having a lattice constant of 8.833 mm, have a refractive index of 3.1 and are surrounded by air. The rods are long enough (12 cm) to be considered infinitely long to a reasonable approximation, if the propagation direction is perpendicular to the rods. The transmission through the device is measured using an HP 8509 A network analyzer and two microwave horn antennas centered between the supporting structures.

Although the applications of these systems are expected in the optical communications area, the microwave equivalents of these systems are much easier to fabricate and test. Besides the simple scaling of wavelengths, an additional difference between our microwave model and the eventual optical system is the length of the rods comprising the photonic crystal. For optical devices, it would clearly be problematic to fabricate dielectric rods many wavelengths long with the required submicron diameters. Instead, the rods' lengths will most likely be on the order of a wavelength, necessitating their treatment in a fully three-dimensional fashion to obtain quantitative predictive results.[10–13] However the physics principles operative in our approximately two-dimensional microwave systems will also be operative in the future optical systems. As a result, it is expected that the device functionality demonstrated here will be at least qualitatively relevant to the optical domain.

II. STUB TUNERS IN PHOTONIC CRYSTAL WAVEGUIDES

For the *E*-polarized waves (*E* field parallel to the axis of the rods), a full band gap exists for waves propagating in a plane perpendicular to the axis of the rods. The measured band gap along the (1,0) direction (solid line in Fig. 2) is from 9.5 to 15.6 GHz. The calculated band gap given by the transfer-matrix method[14] is from 9.3 to 15.8 GHz, which is in good agreement with the measured values.[15] By removing one row of rods along the (1,0) direction [Fig. 1(a)], a waveguide band appears from 10.9 to 15.6 GHz (dotted line in Fig. 2). Finite difference time domain (FDTD) calculations[16] show a waveguide band from 11.2 to 15.8 GHz in good agreement with measurements.

The first stub tuner is created by removing one rod [see Fig. 1(c)] or replacing it with a different diameter rod. The cavity is at the eighth column and it is three unit cells away from the waveguide [see Fig. 1(c)]. The transmission for this stub tuner is shown in Fig. 3. A notch in the transmission appears at 11.8, 12.49, and 13.65 GHz with quality factors (*Q*) of 225, 363, and 488 for defect diameters of 2.03, 1.52,

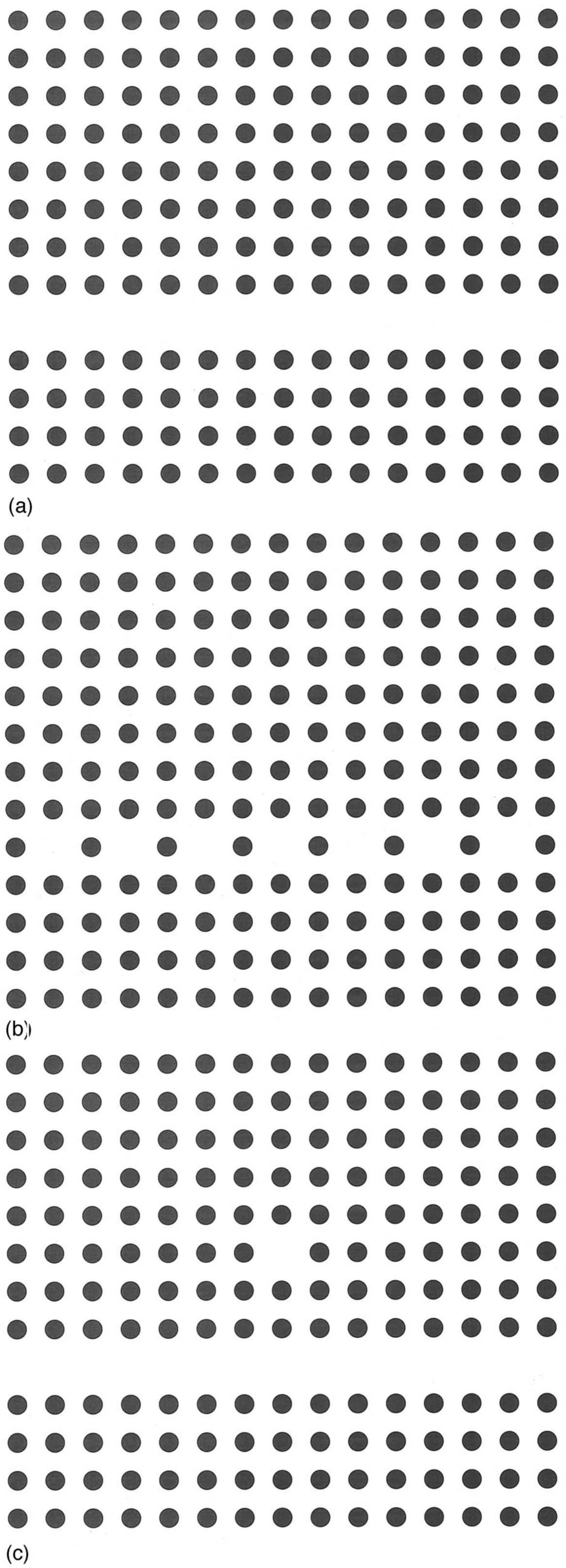

FIG. 1. The diagram of three configurations studied here: (a) the waveguide where one row of rods has been removed; (b) the coupled cavities waveguide; (c) the waveguide with a stub tuner formed by removing one rod at the eighth column (the column number is referenced to the left side of the figure) and three unit cells away from the waveguide.

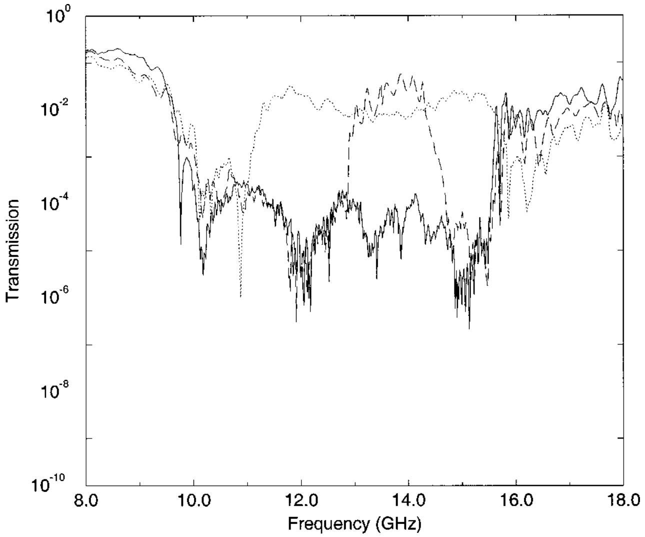

FIG. 2. Solid, dotted, and dashed lines are the transmission profiles for the periodic lattice, simple waveguide [Fig. 1(a)], and coupled cavities waveguide [Fig. 1(b)], respectively.

and 0 mm, respectively (solid, dotted, and dashed lines in Fig. 3). So, as the diameter of the defect rod decreases, the notch in the transmission emerges from the lower edge of the waveguide band and moves close to the center of the band when the rod is completely removed. The case where the rod is replaced with a larger diameter rod (of 4.78 mm) does not show any notch due to the weak coupling between the cavity and the waveguide (dot-dashed line in Fig. 3). The differences between the measured and FDTD results (Table I) are within 1.4%. This is in good agreement considering the limitations of the FDTD method.[16] The calculated Q factors are 695, 280, and 170 for defect diameters of 2.03, 1.52, and 0

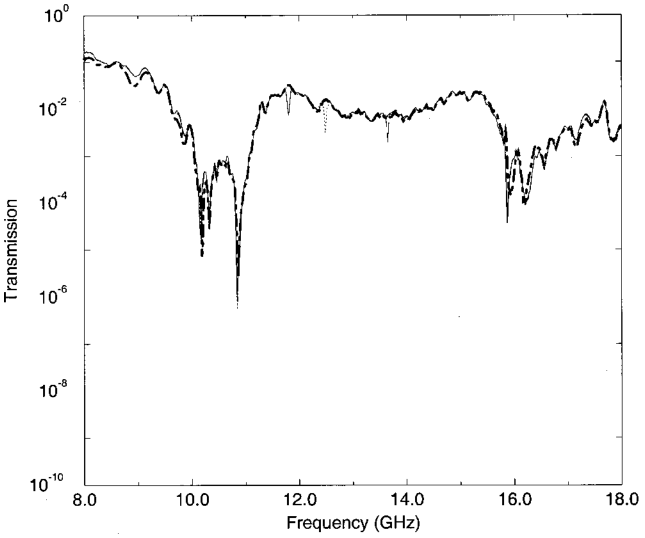

FIG. 3. The transmission for the stub tuner with a cavity at the eighth column and three unit cells away from the waveguide. The cavity is formed by replacing the unperturbed rod by rods of diameters 2.03, 1.52, 0, and 4.78 mm (solid, dotted, dashed, dot-dashed lines, respectively).

TABLE I. Comparison of the theoretical and experimental resonant frequencies in gigahertz for the case studied in Fig. 3.

Diameter of rod (mm)	Theory	Experiment
2.03	11.97	11.8
1.52	12.30	12.49
0	13.65	13.65

mm, respectively, and show some deviation from the measured values. The differences in the *Q* values are most likely due to the finite length of the measured rods compared with the infinitely long rods in the FDTD calculations.

Figure 4 shows the transmission for a stub tuner where the cavity is at the seventh column rather than the eighth column [the column number is referenced to the left side in Fig. 1(c)]. In this case the notch in the transmission appears at 11.78, 12.45, and 13.63 GHz with *Q*'s of 168, 311, and 378 for defect diameters of 2.03, 1.52, and 0 mm, respectively. Again, there is no notch when the defect rod has the larger diameter of 4.78 mm. For an infinitely long waveguide, there should not be any difference between the results of Figs. 3 and 4. However, due to the finite thickness of the waveguide and the subsequent reflections from the ends of the waveguide, the results are slightly different. These differences are even more pronounced for cavities located closer to the end of the photonic crystal.

In another configuration three types of cavities are placed together on a single waveguide (Fig. 5). The 1.52-, 2.03-, and 0-mm diameter rods are placed at the fifth, eighth, and 11th columns, respectively, all of them three unit cells away from the waveguide. Three notches appear at 11.76, 12.44, and 13.69 GHz. These differences are within 0.4% of the results in Figs. 3 and 4. It is not clear if these differences are due to the interference between the cavities or due to placing the cavities in different columns as was explained in the previous paragraph.

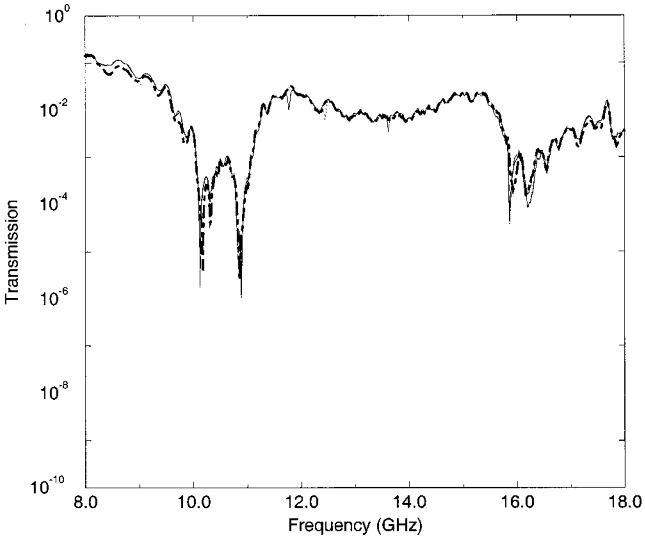

FIG. 4. The same as in Fig. 3 with the cavity at the seventh column.

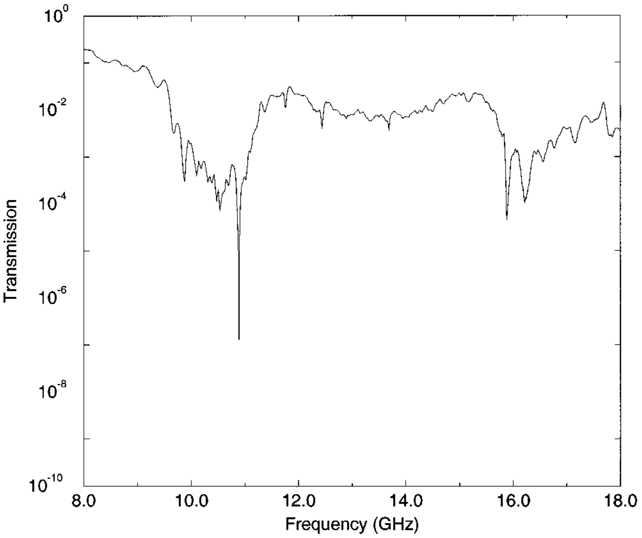

FIG. 5. The transmission for a case having three different cavities together. All the cavities are three unit cells away from the waveguide. Rods of diameters 1.52, 2.03, and 0 mm are at the fifth, eighth, and 11th columns, respectively.

For individual cavities two unit cells away from the waveguide (Fig. 6), the notches become more prominent due to the higher level of coupling between the cavities and the waveguide. The notches appear at 11.77, 12.48, 13.63, and 14.43 GHz for rod diameters 2.03, 1.52, 0, and 4.78 mm, respectively. Even the defect with a diameter of 4.78 mm shows a notch in contrast with the cases shown in Figs. 3 and 4. The frequency of the notch for the 4.78-mm diameter case is closer to the upper edge of the waveguide band indicating that by increasing the diameter of the rods the notch emerges from the upper end of the waveguide band. Bringing the cavities even closer to the waveguide (just one unit cell away; see Fig. 7), the notches become wider due to the higher level of coupling between the cavities and the waveguide.

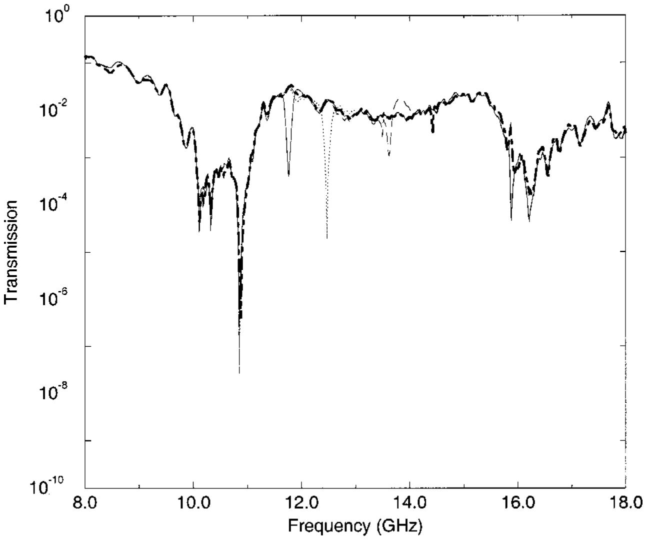

FIG. 6. The same as in Fig. 3 with the cavities two unit cells away from the waveguide.

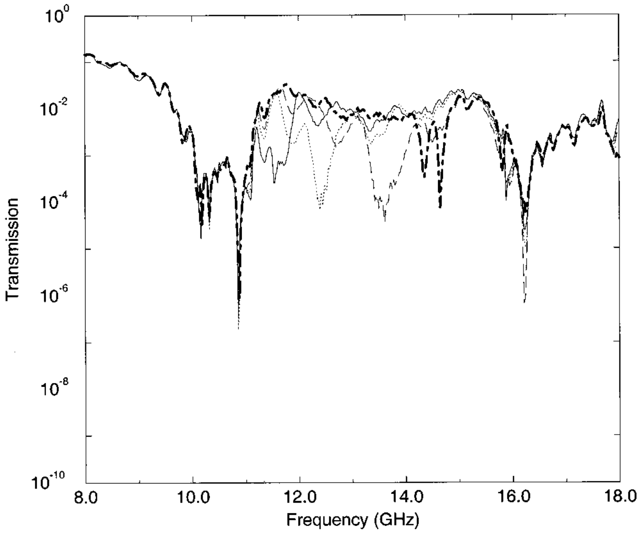

FIG. 7. The same as in Fig. 3 with the cavities one unit cell away from the waveguide.

III. STUB TUNERS IN COUPLED RESONANT-CAVITY WAVEGUIDES

Another way of guiding radiation is through a line of coupled resonators.[17] Figure 1(b) shows a 2D photonic crystal with cavities formed by removing rods along a row. The cavities are two unit cells away from each other. The transmission along this type of guide shows a guiding band between 12.9 and 14.7 GHz (see dashed line in Fig. 2). The width of the waveguide band is narrower compared with the case studied in the previous section. This is due to the weak coupling of the waves between neighboring cavities.

A stub tuner is formed by removing a rod from the seventh column [the column number is referenced to the left side in Fig. 1(b)]. A notch in the transmission appears at 13.62 and 13.64 GHz with Q's of 454 and 487 for a removed rod one and two unit cells away from the waveguide, respectively (see Fig. 8). It is interesting to note that none of the other diameters of defect rod show any significant effect. For cavities at the eighth column and just one unit cell away from the waveguide, the waveguide band is completely distorted. In this case the fourth cavity along the waveguide [see Fig. 1(b)] couples strongly to the stub, creating a reflection of the waves from this cavity for almost all frequencies within the waveguide band. For cavities at the eighth column and two unit cells away from the waveguide, there is no significant effect in the transmission, indicating that the waves are well localized within the cavities along the waveguide.

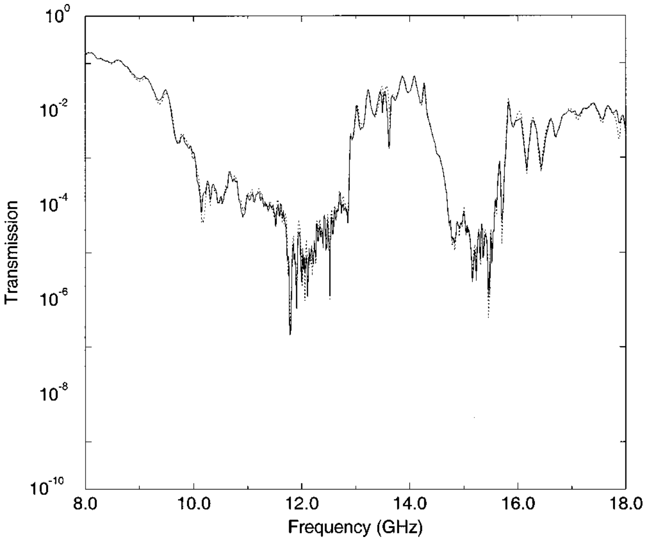

FIG. 8. The transmission for the coupled cavities waveguide and a cavity at the seventh column one and two unit cells away from the waveguide (solid and dotted lines, respectively).

IV. CONCLUSIONS

To summarize, stub tuners in two-dimensional photonic crystals in the microwave region have been studied experimentally. The EM waves of certain frequencies can efficiently be reflected from the stub. By changing the resonance cavity, the operating frequency of the device changes. The notches in the transmission are sharp with Q factors as high as 488. For stub tuners one unit cell away from the center of the waveguide, the notches are wider and the transmission could drop as high as two orders of magnitude. For stub tuners three unit cells away from the waveguide, the notches are much narrower (higher Q's) but the transmission drops less than one order of magnitude as a result of the weak coupling between the stub and the waveguide.

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