Resonant cavity enhanced detectors embedded in photonic crystals

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We report a resonant cavity enhanced (RCE) detector built around a three-dimensional photonic band gap crystal. The RCE detector was built by placing a monopole antenna within the localized modes of planar and boxlike defect structures. The enhanced electric field around these defect structures were then measured by a microwave detector and a network analyzer. We measured a power enhancement factor of 3450 for planar cavity structures. A Fabry–Perot cavity model was used to understand and predict resonant cavity enhancement in this structure. The tuning bandwidth of the RCE detector extends from 10.5 to 12.8 GHz, which corresponds to the full photonic band gap by the crystal. These RCE detectors have increased sensitivity and efficiency when compared to conventional detectors, and can be used for various applications. © *1998 American Institute of Physics.* [S0003-6951(98)02219-0]

There is a great deal of current interest for the possibility of creating three-dimensional photonic crystals in which no electromagnetic (EM) wave propagation is possible for certain frequencies.[1–4] These crystals, built at various dimensions with different techniques,[5,6] offer a wide range of applications in a spectrum ranging from microwave, to optical frequencies.[7–10] Recently, Ho *et al.* have proposed and demonstrated a three-dimensional photonic crystal based on stacked dielectric rods, which can be fabricated at smaller scales by conventional methods.[11–13] Defects or cavities around the same geometry can also be built by means of adding or removing rods from the so called layer-by-layer photonic crystals.[14] The electrical fields in such cavities are usually enhanced,[15] 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. This effect has already been used in optoelectronics to achieve novel devices such as resonant cavity enhanced (RCE) photodetectors and light emitting diodes.[15] In this letter, we demonstrate the RCE effect by placing microwave detectors within the localized modes of photonic crystal defect structures.

In our experiments, we used a layer-by-layer dielectric photonic crystal designed to have three-dimensional band gap with a midgap frequency around 12 GHz. The layer-by-layer structure was constructed by using square-shaped alumina rods ($0.32\,\mathrm{cm}\times0.32\,\mathrm{cm}\times15.25\,\mathrm{cm}$). The photonic crystal has a center to center separation of 1.12 cm, corresponding to a dielectric filling ratio of $\sim$0.29. We used the output port of a microwave network analyzer and a standard gain horn to obtain EM waves. Defect structures built around the crystal were tested by putting them in the beam path of the EM waves propagating along the stacking direction. A square law microwave detector was placed inside the defect volume of the photonic crystal, along with a monopole antenna. The monopole antenna was kept parallel to the polarization vector e of the incident EM wave in all measurements. The dc voltage on the microwave detector was used to measure the power of the EM field within the cavity. We also measured the enhanced field by feeding the output of the monopole antenna into the input port of the network analyzer. The monopole antenna was constructed by removing the shield around one end of a microwave coaxial cable. The exposed center conductor which also acted as the receiver, was 2 mm long. The calibrated enhancement measurements were performed in the following manner. We first measured the enhanced EM field by the probe inside the cavity. While keeping the position of the probe fixed, we removed the crystal and repeated the same measurement. This single pass absorption data of the probe was then used for calibration of the first measurement.

We first investigated a planar defect structure which was built around a 16 layer photonic crystal. The planar defect was obtained by separating the eighth and ninth layers of the structure.[16] This resulted in a planar air gap between two photonic mirrors, each formed of an eight-layer crystal. Figure 1(a) shows the enhancement characteristics of a planar defect structure with a separation width of 8.5 mm. The measurement was done by the network analyzer and the frequency was chosen to cover the photonic band gap of our crystal. We observed a power enhancement factor of 1600 at a defect frequency of 11.68 GHz. The Q factor (quality factor), defined as the center frequency divided by the full width at half maximum, was measured to be 900. We then measured the enhancement characteristics of the same defect structure [Fig. 1(b)], with a microwave detector, inserted inside the same cavity. An enhancement factor of 450 along with a Q factor of 1100, were observed at the same defect frequency.

The discrepancy between two measured enhancement factors can be explained by modeling our structure as a Fabry–Perot cavity[15] [Fig. 2(a)]. The probe we used in our experiments was simulated by an absorption region of thickness d, with a relative absorption coefficient α. The electric

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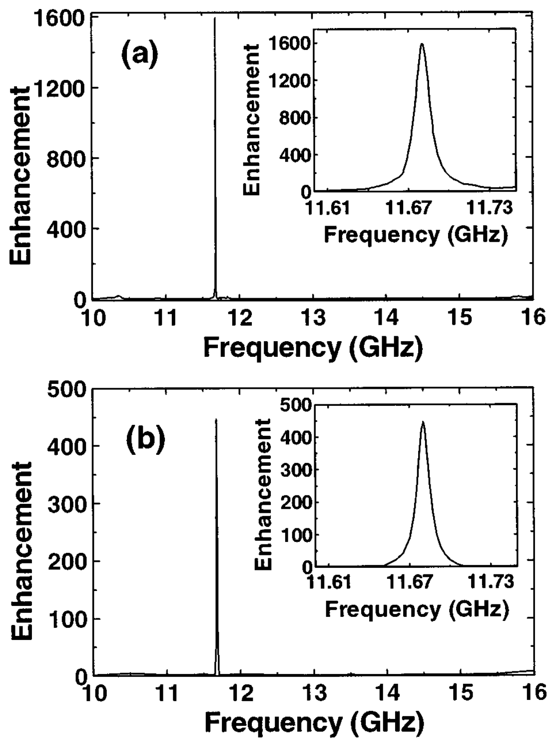

FIG. 1. Experimental enhancement factors obtained for a planar defect structure: (a) using the network analyzer; (b) using the microwave detector.

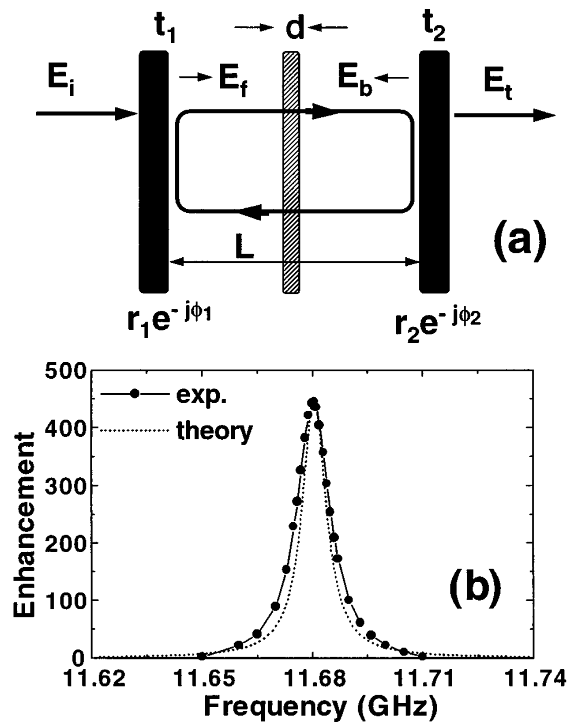

FIG. 2. (a) Schematics of the Fabry–Perot cavity model. The shaded absorption region was used to simulate the detector placed in the cavity. (b) Comparison of the experimental (solid line) and theoretical (dotted line) enhancement factors obtained for the RCE detector in the planar defect structure.

field component for the forward traveling wave E_f inside the cavity can be related to the incident field E_i as

$$E_f=\frac{t_1}{1-r_1r_2e^{-\alpha d}e^{-j(2\beta L+\phi_1+\phi_2)}}\,E_i\,, \tag{1}$$

where $r_1e^{-j\phi_1}$ and $r_2e^{-j\phi_2}$ are the reflection coefficients of the mirrors, t_1 is the transmission coefficient of the front mirror, β is the propagation constant for the traveling EM wave in air, and L is the separation width of the cavity. The backward traveling wave E_b is related to E_f as

$$E_b=r_2e^{-\alpha d}e^{-j(\beta L+\phi_2)}E_f. \tag{2}$$

Using Eqs. (1) and (2), we can calculate the power enhancement factor η, which is defined as the ratio of the stored power inside the absorption layer, to the power of the incident EM wave,

$$\eta=\frac{(1+R_2e^{-\alpha d})(1-R_1)}{1-2\sqrt{R_1R_2}e^{-\alpha d}\cos(2\beta L+\phi_1+\phi_2)+R_1R_2e^{-2\alpha d}}, \tag{3}$$

where $R_1=r_1^2$ and $R_2=r_2^2$, are the reflectivities of the mirrors of the cavity. The above result is normalized with respect to the incident field absorbed by the detector in the absence of the crystal. The aforementioned planar defect structure have symmetric mirrors where $R=R_1=R_2$. We used the measured transmission characteristics to obtain the reflectivities of our photonic mirrors. As the rods are made of high quality alumina with a very low absorption coefficient, the absorption in the crystal can be neglected.[16] At the defect frequency, the transmission of an eight-layer crystal was 30 dB below the incident EM wave. The reflectivity of the photonic mirrors was then obtained as $R=1-T=0.999$. The ideal case which maximizes η corresponds to $\alpha d=0$, which gives a maximum enhancement factor of 2000. We then varied αd to obtain enhancement factors closer to our experimental measurements. For $\alpha d=0.0001$, Eq. (3) yields an enhancement factor of 1600 (which corresponds to the value obtained from the network analyzer), while $\alpha d=0.0011$ results in an enhancement factor of 450 (microwave detector). The increased absorption factor for the detector measurement can be explained by the relatively large volume size of the microwave detector compared to monopole antenna alone. Figure 2(b) compares the measured (solid line) and simulated (dotted line) enhancements obtained for the RCE microwave detector within the planar defect structure. The theoretical Q factor (1500) is comparable with the experimental Q factor (1100).

The Fabry–Perot model suggests that η is maximized for the matching case $R_1=R_2e^{-2\alpha d}$ (Ref. 15). To increase the enhancement, we increased R_2 by adding one more unit cell (four layers) to the mirror at the back. This results in an asymmetric planar cavity with a two unit cell thick front mirror, and a three unit cell thick back mirror. By varying the width of the planar cavity, we measured the enhancement factors at different resonant frequencies. As shown in Fig. 3, the tuning bandwidth of the RCE detector extends from 10.5 to 12.8 GHz. This tuning bandwidth of the RCE detector is in good agreement with the full photonic band gap (10.6–12.7 GHz) of the crystal.[11] As expected, the measured enhancement factors are relatively higher when compared with the symmetrical defect case. The maximum enhancement was measured to be 3450 at a defect frequency of 11.75 GHz. The theory predicted enhancement factors around 5500, which is higher than the measured values. The discrepancy can be explained by the finite size of the photonic crys-

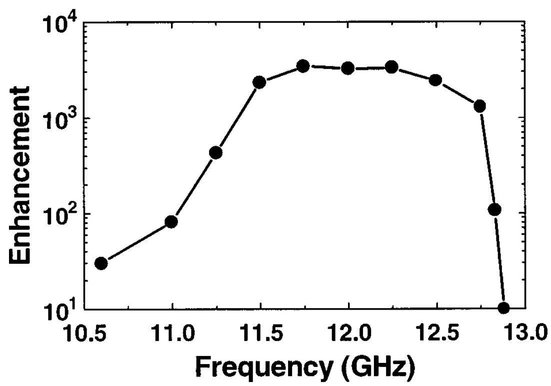

FIG. 3. The power enhancement can be obtained at different resonant frequencies by changing the cavity width. This corresponds to a tuning bandwidth ranging from 10.5 to 12.8 GHz.

tal, which limits the power enhancement of the field within the cavity.

In order to obtain a defect localized in three dimensions, we modified a 16-layer crystal structure in the following manner. Part of the rods on the eighth and ninth layers were removed to obtain a rectangular prismlike cavity. The dimensions of the cavity were $4a \times 4a \times 2d$, where a was the center to center distance between parallel rods (1.12 cm), and d was the thickness of the alumina rods (0.32 cm). We measured the power enhancement characteristics of this structure using the method described earlier. Figure 4 (dotted line) shows the measurement made by the network analyzer. An enhancement factor of 290, and a Q factor of 540 were measured at a defect frequency of 12.32 GHz. We then used a microwave detector within the cavity to probe the EM field inside the localized defect. As shown in Fig. 4 (solid line), the maximum enhancement (245) occurred at the same frequency, along with a Q factor of 680. Both measurements clearly indicate the resonant cavity enhancement for the localized defect.

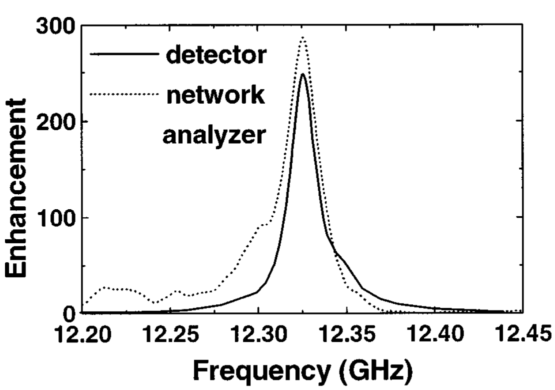

FIG. 4. Enhancement characteristics of the boxlike cavity measured by the network analyzer (dotted line), and the microwave detector (solid line).

In conclusion, our results suggest the possibility of using an embedded detector inside a photonic crystal, as a RCE detector. By using smaller size photonic crystals and higher frequency detectors, the RCE effect can also be obtained at millimeter and far-infrared frequencies. These frequency selective RCE detectors have increased sensitivity and efficiency when compared to conventional detectors, and can be used for various applications.

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