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Enhancement of Cavity-*Q* in a Quasi-Three Dimensional Photonic Crystal

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1. Introduction

Photonic crystals (PhCs) have attracted much interest as key structures in future progress of optical communication or quantum computing because of their potential ability to control photons [1]. A high-Q microcavity with a small mode volume can be fabricated by introducing a point defect into PhCs under the appropriate design. This kind of microcavitiy is of great importance for realizing novel nano-photonic devices including zero-threshold lasers, high-efficient single photon emitters. So far, several groups have demonstrated three-dimensional (3D) PhCs with a complete photonic bandgap [2,3], which enables the ultimate control of photons. In the fabrication of these structures, however, advanced fabrication techniques are required.

On the other hand, air-bridged 2D PhC slab is another candidate for realizing a PhC microcavity with 3D optical confinement. One of advantages of 2D PhC slabs is their simplicity in fabrication. However, Q-factor of the 2D PhC slabs is small due to refractive index confinement in the vertical direction, which limits the total Q-factor of the cavity.

In this paper, we proposed a new type of 3D microcavity with quasi-3D PhC composed of a 2D PhC and 1D DBRs . This structure would be fabricated by means of relatively easy top-down process. The FDTD analysis demonstrated more than 100 times enhancement of Purcell factor compared to conventional 2D PhC slab microcavities. The enhancement is attributed to a large Q-factor and a small mode volume comparable to those of 3D PhC microcavity.

2. Quasi-3D PhC microcavity using 2D PhC structure and 1D DBRs

A schematic image of the proposed structure is illustrated in Fig 1. Quasi-3D PhC is a combination of a 2D PhC and 1D DBRs. A microcavity is formed in a defect layer sandwiched between two DBR mirrors with a point defect surrounded by 2D triangular air-hole-arrayed PhC. In this structure, strong optical localization at the quasi-3D point defect would be achieved when the stop band of DBR and the photonic bandgap of 2D PhC pattern overlap each other.

In order to analyze the cavity characteristics in the structure proposed in this paper, we adopted a DBR structure consisting of air and GaAs layers. Cavity characteristics such as Q-factor (Q_T), mode volume (V_{eff}), and Purcell factor (F_P) in this structure were calculated by using 3D FDTD method. The analyzed region is surrounded by perfectly matched layers to eliminate the effect of reflection from boundaries. Q_T was derived both from the decay rate of the stored energy in the cavity and from the ratio of the stored energy to Poynting vectors, which represent the outgoing energy from the cavity. By using the Poynting-vector approach, we separated Q_T into the two components, $Q_{//}$ and $Q_{\perp}$. $Q_{//}$ corresponds to the energy loss along the defect layer, and $Q_{\perp}$ to the radiation loss in the vertical direction. These values enabled us to determine the direction of energy loss and to investigate the effect of DBRs. In this calculation, the boundaries to separate these components were positioned at $\lambda/2$ (λ is the optical wavelength, 1.3μm) from the surface of the defect layer. Structural parameters were set as follows: Defect layer was λ in length, and DBR structure is 5 pairs of $\lambda/4$ air/GaAs layers. Radius of air hole is 0.4a, where a is the lattice constant of the 2D PhC pattern. In this structural design, the stop band of top- and bottom-DBRs and 2D photonic bandgap in the defect layer overlap. Several cavity modes are formed in this overlapped spectral region.

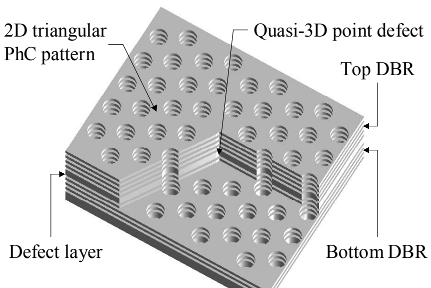

Fig. 1 Schematic illustration of the proposed quasi-3D PhC micocavity.

3. Results and discussion

We calculated cavity mode frequencies under the pulsed excitation condition. The cavity mode frequencies were determined through the peaks in the spectrum obtained by the fast Fourier transform (FFT) on the time evaluation of electromagnetic field in the cavity. In this paper, we paid particular attention to two modes: one is the dipole mode of H_z at the normalized frequency (ω_n) of 0.31128, and another is the monopole mode at the frequency of 0.40283. In Fig. 2, their H_z-field distributions at the center of the defect layer are shown. The characteristics of both cavity modes in the quasi-3D PhC structure are listed in Table I compared to those in the air-bridged PhC slab, which has the same thickness as the defect layer. The mode volume of either mode in the quasi-3D structure slightly decreases with a factor of 20% ~ 30% compared to that in the PhC slab. As for the Q-factor, only a little improvement was obtained for the dipole mode. For the monopole mode,

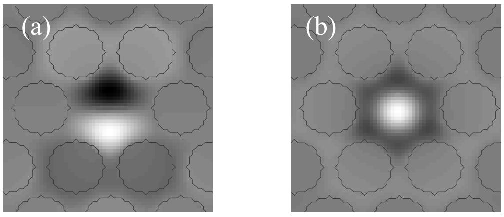

Fig.2 H_z-field distributions at the center of the cavity for the dipole mode (a) and for the monopole mode (b).

however, a large improvement – by a factor of 60 in Q-factor and 70 in Purcell factor - was obtained without the cost of the mode volume. The large enhancement of Q_T in monopole mode can be attributed to the remarkable improvement in $Q_\perp$ because Q_T was limited by $Q_\perp$ in this structure. The difference in the enhancement ratio in $Q_\perp$ for both modes can be understood by considering the mode distribution in the momentum space.

Figure 3 shows 2D spatial FFT spectra of E_x-field at the center of the defect layer for each mode in the 2D PhC slab cavity. In the dipole mode, few Fourier components locate within the air light cone. In the monopole mode, on the other hand, there exists a large amount of Fourier components within the light cone. These components have real wave vectors in the vertical direction, resulting in the vertical radiation loss in air-bridged structures. In the quasi-3D PhC, however, these spatial components are confined by a pair of DBRs. This is the reason for a large improvement of $Q_\perp$ and Q_T in the monopole mode.

Figure 4 shows the dependences of Q-factor and mode volume on the number of DBR layers for the monopole mode. Q-factor increases gradually with increasing the number of layers. This also verifies that the improvement of Q-factor is attributed to the increased optical confinement in the vertical direction by DBRs. When the 2D PhC structure was patterned only into the defect layer, higher improvement factors of 103 in Q-factor and of 120 in Purcell factor were obtained compared to the structure discussed above. In the structure using patterned DBRs, similar values can be achieved by increasing the number of DBR layers and optimizing structural design in order to enhance the vertical confinement further.

Results of our numerical analysis indicate a future direction of high-Q cavity design in quasi-3D PhCs. For further improvement in the Q-factor, it is necessary to design the in-plane defect structure to have moderate

Table I Characteristics of defect modes in quasi-3D PhC for the dipole mode (a) and for the monopole mode (b).

(a)	Air Bridged PhC	Quasi-3D PhC	(b)	Air Bridged PhC	Quasi-3D PhC
ω_n	0.31128	0.31128	ω_n	0.40161	0.40283
Q_T	121	253	Q_T	75	4280
$Q_{//}$	1140	1060	$Q_{//}$	2870	14500
$Q_\perp$	136	333	$Q_\perp$	78	6070
V_{eff}	0.49	0.35	V_{eff}	0.88	0.74
F_p	19	54	F_p	7	473

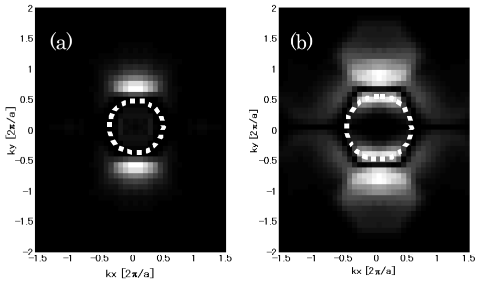

Fig.3 2D spatial FFT spercta of E_x-field for the dipole mode (a) and for the monopole mode (b). Dashed lines represent air light lines corresponding to normalized frequencies of defect modes.

amounts of Fourier components within the light cone. This is completely opposite approach to the design guideline for conventional 2D PhC slab cavity. Our finding also suggests that it would be possible to extract the light from the high-Q cavity toward the vertical direction with a simple radiation pattern in the proposed structure.

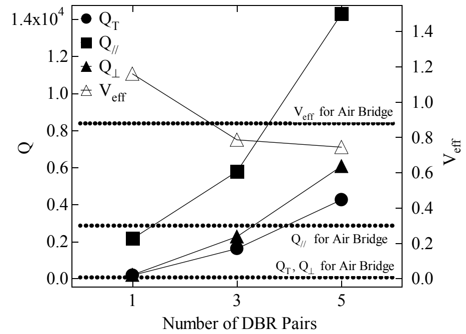

Fig.4 Dependences of Q-factor and V_{eff} on the number of DBR layers for the monopole mode.

4. Conclusion

We proposed a novel microcavity structure fabricated in a quasi-3D photonic crystal with a 2D PhC structure and 1D DBRs. A large enhancement (>100) of both Purcell factor and Q-factor was demonstrated compared to those in the conventional air-bridged PhC slab. In this structure, it would be possible to extract the light from the high-Q cavity toward the vertical direction with a simple radiation pattern. This is promising for the high-efficiency light sources including single photon emitters. Furthermore, it will be a promising structure for current injected devices.

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