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Novel Radiation Pattern of Spontaneous Emission from Photonic Bandgap Crystal Cavity Laser

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Novel surface emitting laser diode consist of a 3-dimensional(3D) photonic bandgap crystal cavity is proposed. The spontaneous emission is controlled to radiate into the lasing direction with narrow radiation angle by introducing a plane phase shift region into the crystal. The radiation angle of spontaneous emission in the photonic crystal cavity is shown to be as narrow as that of the stimulated emission of conventional surface emitting laser by the analysis using 2-dimensional(2D) crystal model. We also show that the photonic crystal cavity laser operates as a light source without threshold and spatial-emission-noise, and is very attractive for use as the light source in the spatially integrated optical circuits.

1.Introduction

There has been a great deal of interest recently in the studies of periodic or disordered dielectric structures owing to the possibility of application to new concept optical devices[1-3]. Especially, 3-dimensional(3D) periodic media with some phase shift region is very attractive for the realization of thresholdless light sources because of controlling the lifetime and the radiation pattern of spontaneous emission by forming the localized impurity mode in the absolute forbidden band.

Several types of spontaneous emission controlled lasers such as micro-cavity lasers[4] or whispering-gallery mode lasers[5] have been proposed and attracting much attention as thresholdless and high efficiency light sources. Micro-cavity lasers can achieve drastic reduction of threshold current and high efficiency operation due to the reduction of the total spontaneous emission probability by decreasing the optical mode number in the cavity. However, it is very difficult to obtain high output power because of very high optical confinement and very small active region.

In this report, we propose a novel surface emitting laser diode which is very suitable for thresholdless , high power and spatial-emission-noiseless operation by using a 3D photonic bandgap crystal cavity.

2.Proposal of Photonic Bandgap Crystal Cavity Laser

Figure 1 shows the schematic of 3D photonic bandgap crystals with phase shift regions and their optical mode density profile in k-space comparing between dot-like and plane phase shift. The photonic crystal with dot-like phase shift operates as the thresholdless laser, however, the lasing power radiates into all direction around the cavity, as shown in Fig. 1. Also, the output power saturates in the low level of injection current because of very small active region. On the other hand, the lasing mode is generated in the poles of forbidden bandgap for the plane phase shift and all emitting power radiate to one direction.

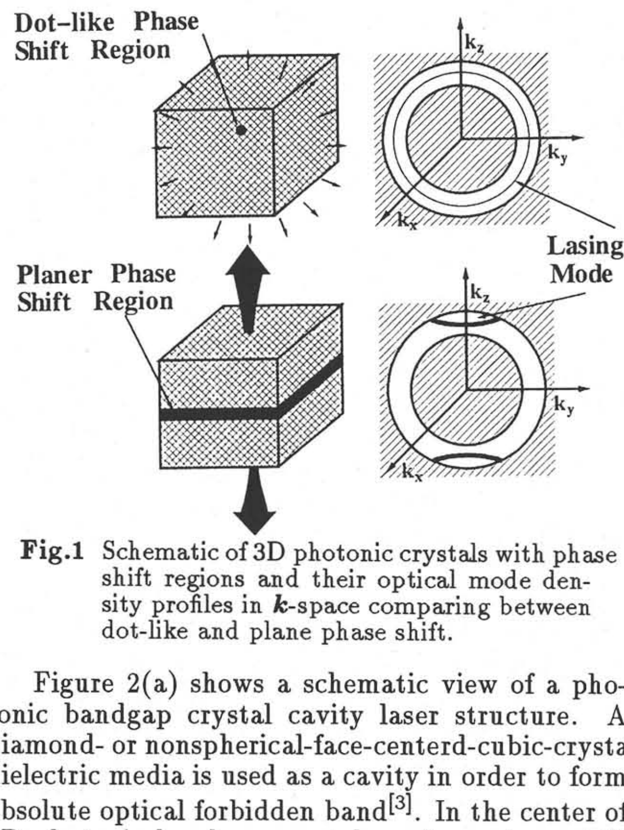

Fig.1 Schematic of 3D photonic crystals with phase shift regions and their optical mode density profiles in $\boldsymbol{k}$-space comparing between dot-like and plane phase shift.

Figure 2(a) shows a schematic view of a photonic bandgap crystal cavity laser structure. A diamond- or nonspherical-face-centerd-cubic-crystal dielectric media is used as a cavity in order to form absolute optical forbidden band[3]. In the center of 3D photonic bandgap crystal, a plane phase shift region (λ cavity) with light emitting active area is assumed in order to make a lasing level in the forbidden band.

Since the phase shift level density is especially high for the poles, the spontaneous emission radiate to lasing direction with narrow angle by tuning the emission wavelength of active region to phase shift level. The photonic crystal media works as both laser mirror and the spatial filter of spontaneous emission.

Figure 2(b) shows a schematic of $I-L$ characteristics comparing between a photonic bandgap crystal cavity laser and a conventional surface emitting laser. Since, almost all emitting power including spontaneous and stimulated emission couple to one direction in the photonic cavity, there is no kink in the $I-L$ curve for photonic crystal cavity laser, contrary to conventional surface emitting lasers. Then photonic crystal cavity laser operates as a light source without threshold and spatial-emission-noise.

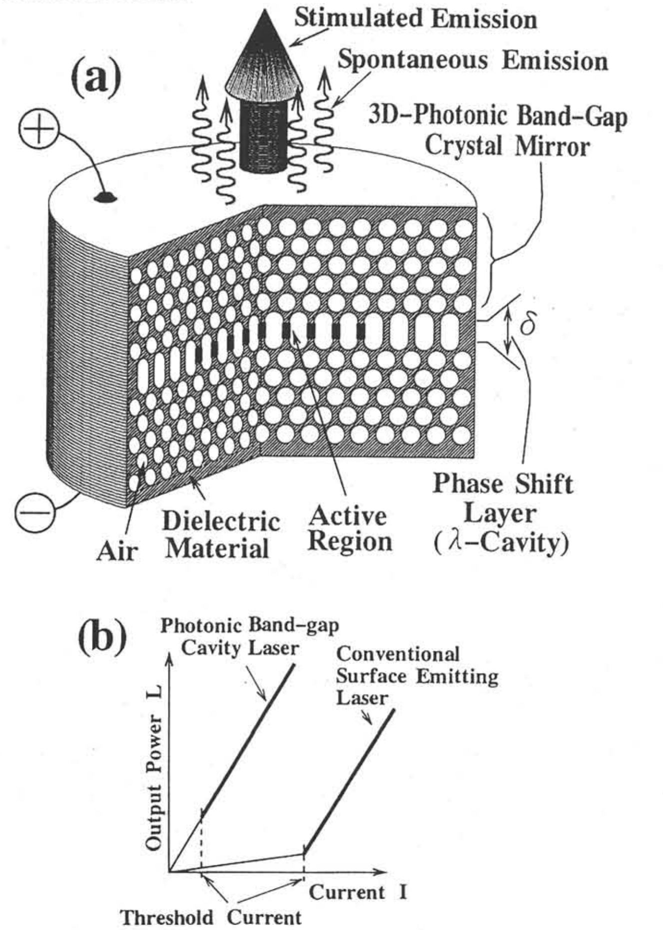

Fig.2 (a)A schematic view of a photonic bandgap crystal cavity laser structure. (b)A schematic of $I-L$ characteristics comparing between a photonic bandgap crystal cavity laser and a conventional surface emitting laser.

Also large lasing power is obtained because of large volume of active region in comparison with micro-cavity lasers. Since there are no optical modes in the forbidden band in contrast to conventional surface emitting lasers, the threshold (lasing) current is much reduced due to the reduction of total spontaneous recombination rate. Owing to, thresholdless, spatial-emission-noiseless, high efficiency and high power operation, the photonic bandgap crystal laser is very attractive for use as the light source in spatially integrated optical circuits, such as optical computers or optical image devices.

3.Analysis

We now analyze the radiation pattern of the localized lasing level in the photonic crystal cavity. The in-plane radiation profile in the 2D crystal cavity should not be so different from that of the 3D one so long due to the similar symmetry of the planer phase shift region, though the detailed pattern may be changed depending on the radiation angle. So the basic properties of 3D photonic crystal cavity can be estimated by analyzing with a 2D model.

Figure 3 shows the photonic crystal cavity laser structure using in this analysis. A 2D triangular crystal consisting of circular rods of air(n=1) in a dielectric atmosphere(GaAs:n=3.6) is assumed with the plane phase shift and active layer. The layer number of the photonic crystal is assumed as 5, taking its refractivity as a cavity mirror into consideration. The diameter of the circular rod is assumed $R = 0.86a$ (where a is the lattice constant) in order to obtain the largest photonic bandgap. The thickness of phase shift and active layer is determined as $d = 1.40a$, as the phase shift level energy approaches to the center of forbidden band.

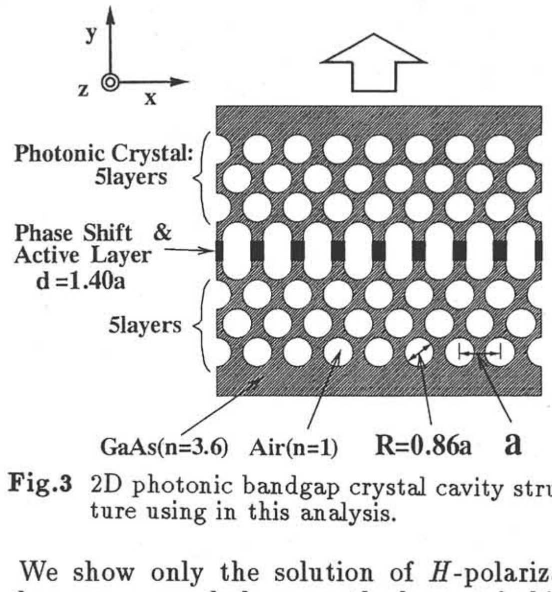

Fig.3 2D photonic bandgap crystal cavity structure using in this analysis.

We show only the solution of H-polarization mode as an example because the largest forbidden bandgap is obtained for H-polarization mode in this 2D crystal structure[6]. These are analyzed by expanding H with the plain wave basis sets[7]. We used ~7200 plane waves to expand the magnetic field H which gives an accuracy better than ~3% in the phase shift eigenmodes. Then we obtained the average mode energy density[8] and the radiation pattern of the 2D photonic crystal cavity.

Figure 4 shows the calculated results of the mode energy density of 2D photonic crystal cavity as functions of normalized frequency and radiation angle for H-polarization (a)odd- and (b)even-mode. We can see the photonic forbidden bandgap in all directions. A high density phase shift level appears in the middle of the forbidden band. The lasing level density is especially high along the perpendicular direction of phase shift layer and its energy is changed by the radiation angle. The radiation pattern is obtained by integrating the mode density and the spontaneous emission spectrum in k-space Figure 5 shows the calculated radiation pattern of the spontaneous emission in the 2D photonic bandgap crystal cavity. The wavelength of the lasing level is assumed as 1.0μm (lattice constant a=0.42μm). The emission spectrum of the active region is assumed to be a gaussian distribution whose peak wavelength is 1.0μm. The full width at half maximum (FWHM) is assumed as 10meV and 50meV. As seen in Fig.5 , the spontaneous emission pattern is very sharp and the leakage power, which emitted to the slanting angle, is 2 orders of magnitude smaller than the forward power. The emission angle is 4° and 10° for FWHM of 10 and 50meV, respectively. This narrow radiation angle may also be obtained with 3D crystal cavities if a plane phase shift region is assumed.

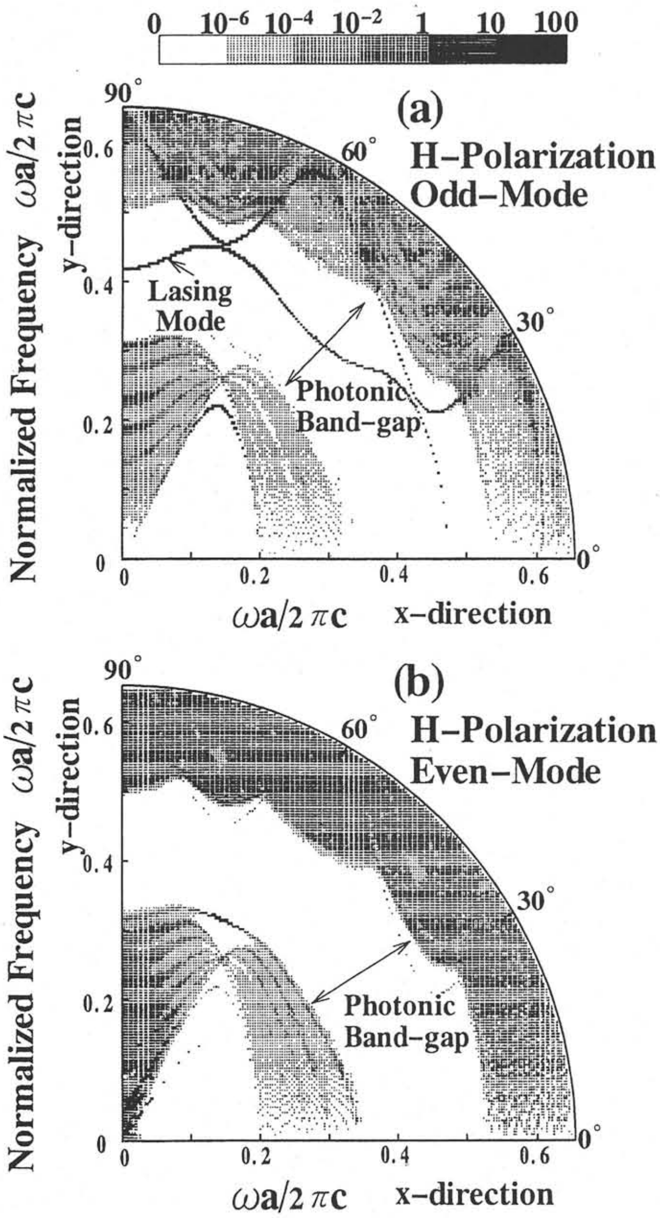

Fig.4 Calculated results of the mode density in of 2D photonic crystal cavity as functions of normalized frequency and radiation angle for *H*-polarization (a)odd- and (b)even-mode.

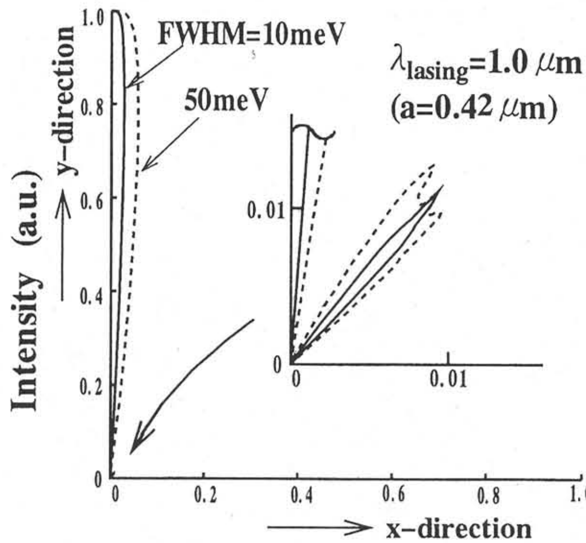

Fig.5 Calculated radiation pattern of the spontaneous emission in the 2D photonic bandgap crystal cavity.

4.Conclusion

In conclusion, we have proposed a novel surface emitting laser diode consisting of a 3D photonic bandgap crystal cavity. The spontaneous emission is controlled so as to radiate along the lasing direction with narrow radiation angle by introducing a plane phase shift region into the cavity. The radiation pattern of the localized lasing mode in the photonic bandgap was analyzed with plane-wave method by using a 2D cavity model. It was shown that the radiation angle of spontaneous emission in the photonic crystal cavity laser is as narrow as that of the stimulated emission of a conventional surface emitting laser, and that the leakage emission around the cavity is negligible. Therefore, the photonic bandgap crystal cavity laser operates as a light source without threshold and spatial emission noise, and is very attractive for sue as the light source in the spatially integrated optical circuits.

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