A unidirectional photonic crystal dispersion-based emitter

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In this letter, we present a unidirectional photonic crystal (PhC) dispersion-based emitter. This device combines a PhC microcavity with a dispersion-based region that is used to produce a unidirectional emission. The three-dimensional finite-difference time-domain method is used to evaluate the performance of the device. The simulation shows a unidirectional emission beam with a small aperture. The principle of this device can be applied in the design of light-emitting diodes or lasers with a unidirection and a small beam aperture in integrated optical circuits. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1713037]

The cavity effect on spontaneous emission has been widely studied and applied in the design of a variety of optoelectronic devices.[1–5] In most cases, the cavity is formed along one dimension by using high index contrast multilayer structures and spontaneous emission of the active material is extracted along the cavity direction. Therefore, although the cavity effect does enhance the spontaneous emission of the active material, normally the overall efficiency is still very low because the total internal reflection (TIR) limits the extraction efficiency. As a result, a lot of methods have been proposed to improve the extraction efficiency through the use of a transparent substrate,[6] rough interfaces,[7] photon recycling (redirecting photons into the narrow escaping cone),[3] surrounding the device with a lens,[8] a taper,[9] or other redirecting structures[10] to release the photons trapped by the TIR. All these methods essentially convert some guided modes into radiation modes. However, none of these approaches completely eliminates all of the guided modes.

To this end, photonic crystal slabs have been introduced to prohibit all guided modes and thereby further improve the extraction efficiency.[1,2] In most applications that use photonic crystals (PhCs) to improve the extraction efficiency of spontaneous emission, the PhC is formed by patterning air holes within the material slabs with high refractive index, in which case, light is extracted vertically from the top or bottom surface of the material. Although these patterned air holes convert what would otherwise be guided modes within the slabs into radiations modes, and thereby improve extraction efficiency, they also introduce the serious surface recombination problem. Moreover, the resulted emission is incoherent and has a large aperture.[1,2]

To overcome these limitations, we propose a mechanism that extracts spontaneous emission from the in-plane direction instead of the vertical direction. This simplified spontaneous emission model is illustrated in Fig. 1.

The model combines two different types of PhC structures, namely structures A and B. Structure A is designed to be a self-collimating structure,[11] wherein a propagating beam that extends over an angular region will be directed only along a given direction. Structure B is a regular PhC defect cavity, which is tailored to control the spontaneous emission. While the lattice of the PhC cavity contains enough layers to ensure high reflectivity, the layers on the side of the self-collimating structure have been reduced to only two layers. In this way, the emission in the PhC cavity is prone to couple through the thin PhC lattice into the collimation structure A and be self-collimated as a narrow beam. In our simplified model, the spontaneous emission is taken at 1.5 μm.

To explain this further, we plot the equi-frequency contour (EFC) of structure A at the design wavelength of 1.5 μm in Fig. 2(a), as indicated by the dotted line. This EFC is obtained using a three-dimensional iterative plane wave method (PWM).[12] An EFC is the cross section of a dispersion surface, which is a surface that characterizes the relationship between all allowed wave vectors in the structure and their corresponding frequencies. The group velocity is equal to the derivative of the dispersion function $\omega(k)$. In other words, energy propagates in the direction of the steepest ascent of the dispersion surface, which is perpendicular to

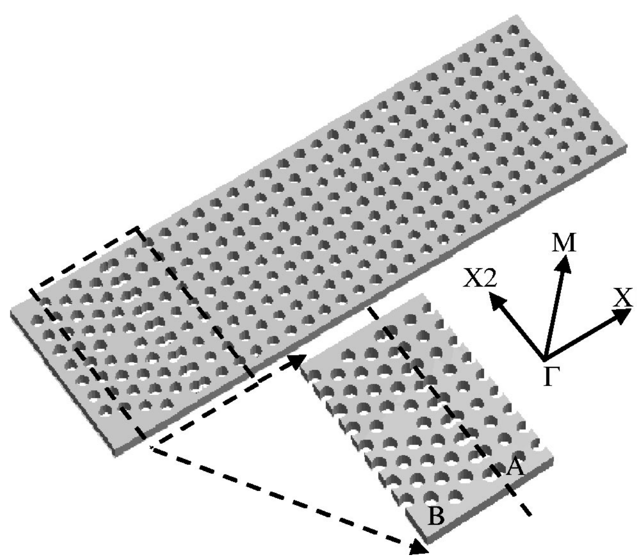

FIG. 1. A unidirectional photonic crystal dispersion-based emitter. The emitter consists of two structures, structure A and structure B. Structure B is the microcavity part which is created by taking one air hole away in a triangular array of air holes in the slab, where the radius of air holes is 0.32*a* (*a* is lattice constant). Structure A is an unperturbed square array of air holes in the slab with a radius of 0.3*a* (*a* is lattice constant). The slab has a thickness of 0.6*a* and the lattice constant for both arrays is 450 nm.

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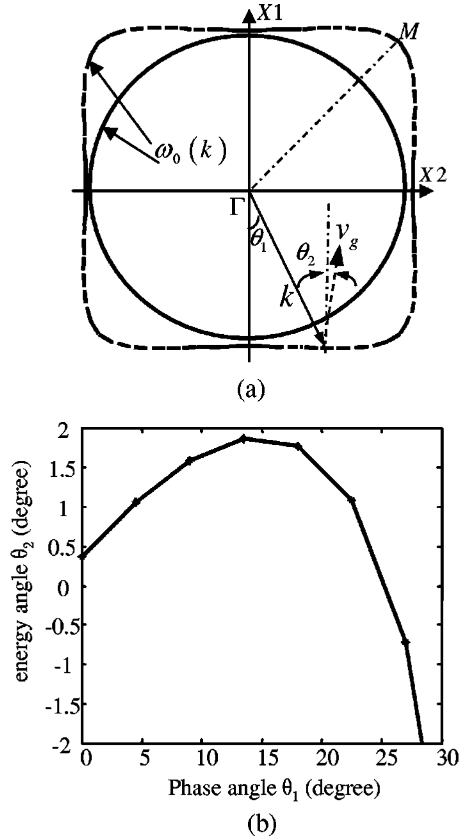

FIG. 2. Phase propagation and energy propagation in structure A shown in Fig. 1: (a) the EFCs of structure A (dotted square with round corners) and the light cone (closed circle) at the wavelength of 1.5 μm, θ_1 is the mode angle and θ_2 is the energy angle in structure A, (b) the relationship between the mode angle and energy angle.

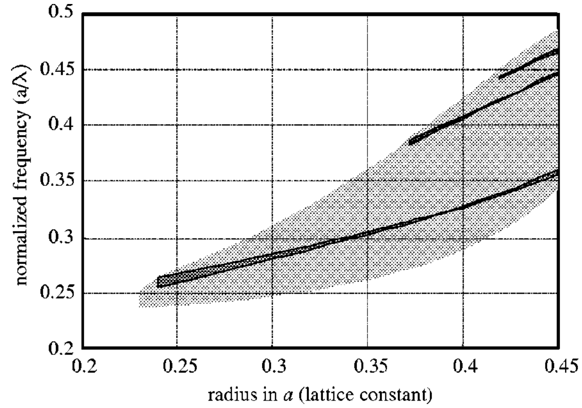

FIG. 3. The map of the band gap of a triangular array of air holes in a slab with a refractive index of 3.5 and the defect modes of a cavity created by taking one air hole away in this array. The slab thickness is $0.6a$. The light shadow region is the band gap region. The heavy shadow regions represent cavity modes.

the EFC. Because some sections of the EFC are approximately flat, the energy in these sections will propagate within a very narrow angular range. Figure 2(b) is the plot of the wave vector angle versus the energy propagation angle in structure A. All the angles in this plot are relative to the $\Gamma-\mathrm{X}1$ or $\Gamma-\mathrm{X}2$ direction, as indicated in Fig. 1. From this figure, one can see that for a beam with an angular range as wide as 28°, its energy propagates within the range of $\pm 2°$. This self-collimation phenomenon can be utilized to collimate the beam emitted by the PhC cavity.

It should be noted that the closed circle in Fig. 2(a) represents the cross section of the light cone, or the EFC of free space, at the same wavelength of 1.5 μm. From the figure, we can see that the EFC of the structure lies outside of the cross section of the light cone, which means all modes supported by the PhC at this wavelength are below the light cone, in which case they can be guided in the slab without vertical loss. This is a very important point since the purpose here is to collect photons along the in-plane self-collimation direction.

With such a self-collimating structure, we desire to extract the spontaneous emission within the PhC cavity into a narrow and highly directional self-collimation beam. In order to maximize the number of photons extracted into the self-collimation beam, i.e., the output power, one needs to carefully design the PhC cavity in terms of its orientation and its position relative to the self-collimation structure. According to Purcell,[13] the higher the Q and the smaller the cavity, the larger the enhancement factor. Thus, from this point of view, one should increase the Q and reduce the dimension of the cavity. However, high Q also implies high photon confinement and thus makes it more difficult for the photons to couple from the cavity to structure A. Therefore, in this case a high Q does not necessarily mean high output power. On the other hand, a small cavity implies small saturation of spontaneous emission simply because of the small active region within the cavity. As such, one should optimize Q and the dimension of the cavity according to the desired output power. During the optimization, there are two other factors that need to be taken into account. One is the vertical loss and the other is the leaky loss along the interface between the cavity structure and the self-collimation structure. Because the goal here is to maximize the output power into the in-plane self-collimated beam, we desire to eliminate, or at least minimize, the vertical loss. To achieve this, we avoided patterning the air hole(s) in the cavity because most of spontaneous emission happens in the cavity and the addition of air hole(s) in the cavity will be a big source of vertical loss. We should also reduce the radius of air holes of the cavity lattice as much as possible in order to reduce the vertical loss, as the vertical loss caused by the air holes surrounding the cavity is proportional to the radius of air holes.[14] To minimize the leaky loss along the interface between the two structures, we considered the interface as a waveguide and offset its guiding spectrum in relation to the cavity and self-collimating spectrum. In this way, the photons tunnel along the interface only within a certain distance and we can thereby minimize the competition for photons at the interface. An additional advantage of doing this is that due to the photon tunneling along the interface we obtain a relatively wide beam illumination on the self-collimating structure, which reduces the incident k spectrum and therefore results in a more efficient self-collimation.[15]

With all these factors in mind, we designed our cavity structure by beginning with a defect mode mapping, which was determined using the two-dimensional PWM with an effective index of 2.88.[16] The results are shown in Fig. 3. Since the assumed emission happens at a wavelength of 1.5 μm, we choose the dimension of the air holes in such a way that the corresponding cavity has a single resonant wave-

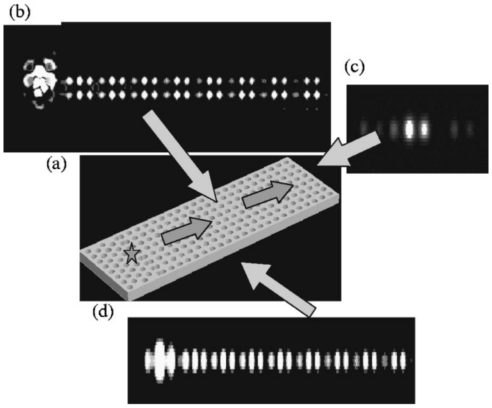

FIG. 4. The steady-state distribution of Hz component: (a) schematic of light propagation in the structure, (b) horizontal cross section view, (c) end-on cross section view, and (d) vertical cross section view. These results are obtained using a 3D FDTD simulation.

length of 1.5 μm. In addition, in order to reduce the scattering along the interface between the two structures, we also want to match lattice constants of the cavity structure and the previously designed self-collimating structure, this is to say that the cavity mode should be $a/\lambda = 0.45/1.5 = 0.3$. As such, the radius of air holes should be $0.33a$ according to Fig. 3. To enhance the coupling of photons to the self-collimating structure, we oriented the cavity structure with respect to the self-collimating structure in a way that the air holes in both structures aligned with each other. We then took this structure as our initial structure and varied the relative position of the two structures and the radius of the air holes comprising the structure to reduce the vertical loss and the leaky loss along the interface of the two structures (detailed discussion will be presented in a separate publication). The purpose of doing this is to increase the power flux coupled into the self-collimation beam at the wavelength of 1.5 μm. The three-dimensional (3D) finite-difference time-domain (FDTD) method is used in this optimization. Doing these, we end up with the structure illustrated in Fig. 1. Figure 4 shows the resulting steady-state field distribution of the Hz component. By calculating the vertical power flow $w1$ on the top of the cavity and the interface, the leaky power flow $w2$ along the interface, and the power flow $w3$ in the self-collimation beam using the field distributions of the six electromagnetic components obtained with the 3D FDTD method, it is found that $w3$ is 2.7 times $w1$ and 28 times $w2$ if a detector with an area of $1.75a$ by the slab thickness is used.

In conclusion, we proposed a unidirectional PhC dispersion-based emitter. In this design, we were able to couple photons, which are confined in a PhC cavity in the vertical direction by TIR and by distributed bragg reflections within the plane, into a self-collimation region. The resulting self-collimated beam is unidirectional and coherent, which can then be directly used in local optical routing or efficiently collected by other optical devices because of its relatively small aperture. In addition, the emission rate is also enhanced due to the PhC cavity effect.

[1] H. Y. Ryu, Y. H. Lee, R. L. Sellin, and D. Bimberg, Appl. Phys. Lett. **79**, 3573 (2001).
[2] A. Padmanabhan, R. H. Baughman, A. A. Zakhidov, and G. Lazarov, in U.S. Patent Office, Publ. No.: U.S. 2003/0148088 A1. August (2003).
[3] D. Delbeke, R. Bockstaele, P. Bienstman, R. Baets, and H. Benisty, IEEE J. Sel. Top. Quantum Electron. **8**, 189 (2002).
[4] E. F. Schubert, Y.-H. Wang, A. Y. Cho, L.-W. Tu, and G. J. Zydzik, Appl. Phys. Lett. **60**, 921 (1992).
[5] Y. Hirayama and Kanagawa-ken, in US patent office, Publ. No.: US 2003/0071564 A1. U.S., 2003.
[6] Y.-J. Lee, S.-H. Kim, J. Huh, G.-H. Kim, Y.-H. Lee, S.-H. Cho, Y.-C. Kim, and Y. R. Do, Appl. Phys. Lett. **82**, 3779 (2003).
[7] R. Windisch, C. Rooman, S. Meinlschmidt, P. Kiesel, D. Zipperer, G. H. Dohler, B. Dutta, M. Kuijk, G. Borghs, and P. Heremans, Appl. Phys. Lett. **79**, 2315 (2001).
[8] S. Moller and S. R. Forrest, J. Appl. Phys. **91**, 3324 (2002).
[9] M. Chien, U. Koren, T. L. Koch, B. I. Miller, M. G. Young, M. Chien, and G. Raybon, IEEE Photonics Technol. Lett. **3**, 418 (1991).
[10] M. Fujita and T. Baba, Appl. Phys. Lett. **80**, 2051 (2002).
[11] J. Witzens, M. Loncar, and A. Scherer, IEEE J. Sel. Top. Quantum Electron. **8**, 1246 (2002).
[12] S. G. Johnson and J. D. Joannopoulos, Opt. Express **8**, 173 (2001).
[13] E. M. Purcell, Phys. Rev. **69**, 681 (1946).
[14] R. Ferrini, R. Houdre, H. Benisty, M. Qiu, and J. Moosburger, J. Opt. Soc. Am. B **20**, 469 (2003).
[15] D. W. Prather, S. Shi, D. Pustai, C. Chen, S. Venkataraman, A. Sharkawy, G. Schneider, and J. Murakowski, Opt. Lett. **29**, 50 (2004).
[16] A. Sharkawy, D. Pustai, S. Shi, and D. W. Prather, Opt. Lett. **28**, 1197 (2003).