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RAPID COMMUNICATION

Horizontally slotted photonic crystal nanobeam cavity with embedded active nanopillars for ultrafast direct modulation*

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A horizontally slotted photonic crystal nanobeam cavity with an embedded active nanopillar structure is proposed for ultrafast direct modulation. By designing the thicknesses of both the nanobeam and the horizontal slot layer, the quality factor (Q factor) and the mode volume (V_n) of the proposed cavity can be engineered independently. As a result, the spontaneous emission (SpE) rate is enhanced with a small V_n of 2.4 while the SpE rate and the cavity photon lifetime have an optimal Q factor of ~ 1000. In our simulation, the modulation bandwidth could be enhanced up to 170 GHz with different emission linewidths of the active nanopillar.

Keywords: photonic crystals, nanocavities, light emitting diodes

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1. Introduction

To reduce power consumption and increase information processing speed for on-chip optical interconnection, an ultrafast directly modulated nanoscale light source is widely desired.[1] Recently, due to the Purcell enhanced spontaneous emission (SpE) of nanocavities, cavity enhanced nano-light-emitting diodes (nanoLEDs) have turned much interest away from the traditional laser diodes owing to their potential in ultrafast direct modulation.[2,3] For such nanoLEDs, it has been clarified that the modulation bandwidth can be dramatically improved by using a meticulously designed nanocavity with a small mode volume (V_n) to achieve a high Purcell enhancement of SpE, while the quality factor (Q factor) should be optimized to achieve a compromise between the SpE rate and the cavity photon lifetime.[4,5]

For such requirements, the photonic crystal (PhC) nanobeam cavity is very promising since the V_n of a PhC cavity is very small and its Q factor can easily be tuned by utilizing a proper design.[6] In our previous work, a staggered photonic crystal nanobeam cavity was designed for this purpose.[7] In addition, a PhC nanobeam cavity with a horizontal slot can achieve a much smaller V_n (~ 0.176) owing to the extremely concentrated electric field in the low refractive index slot layer.[8,9] Meanwhile, the Q factor of such a cavity can easily be tuned by adjusting the thickness of the nanobeam. Thus, both the small V_n and the easily engineered Q factor make the horizontally slotted PhC nanobeam cavity suitable for ultrafast direct modulation. However, the refractive indices of the traditional active materials such as III–V group semiconductors are too high to serve as the low-index slot layer,[10] so the ultra-confinement of horizontally slotted structures cannot be achieved. Therefore, to enhance the electric field of an active material without destroying the ultra-confinement of the field in the slot layer, structures in the active material should be combined with the slot layer.

In the present paper, a horizontally slotted PhC nanobeam cavity with an embedded active nanopillar array is proposed for ultrafast directly modulated nanoLEDs. A high enhancement of the electric field in the active nanopillar array is theoretically demonstrated. Moreover, by tuning the thicknesses of both the nanobeam and the horizontal slot layer, a small V_n of 2.4 and an optimal Q factor of $\sim 10^3$ are obtained. In order to demonstrate the potential of such a cavity in ultrafast directly modulated nanoLEDs, we calculate the achievable 3-dB bandwidth with a typical emission linewidth of the active nanopillar at different temperatures. In our calculation, the 3-dB bandwidth can exceed 170 GHz at the temperature of 2 K and even be as large as 70 GHz at room temperature (RT).

2. Cavity designs

The modulation bandwidth of a cavity enhanced nanoLED is determined by both the photon lifetime and the SpE rate. According to the small-signal analysis of the dynamic rate equations, the 3-dB bandwidth of direct modulation

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can be deduced as[11]

$$f_{3\mathrm{dB,max}} \approx \frac{1}{2\pi} \frac{1}{\sqrt{\tau_{\mathrm{p}}^2 + \tau_{\mathrm{r}}^2}}, \quad (1)$$

where τ_{p} and τ_{r} denote the photon lifetime and the relaxation time of SpE, respectively, and $\tau_{\mathrm{p}} = Q/\omega_0$ is proportional to the Q factor, while τ_{r} is inversely proportional to Purcell factor $F = 6Q/\pi^2 V_{\mathrm{n}}$.[12] Here, the stimulated emission (StE) contribution is ignored and all of the SpE is assumed to couple into the cavity mode. As indicated in Eq. (1), the modulation speed can be improved with a smaller V_{n}, which enhances the SpE rate, and an optimal Q, which can compromise τ_{p} and τ_{r}. Therefore, to achieve the maximum modulation bandwidth, V_{n} should be as small as possible while Q should be optimized to a proper value.

For this purpose, a PhC nanobeam cavity embedded with a horizontal slot layer is utilized and shown in Fig. 1(a). The horizontal slot structure is formed by a low refractive index layer (SiO_2) and two cladding layers with high refractive indices (GaAs). Thus, a TM-polarized mode can be concentrated within the slot area due to the large discontinuity of refractive index in the vertical direction. With the help of the in-plane PhC nanobeam cavity and the horizontal slot in the vertical direction, a small mode volume can be obtained. Unlike the nanobeam cavity in Ref. [8], a nanopillar array of quantum dots is introduced in the cavity region because materials with low refractive indices such as SiO_2 cannot serve as the active materials. Thus, a light emitting structure can be formed by the combination of the nanopillar structure and the nanobeam cavity. Moreover, compared with the traditional weak-index-contrast GaAs/InGaAs/GaAs structure, the nanopillar structure embedded in the slot layer shrinks the vertical optical mode within an ultra-thin slot, so the ultra small mode volume of the proposed cavity can be obtained. Considering the fabrication process, we assume that the nanopillars are high refractive index active pillars containing InGaAs quantum dots and embedded in the slot layer of SiO_2. It could be accessible for the growth of InGaAs quantum dots on the substrate of GaAs. The SiO_2 slot layer and the upper layer could be accessed by a bonding or sputtering process.[13]

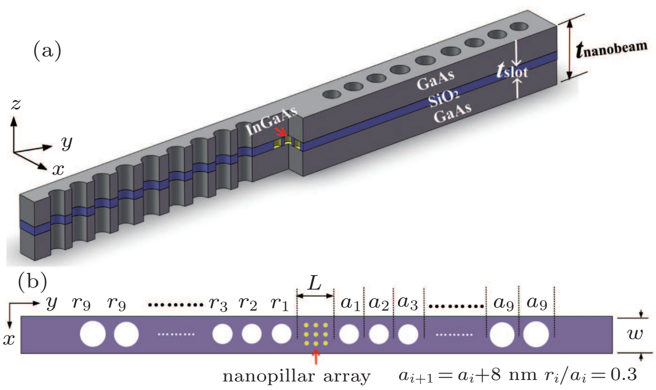

Fig. 1. (color online) (a) The 3D schematic diagram of the proposed horizontally slotted nanobeam cavity with an active nanopillar array, (b) top view of the PhC nanobeam design (3×3 nanopillar array for example).

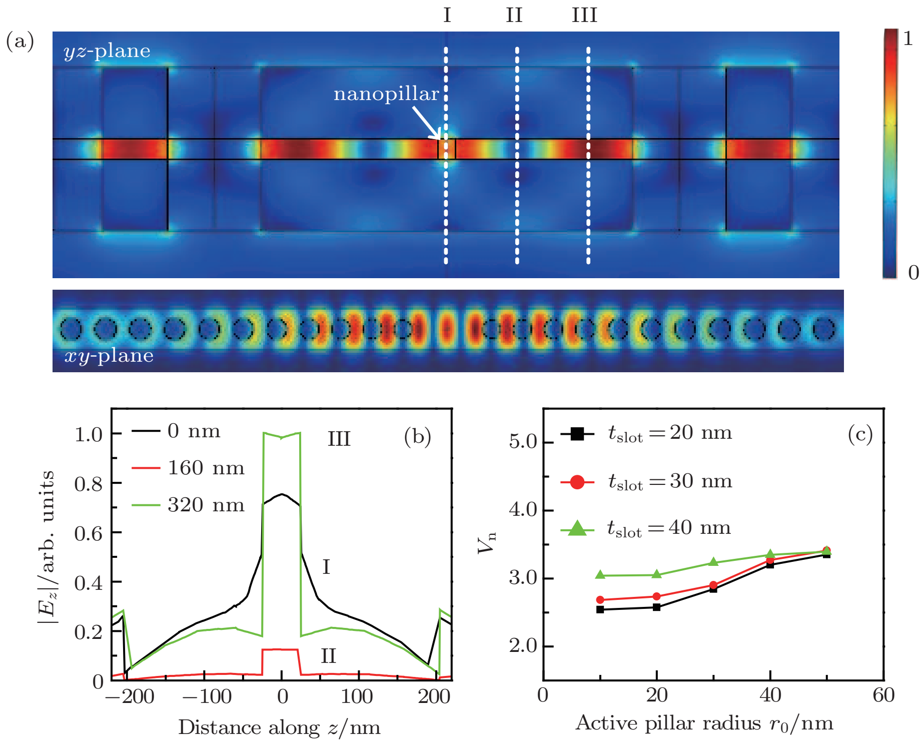

Fig. 2. (color online) (a) Mode profile of the cavity area. (b) The E_z distribution of horizontally slotted nanobeam cavity along z axis with a fixed slot layer thickness of 50 nm. Offsets of 0 nm (I) 160 nm (II), and 320 nm (III) along x axis are chosen. (c) Calculated V_{n} vs. radius of active pillars with different slot thicknesses. The total nanobeam thickness is set to 410 nm.

Since the refractive index of InGaAs is higher than that of SiO_2, we have to examine whether the electric field is still confined in the slot region after introducing the nanopillar array. With FDTD simulation, the mode profile is calculated by setting the thicknesses of GaAs/SiO_2/GaAs layers as 180 nm/50 nm/180 nm. First, we use a 1×1 nanopillar array as an example. The period of the air hole is tuned linearly from $a_1 = 346$ nm to $a_9 = 410$ nm with a fixed radius/period ratio of $r_i/a_i = 0.3$, the radius of the nanopillar is set to 20 nm. Our calculated result is shown in Fig. 2(a). It shows that the electric field is still highly concentrated within the active material. The calculated E_z distribution along the z direction is shown in Fig. 2(b). It should be noted that with the help of the slot layer, the electric field of the nanopillar is also enhanced (black line), although the maximum field is achieved in the low refractive index slot of SiO_2 (green line).

To determine the influence of the slot thickness and the nanopillar size on the field enhancement, mode volumes are calculated with varied slot thicknesses and radii of the active nanopillars while the nanobeam thickness is fixed at 410 nm. As shown in Fig. 2(c), the mode volume V_n can be increased by increasing the radius of the pillar and the thickness of the slot layer. As expected, a smaller mode volume would be achieved with a smaller pillar. However, the variation of the mode volume is not significant since the radius of the nanopillar is small (10–50 nm).

Mode volumes of different cavity structures with different nanopillar arrays are also calculated to reflect how the nanopillar array affects the mode volume of the cavity. Mode volumes for nanopillar arrays with 1×1, 1×3, and 3×3 nanopillars are shown in Fig. 3. It shows that the mode volume of a microarray with more pillars is bigger than that of the one with fewer pillars. The 3×3 nanopillar array has a mode volume of 3.80 while the 1×1 array has a mode volume of 3.55. It can be understood that a high index active material in the slot area makes the energy less concentrated and the maximum field smaller. The introduction of the nanopillar array does not change the mode volume much. In the following discussion of cavity profile and modulation bandwidth, we use the simplest 1×1 nanopillar array structure.

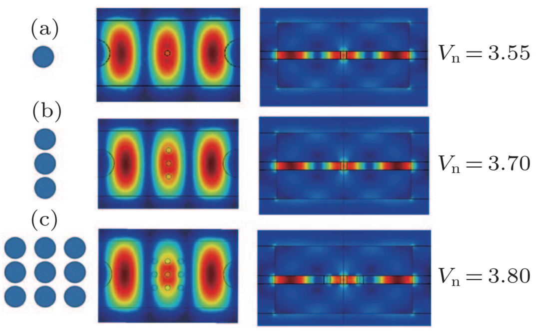

Fig. 3. (color online) Mode profiles of horizontally slotted nanobeam cavities with different structures of nanopillar array ((a) 1×1, (b) 1×3, (c) 3×3).

3. Cavity profile

For the application of high speed direct modulation, the Q factor should be engineered to achieve a compromise between the SpE relaxation time and the cavity photon lifetime. As discussed in Ref. [9], the Q factor of a horizontally-slotted PhC nanobeam cavity is determined by two factors: the total thickness of the nanobeam t and the effective index mismatch between the slot and the cladding. With a fixed slot thickness of 10 nm, we calculate the Q factor of our proposed structure with the nanobeam thickness varied from 310 nm to 590 nm, and the results are shown in Fig. 4(a). It could be seen that the Q factor can be varied from 10^2 to over 10^4. So our proposed structure has great potential for directly modulated nanoLEDs with easily tuned Q factors.

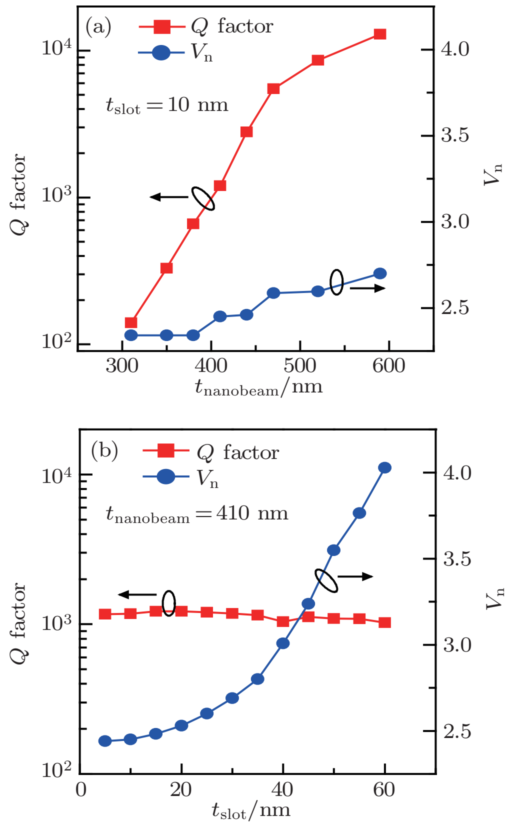

Fig. 4. (color online) The Q factor and V_n versus (a) nanobeam thickness (slot thickness is fixed at 10 nm) and (b) slot thickness (the total nanobeam thickness is fixed at 410 nm).

To investigate the impact of the slot thickness, we also calculate the Q factor and the mode volume V_n with a fixed nanobeam thickness of 410 nm while the slot layer thickness is varied from 5 nm to 60 nm and the radius of the nanopillar is set at 20 nm. The results for Q factor and V_n are shown as red and blue lines in Fig. 4(b), respectively. For the Q factor, the value is varied around 10^3. Roughly speaking, it can be accepted that the Q factor is mainly determined by the thickness of the nanobeam. As for the mode volume, it can be seen that, the mode volume increases along with the slot thickness. In particular, the smallest mode volume of 2.4 can be achieved with the smallest slot thickness of 5 nm. It should be noted that the mode volume V_n calculated here is ~ 10 times larger than that in Ref. [8]. This can be explained by the expression $V_n = (\int \varepsilon(\boldsymbol{r})\boldsymbol{E}^2(\boldsymbol{r})\mathrm{d}^3r/(\varepsilon(\boldsymbol{r})\boldsymbol{E}^2(\boldsymbol{r}))_{\max})(2n/\lambda)^3$. Mode volume V_n here is proportional to the cubic of the refractive index. The refractive index of InGaAs ($n_{\mathrm{InGaAs}} = 3.5$) in this paper is higher compared with the refractive index of SiO_2 ($n_{\mathrm{SiO_2}} = 1.4$) in Ref. [9]. As a result, the difference of V_n here is nearly equal to $(n_{\mathrm{InGaAs}}/n_{\mathrm{SiO_2}})^3$. With both Figs. 4(a) and 4(b), it can be found that the Q factor is mainly determined by the thickness of the nanobeam because of the confinement in the vertical direction, while the mode volume is dominated by the slot thickness. Thus, it can be accepted that the Q factor and the mode volume can be independently engineered, which allows much convenience in the design of an ultrafast directly modulated nanoLED.

4. Nano-light-emitting-diode bandwidth

Till now, we have discussed our proposed cavity in terms of the Q factor and the mode volume. In order to estimate the performance of such a cavity applied on a directly modulated nanoLED, we calculate the achievable 3-dB bandwidth of a nanoLED with such a cavity. In our calculation, τ_r in Eq. (1) is obtained as $\tau_r^{-1} = 2\frac{F}{\tau_{21}\rho_{\mathrm{QD}}}\frac{\Gamma_p}{\Gamma_p+\hbar\Delta\omega}N_0$, which is related to the properties of the emitter.[5,14,15] Definitions and values of the parameters we used are shown in Table 1. Thus, the modulation bandwidth is calculated with the typical emission linewidth at different temperatures. Here the emission linewidths of the InGaAs quantum dot are considered to be $\hbar\Delta\omega = 1.8$ μeV, 0.1 meV, 1.0 meV, 5.3 meV, which correspond to the temperatures of 2 K, 100 K, 200 K, and RT, respectively.[16]

Table 1. Parameters used for the calculation of τ_r.

Parameter	Value
3D density of dots ρ_{QD} [17]	2×10^4 μm^{-3}
Differential bulk lifetime τ_{21} [5]	125 ps
Steady state carrier density N_0 [5]	1×10^4 μm^{-3}
Cavity resonance	0.8 eV
Cavity linewidth Γ_p	$2\hbar/\tau_p$

The calculated results are shown in Figs. 5(a) and 5(b) with varied nanobeam thicknesses (t = 310–590 nm, t = 10 nm) and varied slot thicknesses (t = 5–60 nm, t = 410 nm), respectively. It can be found that the bandwidth is more sensitive to the nanobeam thickness, which dominates the Q factor. Since the Q factor should be carefully designed for a directly modulated LED, the nanobeam thickness of our proposed cavity should be well chosen. Specifically, the optimal nanobeam thickness is around 410 nm with a fixed slot thickness of 10 nm. For the emitter of an InGaAs quantum dot at 2 K, the modulation bandwidth can be as high as 170 GHz. Even at room temperature, the maximum modulation bandwidth is also higher than 70 GHz.

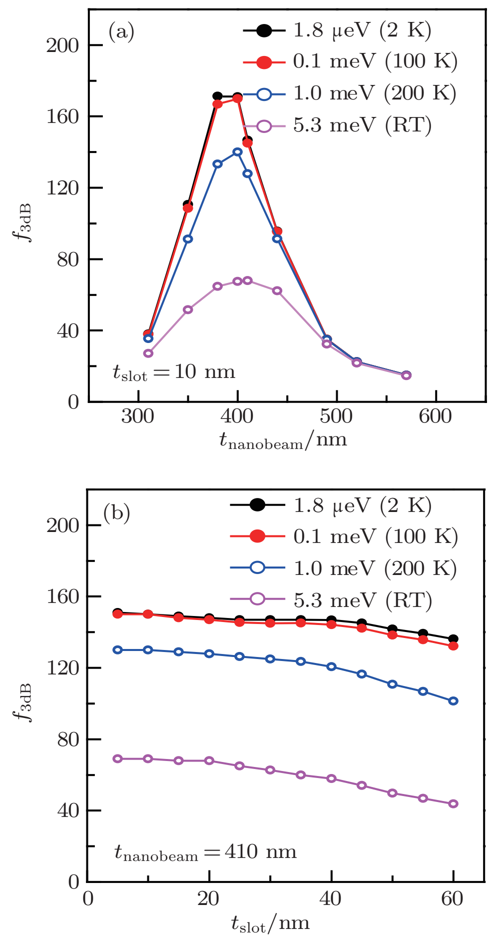

Fig. 5. (color online) The 3-dB bandwidths versus (a) nanobeam thickness (slot thickness is fixed at 10 nm) and (b) slot thickness (the total nanobeam thickness is fixed at 410 nm).

5. Conclusion

In this paper, a horizontally slotted photonic crystal nanobeam cavity with an embedded nanopillar array is proposed and optimized for the ultrafast direct modulation of nanoLEDs. The achieved V_n is as small as 2.4. The Q factor can be tailored in two orders of magnitude (from 10^2 to 10^4) with proper nanobeam thickness and slot thickness. For a given V_n of 2.4 and an optimal Q factor of ~ 1000, a maximum modulation bandwidth as high as 170 GHz can be achieved for the typical emission linewidth of InGaAs quantum dot at 2 K. Even at room temperature, the maximum modulation bandwidth is also higher than 70 GHz.

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