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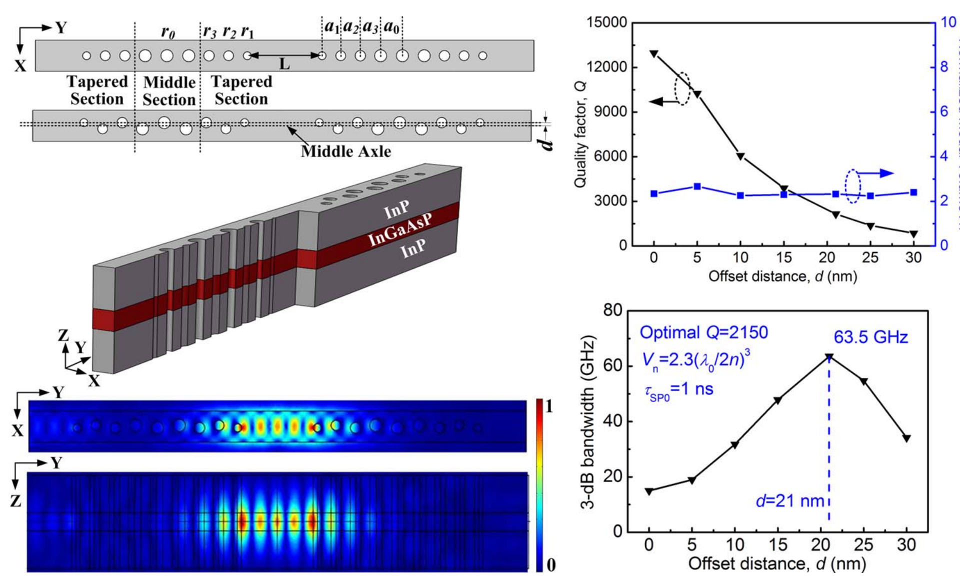
Yongzhuo Li
Kaiyu Cui
Xue Feng
Yidong Huang
Da Wang
Zhilei Huang
Wei Zhang



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Photonic Crystal Nanobeam Cavity With Stagger Holes for Ultrafast Directly Modulated Nano-Light-Emitting Diodes

Yongzhuo Li, Kaiyu Cui, Xue Feng, Yidong Huang, Da Wang, Zhilei Huang, and Wei Zhang

Department of Electronic Engineering, Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing 100084, China

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Abstract: A photonic crystal nanobeam cavity with stagger holes in InP/InGaAsP/InP heterostructure is proposed for ultrafast directly modulated nano-light-emitting diodes (nanoLEDs). With stagger holes, the quality factor Q can be engineered in the range of $10^2 \sim 10^4$ while keeping a small mode volume $(V_{\rm eff})$. As a result, the modulation speed of nanoLEDs can be dramatically improved by a small $V_{\rm eff}$ to enhanced spontaneous emission (SpE) rate and a moderate Q to counterbalance SpE lifetime and photon lifetime of the cavity. In our simulation, the direct modulation bandwidth could be higher than 60 GHz with optimal Q value of 2150 and $V_{\rm eff}$ of $2.3(\lambda_0/2n)^3$.

Index Terms: Photonic crystals, nanocavities, light-emitting diodes (LEDs).

1. Introduction

Nanolasers and nano-light-emitting diodes (nanoLEDs) have been widely investigated driven by the application of on-chip systems [1]–[6]. Recently, nanoLEDs with enhanced spontaneous emission (SpE) rate are more attractive because they open the possibility of dramatically improving the modulation bandwidth of light sources [7]. In 2011, its firstly reported in experiment that direct modulation bandwidth can reach to 10 GHz for nanoLEDs [8]. Different from nanolasers, the SpE rate in nanoLEDs can be enhanced even higher than that of the stimulated emission (StE) due to Purcell effect. Up to now, a lot of research works on nanocavities are working toward extremely high quality factor Q with ultrasmall mode volume $V_{\rm eff}$ to obtain larger Purcell factor, but this is not valid for increasing the modulation bandwidth. It has been clarified that the modulation bandwidth could be dramatically increased, if $V_{\rm eff}$ was as small as possible, while Q should be meticulously designed to an optimal value [9].

The photonic crystal nanobeam cavity is a good candidate to serve for ultrafast modulation nanoLEDs because $V_{\rm eff}$ of those cavities is very small [10]–[13]. It has been reported that the $V_{\rm eff}$ of nanobeam cavity can be very close to $\sim(\lambda_0/2n)^3$, which is the limit of an optical cavity. However, the Q value of nanobeam cavity is usually extremely high (10^5-10^7) and difficult to be varied precisely and continuously while only controlling the number of periodic air holes or the structural parameters of tapered sections. Meanwhile, $V_{\rm eff}$ of the cavities would be also varied with Q value.

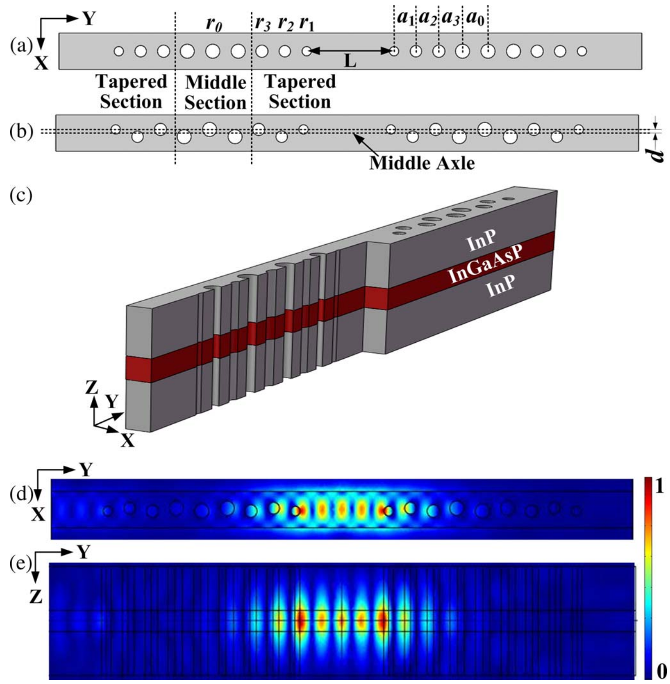

Fig. 1. (a) Top view of regular nanobeam cavity. (b) Top view of the proposed nanobeam cavity with stagger holes. (c) 3-D schematic of the proposed photonic crystal nanobeam cavity with stagger holes in InP/InGaAsP/InP material. (d), (e) Top view and side view of the mode profiles in the nanobeam cavity with stagger holes, respectively.

In this paper, aiming to controlling the Q value while keeping a small V_{eff}, a photonic crystal nanobeam cavity with stagger holes is proposed. With stagger holes, the Q value can be engineered in range of $10^2 \sim 10^4$ while keeping a small V_{eff} of $2.3(\lambda_0/2n)^3$. Then, with the numerical simulations, we investigate the direct modulation bandwidth of a nanoLED based on the proposed cavity. The calculated results show that the 3-dB bandwidth could be in excess of 60 GHz.

2. Cavity Designs

The modulation bandwidth of nanoLEDs can be estimated from a small-signal analysis of dynamic rate equations. Given the application for nanoLEDs, the StE contribution is ignored, and we assume that the SpE's all couple into the cavity mode. The modulation bandwidth is expressed as [9]

$$f_{3\text{ dB,max}} \approx \frac{1}{2\pi}\frac{1}{\sqrt{\tau_p^2+\tau_{\text{sp}}^2}} = \frac{1}{2\pi}\frac{1}{\sqrt{\frac{Q^2}{\omega_0^2}+\frac{(\tau_{sp0}\pi^2 V_n)^2}{(6Q)^2}}} \tag{1}$$

where τ_{sp} and τ_p are SpE lifetime and photon lifetime of the cavity, ω_0 is the resonant frequency of the optical cavity, $V_n = V_{\text{eff}}/(\lambda_0/2n)^3$, λ_0 is the modal wavelength, and n is the effective index of cavity mode. Here, the Purcell enhancement is involved and proportional to Q/V_n, $\tau_{\text{sp0}} = 1$ ns [9], [14]. As indicated in (1), the modulation speed can be improved with a small V_{eff} to enhance the SpE rate and a moderate Q to counterbalance τ_{sp} and τ_p. So, to achieve the maximum modulation bandwidth, V_{eff} should be as small as possible, while Q should be meticulously designed to an optimal value.

For a regular nanobeam cavity, as shown in Fig. 1(a), V_{eff} could be as small as $\sim(\lambda_0/2n)^3$, i.e., $V_n = \sim 1$, with an extremely high Q of $10^5 - 10^7$ by introducing tapered sections and increasing the number of periodic air holes in the middle section. With (1) and such level of V_n, the optimal Q should be in the order of 10^3. So, in order to achieve the maximum modulation bandwidth, Q value of nanobeam cavity should be reduced while keeping a small V_{eff}. For this purpose, stagger holes

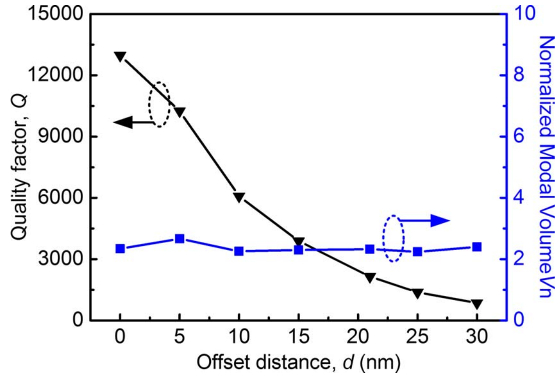

Fig. 2. Simulated Q and V_{eff} in the nanobeam cavity with stagger holes versus different d from 0 nm to 30 nm.

are introduced into a nanobeam cavity. Different from regular nanobeam cavities, the air holes are staggered along the middle axle in Y-direction, as shown in Fig. 1(b). The offset distance of the hole central position is defined as d and denoted in Fig. 1(b). Here, the offset distances of even holes are the same as those of odd holes with opposite directions. As shown in the following section, such arrangement can introduce additional radiation loss by proper setting the d value so that the Q value of the cavity can be precisely and continuously controlled.

To demonstrate the characteristics of our proposed cavity, we consider a practical example as shown in Fig. 1(c), in which the stagger-hole nanobeam cavity is fabricated in a 500-nm-wide ridge waveguide. In vertical direction, the waveguide is formed by a 287-nm-thick InGaAsP core layer (red region, refractive index 3.4) and two 500-nm-thick InP cladding layers (gray regions, refractive index 3.1). The cavity length (L) is increased to 1.15 μm, which is suitable to fabricate an electrical contact on such long region for vertical electrical injection. The tapered sections consist of three aperiodic holes with diminishing diameter and spacing ($r_1 = 65$ nm, $r_2 = 80$ nm, $r_3 = 85$ nm, $a_1 =$ 300 nm, $a_2 = 315$ nm, $a_1 = 325$ nm). The middle sections are periodic holes with radius (r_0) of 98 nm and period (a_0) of 350 nm. The profiles of TE mode are calculated via 3-D finite-element method (FEM) and the top-view and side-view results are shown in Fig. 1(d) and (e), respectively. It can be seen that lightwave is confined by the combining mechanism of in-plane photonic band gap and vertical total internal reflection.

3. Cavity Optimization

Then, with varying d from 0 to 30 nm, we calculate both Q and V_{eff}. The results are summarized in Fig. 2. It can be seen that Q decreases from 13000 to 850 with increasing d from 0 to 30 nm, while V_{eff} is a nearly constant value of $2.3(\lambda_0/2n)^3$ (0.031 μm^3), which is close to the limit of an optical cavity.

To get deep insight of the relation between Q and d, the mode distributions in momentum space are calculated from mode profiles in real space through Fourier transform [15], [16]. Fig. 3 shows the calculated E_x distributions and the corresponding Fourier transformed (FT) profiles with $d = 0$ nm and $d = 25$ nm. The white circle in Fig. 3(b) and (d) is the light cone, inside which in-plane wave vector $k_\perp$ is less than that in the air ($k_\perp < k_0$). In contrast, the wave vectors outside the circle are well confined with no intrinsic losses. Hence, the more wave vectors within the white circle indicates a larger additional vertical radiation loss, accordingly a smaller Q of the cavity. Compared with the case of $d = 0$ nm, there are more wave vectors within the light cone with $d = 25$ nm due to the modification of air holes' positions in X-direction. Thus additional vertical radiation loss would be introduced in the nanobeam cavity with stagger holes and the Q value is decreased in success.

As mentioned above, the V_{eff} would be varied with reducing Q value for a regular optical cavity. However, as shown in Fig. 2, V_{eff} of our proposed structure is nearly independent to Q and d. This result can be understood with two aspects. The first one is that increasing d would not introduce

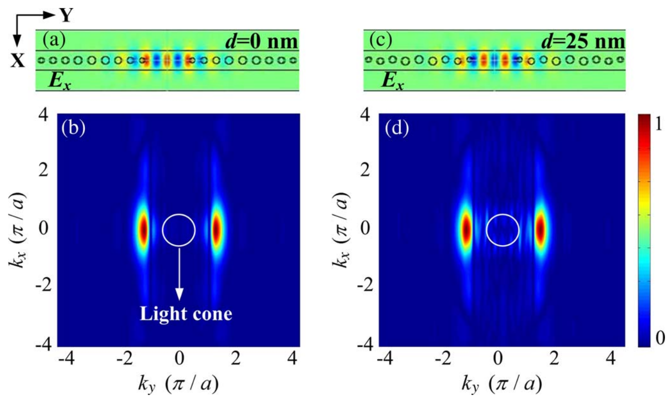

Fig. 3. Mode profiles of the electric field components E_x for the cavity design (a) $d = 0$ nm and (c) $d = 25$ nm, respectively. FT profiles in momentum space of the electric field component profiles (E_x) in the XY-plane with (b) $d = 0$ nm and (d) $d = 25$ nm.

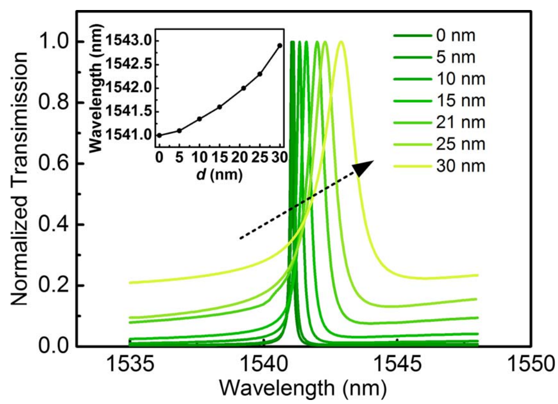

Fig. 4. Transmission spectra of nanobeam cavities under different d from 0 nm to 30 nm. The inset shows resonant wavelengths versus d.

higher order modes in Z-direction so that V_{eff} would not be dramatically varied. The other one is that mode distribution in XY-plane would not be varied with d, which can be indirectly proved by the small variation of resonant wavelengths, as shown in Fig. 4. There is only 1.9-nm tuning of resonant wavelength after increasing d from 0 to 30 nm, while the resonant wavelength would tuned as large as 34.6 nm after increasing the distances between air holes with the same level in Y-direction. Thus, the insensitivity of V_{eff} to d provides a method to optimize Q while maintaining V_{eff} at a small value. Namely, for a given V_{eff}, Q can be optimized by modifying d, which is desired to achieve the maximum direct modulation bandwidth for nanoLEDs.

4. NanoLED Bandwidth

Based on (1), the 3-dB modulation bandwidths of nanobeam cavities with stagger holes are calculated with varying d from 0 to 30 nm ($\tau_{\mathrm{sp0}} = 1$ ns). As shown in Fig. 5, the maximum 3-dB bandwidth is 63.5 GHz at $d = 21$ nm, and the related Q and V_{eff} are 2150 and 0.031 $\mu\mathrm{m}^3$ $(2.3(\lambda_0/2n)^3)$, respectively.

In our calculation, the electronic density of states (DOS) is not taken into account. It has been demonstrated that the 3-dB bandwidth is related to the characteristics of emitters [17], [18]. Thus, our calculation presents the upper limit of the direct modulation bandwidth with our proposed nanobeam cavity with stagger holes. It should be mentioned that, if the spectrum of electronic DOS is wider than that of the cavity, e.g., quantum well or bulk devices, the SpE rate would be depressed

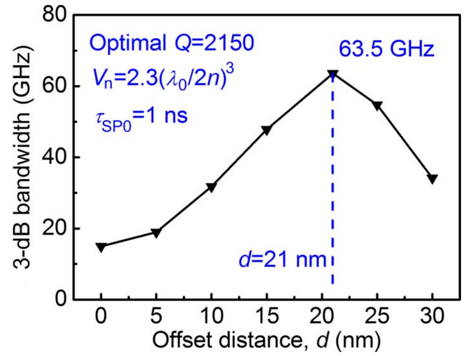

Fig. 5. 3-dB bandwidths of nanobeam cavities with stagger holes versus different d from 0 nm to 30 nm.

and 3-dB bandwidth would be reduced simultaneously. Recently, its reported that narrow spectral linewidth can be achieved from single site-controlled quantum dots with high uniformity [19]. Therefore, if an appropriate emitter is chosen, e.g., quantum dots with linewidth narrower than that of the cavity, the 3-dB bandwidth can be very high and close to the value shown in this paper.

5. Conclusion

In this paper, a photonic crystal nanobeam cavity with stagger holes has been proposed and optimized for ultrafast direct modulation of nanoLEDs. The achieved V_{eff} is as small as $2.3(\lambda_0/2n)^3$ $(0.031\ \mu\text{m}^3)$. The Q can be adjusted in two orders of magnitude (from 10^2 to 10^4) with proper setting the offset distance (d) of the central position of stagger holes in the X axle. For a given V_{eff} of 0.031 μm^3, Q can be optimized with setting $d = 21$ nm so that maximum modulation bandwidth as high as 63.5 GHz can be achieved in success.

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