Ultraefficient control of light transmission through photonic potential barrier modulation

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An optical modulation mechanism based on dynamically shifting the photonic potential barrier of a photonic crystal waveguide is presented. The modulation mechanism is modeled by the one-dimensional quantum tunneling effect using the Schrödinger equation. The calculation results show that the modulation efficiency is 200 times higher than that of the conventional Mach–Zehnder modulator. Based on this innovative concept, an engineering design of an ultracompact silicon photonic crystal waveguide modulator with 10 μm $\times 5$ μm footprint is presented. © 2009 Optical Society of America

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The strong research interest in photonic crystals [1,2] (PCs) stems from the unique features provided by the periodic dielectric structure. These features include slow photon effect [3], super prism phenomena [4], and negative refraction [5]. In past decades, PC devices for dynamic control of light transmission have been demonstrated by various research groups, with emphasis on slow group velocity of the light close to the band edge [6,7], or high-Q resonator due to the strong reflection [8]. These nanophotonic devices achieved outstanding performances with sacrifices of high propagation loss induced by slow photon, or very narrow optical bandwidth due to high-Q factor. Reviewing all prior works, we find that photonic bands, the fundamental property of photonic crystals, have not been fully utilized to develop a useful nanophotonic device for the dynamic control of light transmission. In this Letter, we present a dynamic control mechanism based on photonic bandgap modulation that is fundamentally different from all existing approaches.

As a well-known fact, a crystal waveguide (PCW) formed by a line defect introduces a conducting band within the photonic bandgap of the PC slab [9]. The design principle of the device is illustrated in Fig. 1: the input and output sides have identical band structures covering a certain frequency range; the active region, which controls the light transmission, allows the input light passing through it at the frequency very close to the band edge, as shown in Fig. 1(a). If a control signal is applied to blueshift the conducting band in the active region to a higher frequency level, a potential barrier will be formed in the active region, which will block the transmission of the input light, as shown in Fig. 1(b) [10]. This modulation mechanism is very similar to the one-dimensional (1-D) quantum tunneling effect [11]. The tunneling light (leakage to the output side) is determined by the barrier height and the barrier width. The benefit of using 1-D quantum tunneling model can eliminate the sophisticated and time-consuming numerical simulation of a PCW based on planar lightwave expansion and finite-difference time-domain (FDTD) methods, and it gives us a deeper understanding of the physics associated with the modulation mechanism.

Consider the time-independent Schrödinger equation for one particle in one dimension. This can be written in the form as

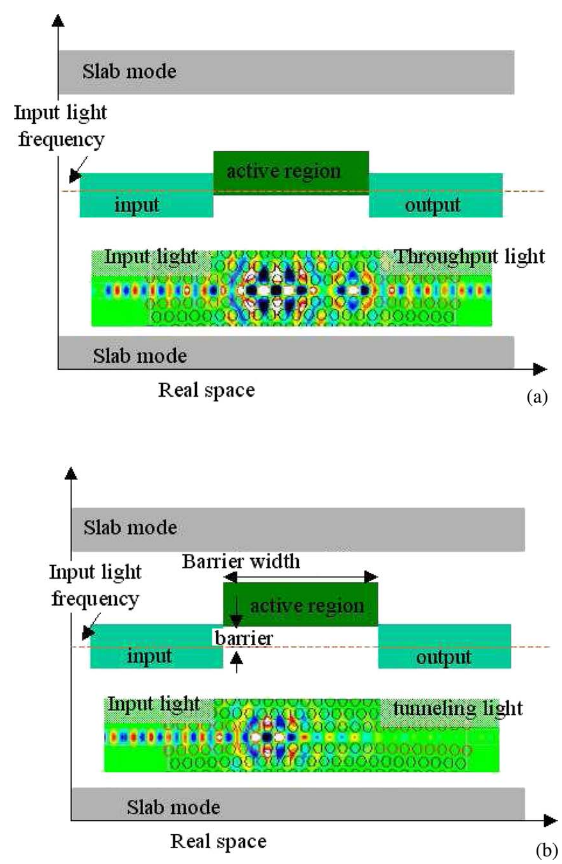

Fig. 1. (Color online) Design principle of the photonic band modulation: (a) ON state with light passing through the active region (Media 1), (b) OFF state rejecting the incident light (Media 2).

$$-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2}{\mathrm{d}x^2}\psi(x)+V(x)\psi(x)=E\psi(x), \tag{1}$$

where $\hbar$ is the Planck's constant divided by 2π, m is the particle mass, x represents distance measured in the direction of motion of the particle, and $\psi(x)$ is the Schrödinger wave function. $V(x)$ is the potential energy of the particle, and E is that part of the total energy of the particle that is associated with motion in the x direction. We can rewrite Eq. (1) into

$$\frac{\mathrm{d}^2}{\mathrm{d}x^2}\psi(x)=\frac{2m}{\hbar^2}[V(x)-E]\psi(x)=\kappa^2\psi(x), \tag{2}$$

where $\kappa^2=2m/\hbar^2[V(x)-E]$ and $V(x)-E$ represents the potential barrier height. By solving the differential equation of Eq. (2), the transmission coefficient for a particle tunneling through a single potential barrier is found to be

$$T=\left|\frac{C_{\mathrm{outgoing}}}{C_{\mathrm{incoming}}}\right|=\frac{e^{-2\int_{x1}^{x2}\mathrm{d}x\sqrt{2m/\hbar^2[V(x)-E]}}}{\left(1+\dfrac{1}{4}e^{-2\int_{x1}^{x2}\mathrm{d}x\sqrt{2m/\hbar^2[V(x)-E]}}\right)^2}, \tag{3}$$

where C_{outgoing} and C_{incoming} are the coefficients of the traveling wave and $x1$ and $x2$ are the two classical turning point for the potential barrier. Back to our device model, we need to consider the incident light as photons with

$$E=\frac{\hbar^2}{2m}k^2=\frac{\hbar^2}{2m}\left(\frac{2\pi n}{\lambda}\right)^2, \tag{4}$$

where n is the refractive index of the media and k is the wave vector. Thus Eq. (5) can be written as

$$T=\frac{e^{-2\int_{x1}^{x2}2\pi n/\lambda\,\mathrm{d}x\sqrt{[V(x)-E]/E}}}{\left(1+\dfrac{1}{4}e^{-2\int_{x1}^{x2}2\pi n/\lambda\,\mathrm{d}x\sqrt{[V(x)-E]/E}}\right)^2}. \tag{5}$$

The expression of Eq. (5) indicates the operation efficiency of photonic band modulation device. It is obvious to find that T is determined by $\int_{x1}^{x2}\sqrt{[V(x)-E]/E}\mathrm{d}x$. If the barrier is uniform in the active region, $\int_{x1}^{x2}\sqrt{[V(x)-E]/E}\mathrm{d}x=\sqrt{\Delta E/E}L$, where $L=x2-x1$ is the active region width. This is very similar to $V_\pi L$ for the Mach–Zehnder (MZ) modulator. Since electro-optic efficiency (γ_{33} or plasma dispersion coefficient) of different materials can vary significantly, it is not convenient to use $V_\pi L$ to describe the performance of a device structure. Instead, we will use ΔnL to compare the performance of the MZ modulator and the photonic band modulation device in this Letter, where Δn is the refractive index change of the active region. This definition can eliminate the influence of materials used for the device.

A typical W1 silicon PCW with triangular lattice structure is adopted in this numerical comparison. The cladding material is silicon dioxide. The lattice constant is 385 nm, the slab thickness is 240 nm, and the filling factor is 50% (hole diameter is 192.5 nm). Figure 2 shows the band diagram of the defect mode as a function of the refractive index change Δn. It is straightforward to derive an empirical formula as

$$\frac{\Delta E}{E}=\frac{0.0615\Delta n}{0.2413}. \tag{6}$$

Figure 3 shows the simulation results of the transmitted light as a function of ΔnL for a conventional MZ modulator, a PCW MZ modulator with 20-fold reduction of group velocity, and a photonic band modulation device with an active region of 10 μm. The simulation results in Fig. 3 clearly demonstrate the exclusive advantage of photonic band modulation mechanism. If the extinction ratio is required to be 10 dB ($T=0.1$), the ΔnL for photonic band modulation is about 10% of a 20-fold slow-photon-enhanced PCW MZ modulator, and only 0.5% of a conventional MZ modulator. It is interesting to point out that unlike the MZ modulator, the ΔnL for a photonic band modulation device is not a constant regarding to the length of the active region (L). This is because Eq. (5) requires $\sqrt{\Delta n}L$ to be a constant, not ΔnL.

From the engineering point of view, it is essential to keep the device length as short as possible, especially for on-chip optical interconnects, where the footprint on the chip for optical components is very small. Another major drawback of a long device is the high optical loss of the PCWs. For silicon PCWs working at slow photon region, the propagation loss can be as high as 20 dB/mm [12]. Minimizing the active region length can significantly reduce the total insertion loss of the device. An important concern associated with light transmission through the photonic band modulation device is impedance mismatch. The key point of the design in Fig. 1(a) is that the input light frequency should be as close to the band edge of the active region as possible to fully utilize the potential change. However, the frequency close to the band edge is usually in slow photon region. Directly coupling into the active region will result in a poor coupling efficiency. Figure 4(a) presents the working principle of the device. The active region consisting of eight periods of PCWs has a very high

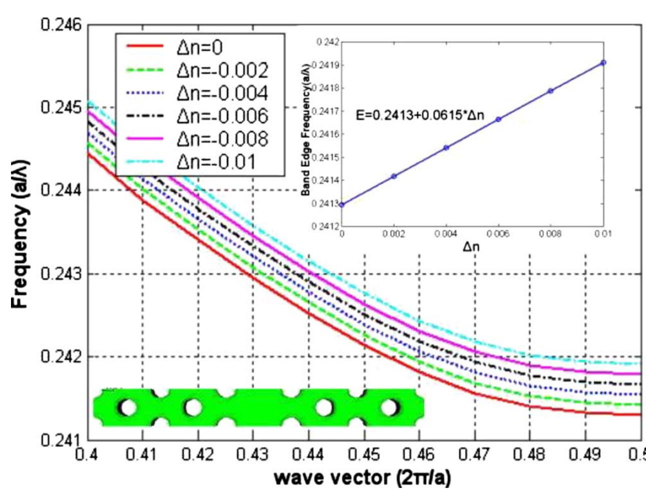

Fig. 2. (Color online) Photonic band diagram of W1 silicon PCW at different index modulation levels (Media 3).

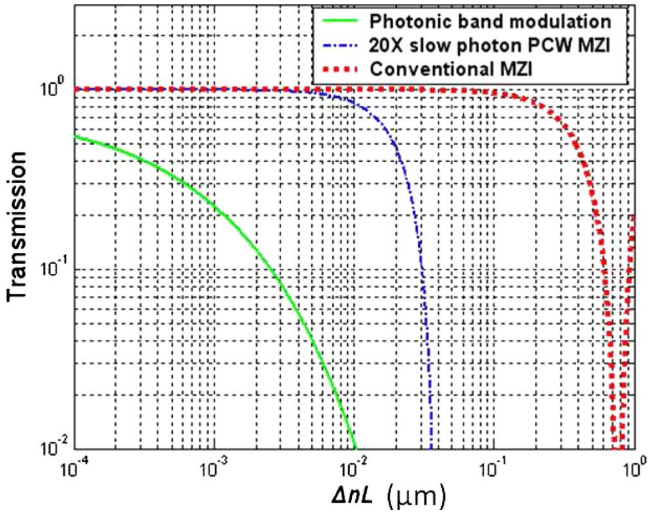

Fig. 3. (Color online) Performance comparison of conventional MZ modulator, 20× slow-photon-enhanced MZ modulator, and photonic band modulation device (Media 4).

group index n_k close to the band edge. The PCW impedance taper [13] contains eight periods of PCWs with gradually decreased waveguide core width along the direction from the input waveguide to the active region, and thus each period of the PCW has a different group index $n_0, n_1, \ldots, n_{k-1}$. The group index n_0 is close to normal silicon refractive index (working at indexlike regime), and n_1 to n_{k-1} gradually increase to n_k. This means that the coupling efficiency from the normal waveguide into the slow-light PCW can be dramatically improved. The total device footprint is less than 10 μm×5 μm, which is the smallest electro-optical modulator design that has ever been proposed (to our knowledge). Figure 4(b) shows the FDTD simulation of the transmission spectrum of the device in Fig. 4(a) with an L of 3.1 μm (eight periods). The 3-D device structure is simplified into 2-D structure using the effective index method. The injected carrier density is $5\times10^{18}/\text{cm}^3$, corresponding to $\Delta n = -0.012$. This will lead to a barrier change of $\Delta E = 7.38\times10^{-4}$. If we take a look at the band diagram, we will see the input wavelength is around 2 nm away from the band edge (because the efficiency to couple light exactly at the band edge is very poor). Since the band edge is 1508 nm in wavelength, and 0.2413 in normalized frequency domain in Fig. 2, a 2 nm wavelength change corresponds to an overhead of 3.18×10^{-4}. Thus the effective barrier height will be 4.2×10^{-4}. According to Eq. (5), the light transmission will be 2.6% (−15.8 dB). The FDTD simulation in Fig. 4(b) shows an extinction ratio of −16.9 dB, which agrees very well with the results predicted by the 1-D quantum tunneling model.

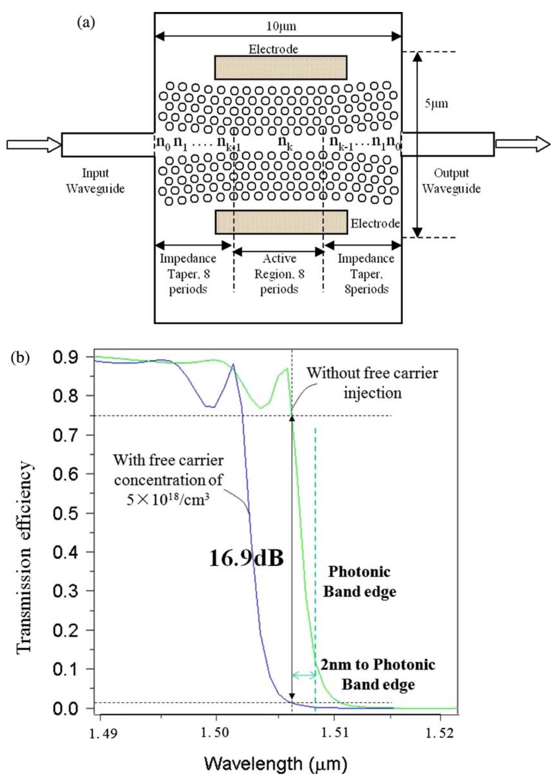

Fig. 4. (Color online) (a) Schematic of the photonic band modulation device with 10 μm×5 μm footprint (Media 5). (b) Simulated transmission spectrum by 2-D FDTD method (Media 6).

In conclusion, we have presented an ultraefficient mechanism for controlling light transmission through photonic potential barrier modulation. The modulation mechanism is modeled by 1-D quantum tunneling effect, demonstrating 200× superior performance than that of conventional MZ modulators, and 10× higher performance than that of the slow-photon-enhanced MZ modulator. At the same time, the photonic band modulation device can achieve exclusive engineering merits, such as ultrasmall footprint (10 μm×5 μm) and very low insertion loss.

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