Coupled Photonic Crystal Microcavities for Optical Switching over Wide Spectral Range

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Abstract: A compact thermo-optic switch comprising a 3.78µm-long coupled photonic crystal resonators coupled to a photonic crystal waveguide is demonstrated with 6nm optical bandwidth, 20dB optical extinction ratio, 18.2mW switching power, and 14.8µsec rise time.

Integrated optical switches are important building blocks in silicon photonics and have many potential applications such as optical interconnects, optical routing, protecting switching, and switch arrays for optical add-drop multiplexing [1]. Thermo-optic (TO) switches based on TO effect are very attractive due to their small size, large scalability, and potential for integration with wavelength-division-multiplexing (WDM) multiplexers. The speed of TO switches is adequate for all routing applications [2]. Conventional Mach–Zehnder interferometer switches or directional coupler switches [3] have large size and require relatively high switching power, which limits the integration density and energy conservation. One of the most widely-used compact and efficient structure for optical switching is microring resonator [4]; however, one drawback of microring switches is the very narrow operational optical bandwidth (<1nm). To address this issue, cascaded microrings along one waveguide have been developed [5], but the total device size has to increase. Another type of switches are based on band-edge shifting photonic crystal waveguides (PCWs) [6]; nevertheless, this device needs to be operated very close to its photonic band edge where the large group index causes high optical loss, and also its high dispersion limits the operational optical bandwidth. Therefore, a TO switch with compact size, wide optical bandwidth, low loss and low switching power, as well as ease of fabrication, is highly required.
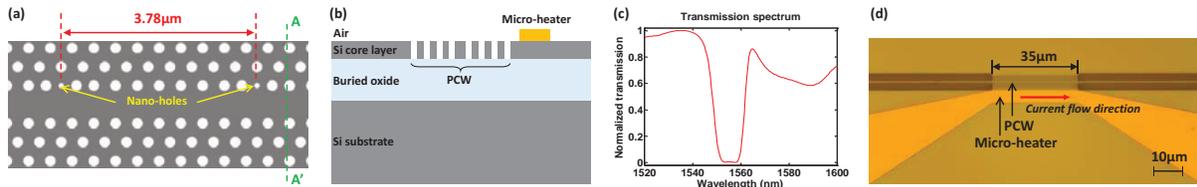

Fig. 1. (a) Top view of the W1 PCW with a coupled PC microcavity. (b) Cross section of the W1 PCW integrated with a micro-heater on an SOI substrate [along A-A' in (a)]. (c) Simulated transmission spectrum of the coupled PC microcavity, showing a 6nm-wide resonance dip. (d) Top view microscope image of fabricated TO switch.

In this paper, we design, fabricate and characterize a compact and high-performance TO switch based on two coupled L0 type cavities integrated with a micro-heater. Various coupled photonic crystal (PC) microcavities have been studied previously for switching in the context of gap solitons [7] and optical analogs to electromagnetically induced transparency [8]. The L0 PC microcavity is formed by simply shifting two PC air holes adjacent to the W1 PCW by 0.2a as shown in Fig. 1(a) where a is the lattice constant. The cavity is further modified by inserting a nanohole with radius r_{NH}=0.5r where r is the radius of the air holes in the bulk PC lattice. The length of the coupled PC microcavity is only 3.78µm. Figs. 1 (a) and (b) show a simple schematic of the TO switch on an SOI substrate (Si thickness=250nm, buried oxide thickness=3µm). A 35µm-long W1 PCW is designed with a lattice constant of 420nm, hole diameter of 201nm, and with 7 rows of holes on each side. Two nanoholes with radius r_{NH}=100.5nm are separated by 9 periods of holes. The nanoholes are in the center of the individual L0 PC microcavities formed by shifting two adjacent air holes by 84nm from their lattice positions, away from each other, forming a 3.78µm-long cavity, as shown in Fig. 1 (a). Coupling of the two resonators leads to an 6nm-wide resonance dip [8], as shown by the simulation result in Fig. 1 (c). This resonance is located ~70nm far away from the band edge (at ~1620nm). The group index in this low-dispersion region is ~6, which is relatively lower compared to band-edge shifting switches [6] and promises low optical loss. The input and output strip waveguides are connected to the PCW using low-loss group index tapers.

To efficiently drive the device through TO effect, a gold strip micro-heater electrode [9] is used, as shown in Figs. 1 (b) and (d). This resistive micro-heater is 35um long, 5um wide, and 150nm thick, and is placed sideways the PCW with a separation of 3um from the PCW center, far enough to avoid extra optical loss. The direct contact between the micro-heater and the silicon core layer allows an efficient heat transfer owing to the high thermal conductivity of silicon (149 W·m^{-1}·K^{-1}). In addition, the buried oxide layer of SOI wafer functions as a vertical thermal barrier, which further

facilitates lateral heat exchange between the heater and the waveguide region [9]. This efficient micro-heater, together with the large TO coefficient of silicon ($1.86\times10^{-4}K^{-1}$), is beneficial for high-speed and low-power operation. Air serves as top cladding, and no passivation layer is required, which simplifies the fabrication steps. The silicon PCW with cavities is fabricated using e-beam lithography and RIE in a single patterning/etching step, while gold micro-heater is patterned by photolithography, e-beam evaporation and lift-off process. A microscope image of the fabricated TO switch is shown in Fig. 1 (d).
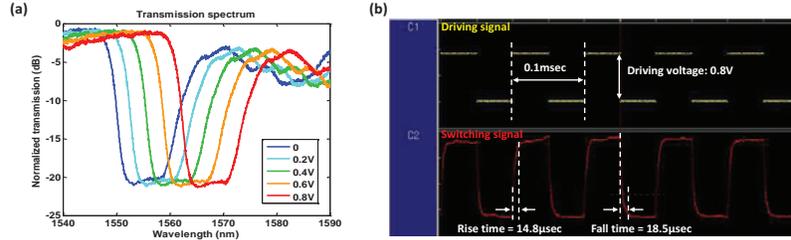

Fig. 2. (a) Measured normalized transmission spectra of the PCW TO switch under different driving voltage. (b) Measured on-off switching characteristics at 10KHz.

To characterize the coupled PC microcavity TO switch, light from a broadband amplified spontaneous emission (ASE) source is amplified by an Erbium-doped fiber amplifier (EDFA) and then coupled into and out of the device via grating couplers. The on-chip optical loss is about 1dB. The optical output is sent to an optical spectrum analyzer. The measured normalized transmission spectrum of the device is shown by the dark blue curve in Fig. 2 (a). A resonance with an almost flat dip is observed from 1552nm to 1558nm. The measured loss on the PCW is about 1dB at the left transmission band. Next, constant voltage is applied onto the micro-heater, and the voltage is tuned from 0V to 0.8V in step of 0.2V, corresponding to the power of 0mW, 1.2mW, 4.7mW, 10.4mW and 18.2mW. As a result, the measured transmission spectrum is red-shifted as the power increases, as shown by the overlaid spectra in Fig. 2 (a). Based on Fig. 2 (a), if a laser wavelength is fixed at 1552nm which is the left edge of the resonance dip, then the required power to switch the optical output power from minimum to maximum is 4.7mW. If a laser wavelength is fixed at the right boundary of the resonance dip, 1560nm, then the required switching power 18.2mW. This 18.2mW is the constant power for switching from off-state to on-state for all 6nm-wide wavelength range. The optical extinction ratio measured from Fig. 2 (a) is 20dB.

Furthermore, an on-off switching test is performed. A tunable laser passing a polarization controller is used to provide TE-polarized optical input, and its wavelength is tuned to 1555 nm which is within the resonance dip in the spectrum. Square wave RF signal with $V_{pp}=0.8V$ at 10KHz is applied on the micro-heater. The switching optical signal is sent to a photodetector and displayed on an oscilloscope, as shown in Fig. 2 (b). The switching rise time (from 10% to 90% transmission) and fall time (from 90% to 10% transmission) are measured to be 14.8μsec and 18.5μsec, respectively. We also observe the switching characteristic when the laser is tuned from 1552nm to 1558nm, indicating the 6nm-wide operational optical bandwidth, which is much better than ring resonator switches whose operation optical bandwidth is smaller than 1nm. This relatively wide resonance dip enables broader operational optical bandwidth than widely-used ring resonators and are potential for applications such as coarse WDM in cable television networks [10].

In summary, we demonstrate a compact and high-performance TO switch based on two coupled L0 type cavities. The measured transmission spectrum shows a ~6nm-wide resonance dip with an optical extinction ratio of ~20dB. The resonance shifts are measured under different DC driving power, and a constant switching power for this 6nm-wide operational spectrum is measured to be 18.2mW. On-off switching is performed under 10KHz, and a rise time of 14.8μsec and a fall time of 18.5μsec are measured. In our future work, to improve the switching speed, the L0 PC microcavity can be appropriately doped to form a p-n or p-i-n structure and be operate as a fast electro-optic switch.

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