High-speed electro-optic control of the optical quality factor of a silicon microcavity

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We demonstrate electro-optic ultrafast control of the optical quality factor of an on-chip silicon microcavity. The micrometer-sized cavity is formed by light confinement between two microring resonators acting as frequency selective mirrors. The ring resonators are integrated into p-i-n junctions enabling ultrafast injection and extraction of carriers. We show tuning of the cavity quality factor from 20,000 to 6,000 in under 100 ps. We demonstrate both high-Q to low-Q and low-Q to high-Q transitions. © 2008 Optical Society of America

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Dynamic tuning of optical microresonators has been shown to provide new functionalities for on-chip optical communications and information processing [1–3]. Fast tuning of the optical quality factor (Q) is an important condition for optical processing based on dynamic photonic structures [4,5]. To date, most approaches have shown only a weak tuning of the Q [6] or used all-optical techniques [7] or slow thermal processes [8,9]. An integrated electro-optic ultrafast tuning mechanism for the Q can lead to significant advances in the control of light on a microchip including functionalities such as on-chip optical buffers, wavelength converters, reconfigurable switches, and filters. In this Letter we show strong changes in the Q of a micrometer-sized cavity, from 6000 to 20,000, achieved by in-plane integrated electro-optic tuning in under 100 ps.

The cavity used here consists of two microrings that are coupled to a pair of parallel waveguides. An optical cavity is formed by confinement of light between the two resonators, which act as reflectors near their resonant wavelengths. By controlling the center wavelength of the resonators, one can change the reflectivity of the mirrors and control the quality factor of the cavity formed. The existence and nature of a supermode formed by confinement of light between two resonators has been theoretically and experimentally described earlier in detail [10,11]. The device, as shown in Fig. 1(a), consists of two microrings each with a diameter of approximately 14 μm, which are coupled to a pair of parallel waveguides. In Fig. 1(b), we show the transmission spectrum of the device for TE polarized light (dominant electric field parallel to the silicon substrate). The drop port spectrum is shown in the inset. The measured transmission spectrum agrees with a time-domain model where the optical transmission is calculated iteratively. The amplitude coupling coefficient from the waveguides forming the straight sections to the ring is 0.8%, and the propagation loss of the curved waveguide forming the ring is 8.0 dB/cm.

The device is defined on a silicon-on-insulator (SOI) wafer integrated into an electro-optic structure by creating p-i-n junctions, which allows for the electro-optic tuning of the resonances of the microrings.The coupling waveguides and the rings all have a width 560 nm and a height 250 nm. The center-to-center (CTC) distance between the waveguides forming the rings and the straight waveguides is 720 nm, and the CTC distance between the rings is 44 μm [see Fig. 2(a)]. Concentric $p+$ and $n+$ doped regions are defined inside and around the resonating devices to allow for electrical carrier injection and extraction, which modify the index of refraction of the Si and in turn control the spectral position of the resonances. The microscope image of the device is shown in Fig. 2(b).

The p-i-n junction induces ultrafast changes in carrier concentrations by active injection and extraction of carriers. The carriers can be extracted in ~10 ps, a value that is limited only by the time taken by the carriers to drift across the waveguide at the saturation velocity of 10^7 cm/s (which is determined by the optical phonon generation rate in silicon). The injection transients can also be as short as ~50 ps [12]. Hence the structure is capable of producing index

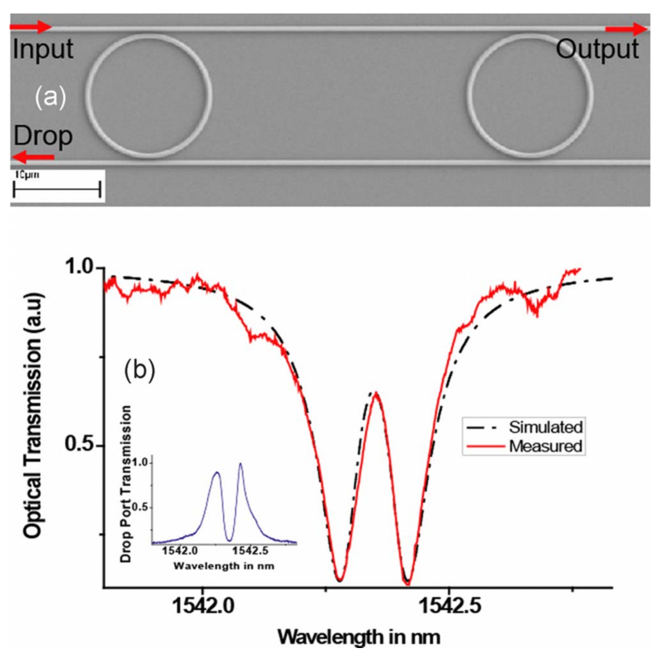

Fig. 1. (Color online) (a) SEM image of double-ring cavity. (b) Transmission spectrum of the device (the drop port spectrum is shown in the inset).

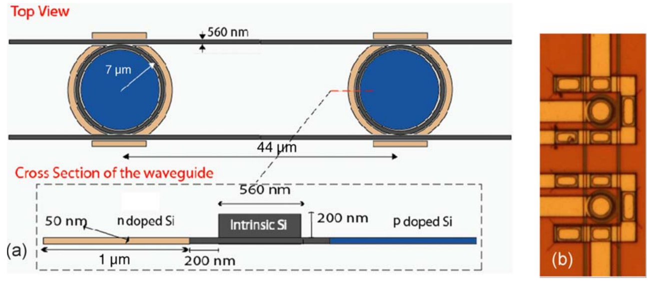

Fig. 2. (Color online) (a) Schematic of an electro-optically integrated double ring-cavity. (b) Microscope image of the device.

changes at rates of 10 GHz with a relative index change ratio of $\delta n/n > 10^{-4}$.

The waveguiding structures are defined on an SOI substrate using electron beam lithography (*e*-beam) followed by reactive ion plasma etching. After the definition of the waveguides, the excess Si is etched away, but 50 nm remains, allowing for the injection and extraction of carriers from the intrinsic Si waveguide. N^+ and P^+ regions of the diode are each defined with *e*-beam lithography and implanted with phosphorus and arsenic to create concentrations of 10^{19} cm^{-3}. The device is then clad with 1 μm of plasma enhanced vapor deposited SiO_2 and annealed to activate the dopants. Following the activation, *e*-beam and reactive ion etching are used again to define and etch through the cladding down to the doped regions for the electrical contacts using nickel. Aluminum contact pads are then defined using *e*-beam lithography and evaporation followed by lift-off.

By controlling the center wavelength of the resonators, one can change the reflectivity of the mirrors and control the supermode quality factor (i.e., the transparency window). Hence, the spectral width of the cavity formed between the two resonators is a strong function of the frequency separation between the resonant frequencies of the two microrings. We measured the transmission spectra of the device for various applied voltages as the central wavelength of the ring 1 (corresponding to a center wavelength of 1542.28 nm) is changed by the injection of free carriers through the p-i-n junction. As free carriers are introduced into ring 1, free carrier dispersion [7] leads to change in center wavelength of ring 1, which leads to a change in the spectral width of the supermode resonance. We measured the transmission spectra of the device as the applied voltage is varied from 0 to 1.2 V. We can see from the transmission characteristics in Fig. 3(a) that a supermode with a Q of 20,000 is formed when no voltage is applied in the coupled ring device. When a forward bias is applied the spectral width of the transparency region is clearly increased, indicating a decrease in the cavity Q to 6000 [Figs. 3(b)–3(d)]. Hence, we show that the Q of the transparency window can be electro-optically tuned from 20,000 to 6000 by controlling the carrier concentration in the device.

To ensure that the effect observed here is due to the presence of the supermode, and is not due to spectral filtering, we simulated the sensitivity of the supermode transmission feature to changes in the cavity length. We show that the supermode transmission spectrum is significantly affected as the length of the cavity in the model is varied from 43.11 to 45.26 μm corresponding to a +2% change in the cavity length (Fig. 4). Note that in these simulations the resonance wavelength of the cavities is kept the same. For example, at 44.42 μm, a 1% change on the cavity length from the nominal length leads to a 30% change in the supermode peak transmission, indicating that the transparency window indeed corresponds to a supermode formed by confinement of light in the cavity formed by the two resonators acting as reflectors. We used a time-domain iterative model to calculate the fields in the resonators.

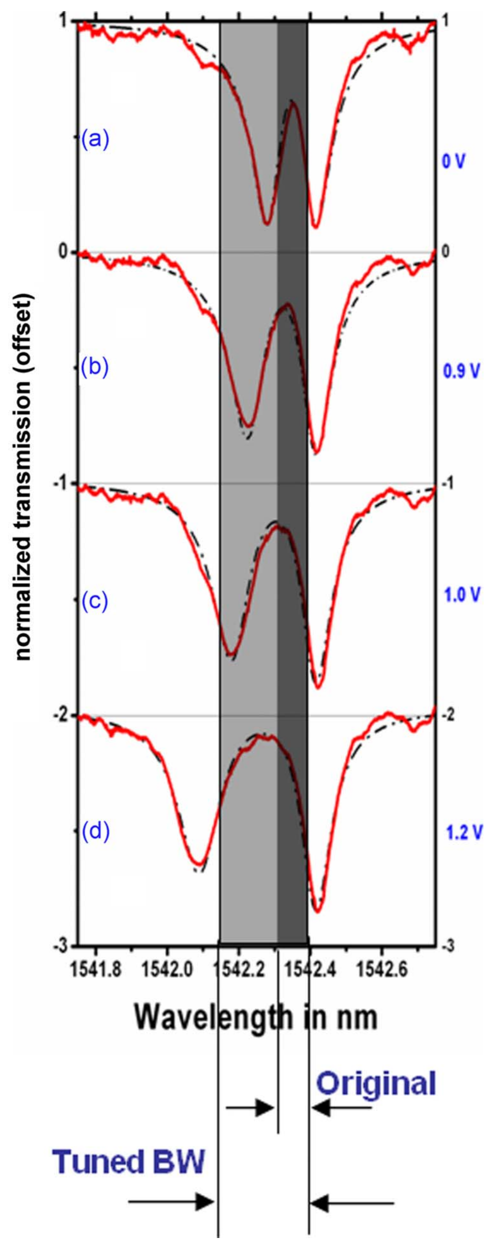

Fig. 3. (Color online) Experimental transmission spectra (solid curve) and theoretical fits (dashed curves). The curves correspond to transmission spectra as the applied voltage to one of the resonators is varied from 0 to 1.2 V. The transmission spectra (b)–(d) are vertically offset for clarity.

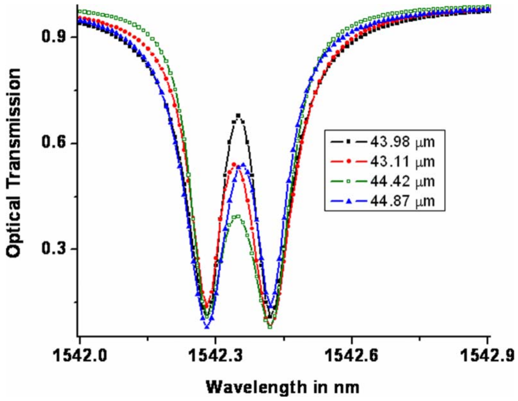

Fig. 4. (Color online) Sensitivity of the supermode transmission to changes in the distance between the coupled cavities. A 1% change in the distance between the cavities shows a 30% change in the transmission of the supermode.

We measured ultrafast transitions of the Q by probing the transmission dynamics through the device at a wavelength where the modulation of Q leads to a modulation in the amplitude of the transmitted light. We applied a 0.1 GHz repetition rate square wave with a 5 V amplitude and 100 ps fall and rise times. The dc bias voltage was varied between −3.5 V and zero to obtain optimum transitions. Note that no pre-emphasis or predistortion of the electrical signals has been used. We use forward bias to inject carriers and reverse bias to actively extract the carriers. In Fig. 5(a) we show the transmission spectra through the device in a low-Q state (injected carriers) and in a high-Q state (depleted carriers). We choose a wavelength λ_{probe} on the spectrum where a change in the Q produces a corresponding change in the amplitude of the transmitted light. In Fig. 5(b) we show the time response of the transmission at λ_{probe} as the Q of the device is switched from a low- to a high-Q state and in Fig. 5(c) as the Q of the device is switched from a high- to a low-Q state. One can see that both transitions (low Q to high Q, high Q to low Q) occur within 100 ps.

The demonstrated approach is an order of magnitude faster than the all-optical methods in restoring

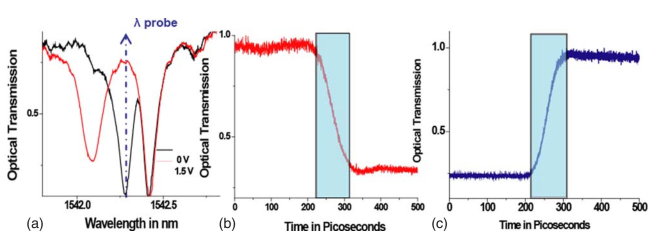

Fig. 5. (Color online) (a) Gray curve shows the transmission spectrum when a forward bias is applied to the ring corresponding to lower wavelength resonance. The black curve shows the transmission of the unperturbed device. (b) Time response of the transmission at λ_{probe} as the Q of the device is switched from a low- to a high-Q state. (c) Time response of the transmission at λ_{probe} as the Q of the device is switched from a high- to a low-Q state.

the cavity to a high-Q state (or a low-Q state depending on the scheme) after the carriers are injected. The all-optical methods rely on a recombination of the carriers to restore the unperturbed cavity condition. In contrast an electro-optic integrated device as shown here can restore the cavity condition by active extraction of free carriers. A fast cyclical modulation of the Q from low to high and high to low states is essential for various optical processing techniques [4,5]. Novel device structures may be used to induce fast extraction as well as the injection of carriers in ~10 ps using a high field carrier transport [13].

In summary, we have shown ultrafast tuning of the optical quality factor in an integrated photonic structure on a silicon chip in 100 ps. Control of the cavity Q in these time scales will enable novel functionalities such as wavelength conversion, pulse compression, fast tunable optical filters, delay lines, and light-stopping schemes, which were previously only demonstrated using all-optical systems [1,7].

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