On-chip generation of high-intensity short optical pulses using dynamic microcavities

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We experimentally demonstrate generation of high-intensity short optical pulses obtained by the controlled ultrafast release of the stored energy confined in silicon microcavities. This is achieved using ultrafast tuning of the coupling from a coupled-ring cavity to an external waveguide on time scales shorter than cavity photon lifetime. © 2009 Optical Society of America

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Optical microcavities make possible high-performance devices based on the buildup of resonant energy in a small volume [1–3]. The long photon lifetime and large free spectral range of recently demonstrated optical microcavities with high-quality factors should also enable dynamic and adiabatic manipulation of the properties of light, such as bandwidth and frequency [4–14]. The predicted and demonstrated effects using such dynamic microcavities include slowing/stopping of light [4,5], adiabatic wavelength conversion [6–9], time-reversal of optical pulses [10], and optical pulse compression [12] and generation [13,14]. Here we experimentally demonstrate the use of dynamic microcavities for producing high-intensity short pulses on-chip from CW input light.

We demonstrate here that when the coupling of light from a microcavity to an adjacent external waveguide is increased within a time scale shorter that the photon lifetime, the energy built up in the cavity can be released as a high-intensity short optical pulse. We assume that a waveguide and a microcavity are initially coupled with a coupling coefficient κ. We consider the critical coupling condition in which the coupling coefficient equals the round-trip loss. If CW light is input into the waveguide with a power P_0, the energy is built up in the microcavity. The maximum energy stored in the cavity is $E=QP_0/\omega_0$, where Q is the intrinsic quality factor and ω_0 is the resonant angular frequency. Following the cavity energy buildup, one can tune the coupling coefficient κ to a much larger value. If the tuning time Δt is much shorter than the photon lifetime, the stored cavity energy is forced to couple out into the waveguide, generating a high-intensity short optical pulse. The pulse duration is approximately equal to the sum of the tuning time Δt, the round-trip time τ_{rt} of the cavity, and the final photon lifetime of the cavity τ_{fp} following the tuning; that is

$$\tau \approx \Delta t + \tau_{rt} + \tau_{fp}. \quad (1)$$

The peak power of the generated pulses is the released energy divided by the pulse duration. In the situation that the coupling coefficient after tuning is close to one, the peak power is given by

$$P_{peak} = \frac{\tau_{ip}}{\tau} P_0. \quad (2)$$

Here, τ_{ip} is the initial photon lifetime before tuning, which is expressed by $\tau_{ip}=Q/\omega_0$.

Note that the effects of cavity dumping in free-space large cavities [15,16] have been well understood and demonstrated; however, these effects are limited to both a relatively low ratio of generated peak power to incident power P_0 [i.e., the round-trip time in Eq. (2) is large] and nonadiabatic effects (i.e., coupling between different modes of the cavities) due to the relatively large size of the free-space cavities. Here we demonstrate adiabatic release of trapped energy. To estimate how much peak power one can obtain in a realistic microcavity, we use a quality factor of 10^8 and a photon lifetime of $\sim$100 ns, experimentally obtainable on-chip [2]. If we assume that the generated pulse duration is less than 1 ps, the generated peak power can be on the order of 10^5 times the input power. The key step in realizing this effect is to dynamically tune the coupling between the microcavity and the external waveguide in a timescale much shorter than the photon lifetime. In order to achieve adiabatic tuning, the tuning time is required to be longer than the round-trip time of the microcavity [17].

To achieve ultrafast tuning of the coupling between a cavity and its adjacent waveguide we use a resonator system consisting of two silicon microring resonators coupled to parallel waveguides, as shown in Fig. 1(a). The waveguides and rings have a height of 250 nm and a width of 560 nm. The ring radius is 7 μm, and the edge-to-edge distance between rings and waveguides is 160 nm. The center-to-center distance between the two rings is 87.96 μm. We have demonstrated previously [5,18] that in such a configuration each ring acts as a narrowband reflector and as a result a Fabry–Perot mode is formed. The resonant wavelength and bandwidth of the ring are determined by the ring radius and the distance between the waveguides and the rings. The Fabry–Perot resonant wavelength of this system can be independently controlled by the separation between two rings.

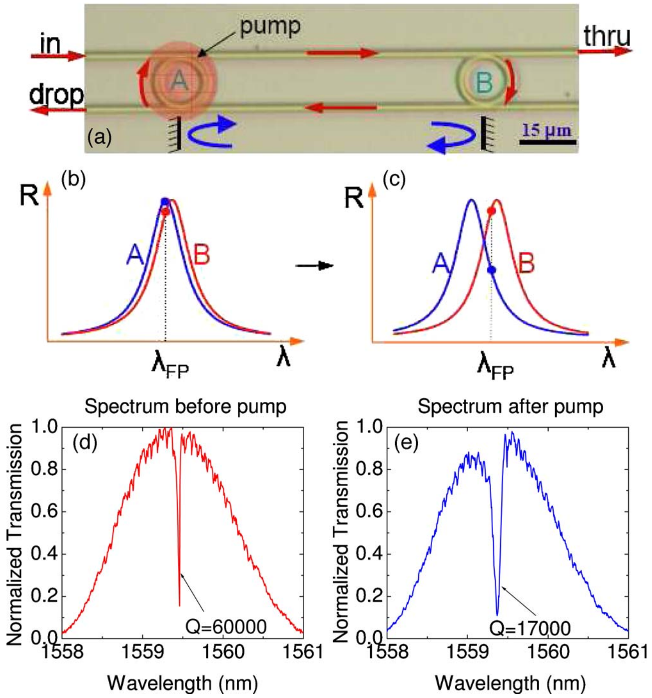

Fig. 1. (Color online) Coupled-ring resonator to realize dynamic tuning. (a) Microscope picture of the device. (b), (c) Diagrams of reflection spectra of the rings before and after tuning. Before tuning, the Fabry–Perot resonant wavelength is close to the resonant wavelength of both rings, so that a high-quality-factor mode is formed via constructively interfering reflection between the two rings. After tuning, ring A has a blueshift in the reflection spectrum; equivalently, the outcoupling from the microcavity to the drop port increases. (d) Spectrum without pump. (e) Spectrum after pump pulses with a pump energy of 0.07 nJ. The spectra are measured from the drop port.

The output at the thru port and drop port, as labeled in Fig. 1(a), correspond to the transmission and reflectance response of the Fabry–Perot resonator. In this device, the resonant wavelengths of the rings are designed to be almost equal to the Fabry–Perot mode, so that a high-quality-factor Fabry–Perot mode can be achieved due to high reflection from both of the rings [shown in Fig. 1(b)]. The spectrum of the drop port is shown in Fig. 1(d). The loaded quality factor of individual rings is ~1000. The sharp drop at the center of the spectrum represents the realization of the Fabry–Perot resonance with a loaded quality factor of 60,000. Dynamic tuning of the coupling of the Fabry–Perot resonator to the drop waveguide can be realized by shifting the resonant wavelength of ring A (which is equivalent to lowering the reflection of one of the mirrors in this Fabry–Perot cavity). In doing so, for example, if the resonant wavelength of ring A undergoes a blueshift as shown in Fig. 1(c), the reflection of ring A at the Fabry–Perot resonance drops and therefore the outcoupling from the Fabry–Perot cavity to the drop port increases.

To realize this, we use the free-carrier plasma dispersion effect [19] to produce an ultrafast change of the refractive index of the ring resonator [20]. The free carriers are generated by illuminating the top of the ring with a femtosecond pulsed laser centered at a wavelength of 415 nm and with a repetition rate of 76 MHz. At this pump wavelength the laser is strongly absorbed by the silicon layer and free electron–hole pairs are generated in a time scale approximately equal to the pulse duration of the pump (~1.5 ps), which is much smaller than the photon lifetime of the cavity (~100 ps). The generated electron–hole pairs produce a blueshift of the resonance of ring A and a slight loss increase of ring A. Thereafter, the free carriers are subjected to dynamic recombination processes on a time scale of ~700 ps [5].

We plot in Fig. 1(e) the spectrum following the pump pulse incidence on the ring A. (The method of measuring the transmission spectra after the pump pulse excitations has been explained in [12].) The pump energy is 0.07 nJ. We observe that the quality factor of the Fabry–Perot mode drops to 17,000 from the initial quality factor of 60,000 within approximately ~1.5 ps, indicating that the coupling between the Fabry–Perot cavity and the drop waveguide has been tuned within this interval. The adiabatic nature of such tuning, due to the large free spectral range of ~12 nm of this cavity system, has been discussed in [5]. The adiabatic manipulation should retain the coherence of the light [10,14].

This dynamic tuning of the quality factor of the Fabry–Perot mode produces high-intensity short optical pulses as the energy stored in the cavity is expelled. We observe this effect using a fast detector connected to a sampling oscilloscope. The recorded waveform of the output power measured through the drop port is shown in Fig. 2. The CW input is tuned to the Fabry–Perot resonance of 1559.450 nm before pump pulses arrive. Following the pump pulse, one can see that a short pulse is generated with a pulse duration of ~25 ps. The power at the drop port after the generated pulse does not immediately drop to the low level. This is due to the free-carrier injection—the Fabry–Perot resonance not only undergoes an increase in bandwidth but also a slight blueshift in its resonant wavelength [observed by comparing spectra

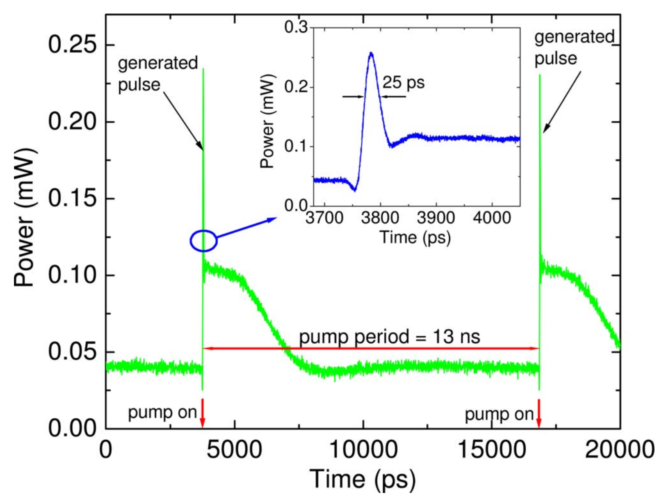

Fig. 2. (Color online) Short pulse generation during dynamic tuning of the device. The output power is measured from the drop port when the pump energy is 0.07 nJ.

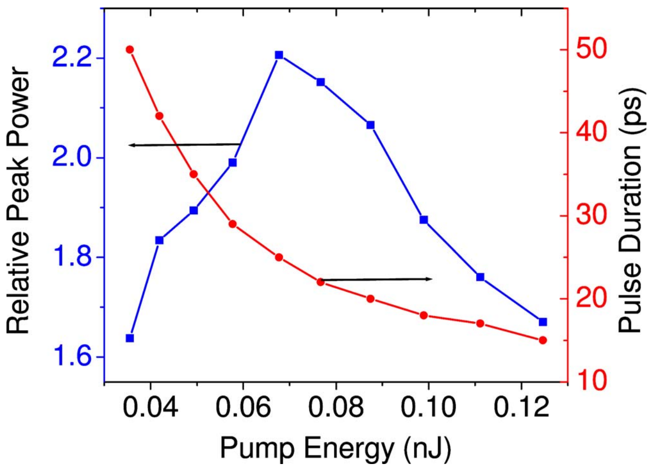

Fig. 3. (Color online) Relative peak power and pulse duration of the generated optical pulses as a function of pump energy.

in Figs. 1(d) and 1(e)]. After the free carriers produced by the pump pulses recombine, the Fabry–Perot resonant wavelength returns to its initial value and the input light couples into the Fabry–Perot resonance again. As the second pump pulse arrives, a second pulse is generated. Therefore, the generated pulse period is the same as that of the pump pulses, which in our experimental setup is 13 ns. (This time is long enough to build up the cavity energy after the first pulse is generated.) From the output power waveforms for different pump energies, we extract the pulse duration and the relative peak power, defined as the ratio between the peak power of the generated pulses to the maximum power of the drop port without pump (at a wavelength off resonance of the Fabry–Perot mode) as a function of pump energy. The measurement results are shown in Fig. 3. The pulse duration decreases with the pump energy, since increased blue shift of ring A corresponds to an increase in the outcoupling. The generated peak power reaches a maximum of 2.2 at a pump energy of 0.07 nJ and decreases with further increase of the pump energy. This decrease is due to the free-carrier-induced loss [19].

In conclusion, we experimentally demonstrate the generation of high-intensity short optical pulses as a result of the dynamic control of a silicon optical microcavity from a CW input light. Similar effects using a pulsed input have also been observed in [5,13,14], but here we present a simpler technique for pulse generation. The measured relative peak power in our work can reach 2.2; however, it can be greatly enhanced using ultrahigh-quality-factor microcavities, such as photonic crystal cavities [3] and microtoroid cavities [2]. Recent works on silicon electro-optic modulators have demonstrated that electrical injection and/or extraction of carriers can alter the refractive index of silicon with ultrafast time responses ($\sim$10 ps) [21,22]. This can be used to demonstrate optical pulse generators using electrical control rather than the optical pump in this paper. In silicon microcavities, free-carrier absorption causes additional loss, which limits the peak power of the generated pulses. Optical microcavities based on III-V semiconductors or nonlinear optical crystals that take advantage of the Pockels effects can be used to solve this problem. These on-chip miniature optical sources that can generate high-intensity short pulses could find numerous applications in physics, chemistry, and biology.

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