Tunable superluminal propagation on a silicon microchip

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We demonstrate tunable superluminal propagation in a silicon microphotonic device in a solid-state room-temperature device of tens of micrometers in dimension allowing easy integration with high-bandwidth room-temperature systems. We achieve tunable negative delays up to 85 ps and effective group indices tunable between −1158 and −312. © 2008 Optical Society of America

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Controlling the speed of propagation of optical pulses is an important requirement for high-performance optical information technology. In particular, superluminal propagation has been experimentally demonstrated using electromagnetically induced absorption [1], gain doublet in specific material systems [2–6], coherent population oscillations [7], and bulk photonic components [8]. However, these techniques suffer fundamentally from low bandwidth [1–5,7] and/or are constrained severely in temperature and operating wavelengths, making their integration on-chip challenging [1–8].

To demonstrate fast light on a microphotonic platform, we designed and fabricated a photonic structure formed by two interacting optical resonators, where an induced absorption line is created in a broader transmission spectrum. In atomic physics, coherent interaction between optical fields and electronic energy states has been used to create sharp electromagnetically induced absorption (EIA) lines and fast light [9]. Earlier works have suggested sharp induced absorption lines in the spectra of coupled macroscale optical cavities [10]. Here, by designing an optical device with a sharp absorption feature in a broader transmission spectrum we demonstrate fast light in a microphotonic platform. The top view microscope image of the device is shown in Fig. 1. The present optical device works similar to a Fabry–Perot (FP) cavity but with two salient distinctions: (a) the mirrors forming the FP cavity are frequency sensitive, which as we show later leads to the tunability of fast light, and (b) the reflection from the mirrors is routed into a second waveguide, which allows for the formation of a super mode. In Fig. 2, the resonators A and B can be understood as frequency selective mirrors. Light is confined in the waveguide region between the mirrors similar to an FP cavity, as shown by the mode profile. However, the device is designed such that the light rerouted to Port A is coherently interfering with the light leaking out of the supermode cavity, producing a sharp absorptionlike feature [9] [Figure 3(a)]. The bandwidth of this absorption feature is determined by the bandwidth of the cavity formed by the two reflectors. Moreover, the loaded bandwidth of the spectral feature, and therefore the bandwidth in which the pulse advancement occurs, can be controlled externally by tuning the reflectivity of the resonators.

We fabricated the device on a silicon on insulator platform. The waveguides forming the ring and the straight sections have a width of 560 nm and a height of 250 nm. The rings have a radius of 7 μm. A small difference (8 nm) in the perimeter of one of the rings is used to produce a wavelength detuning between the rings. The center-to-center distance of the rings is 22 μm. The waveguides and rings are patterned on silicon using electron-beam lithography followed by reactive ion plasma etching. The resulting

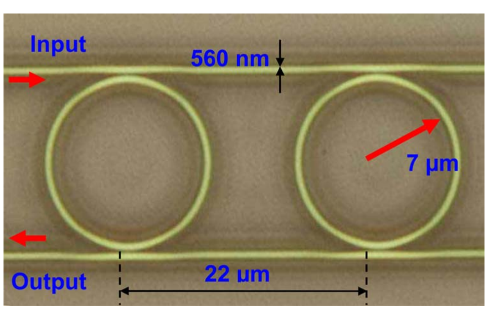

Fig. 1. (Color online) Top-view microscope image of the device.

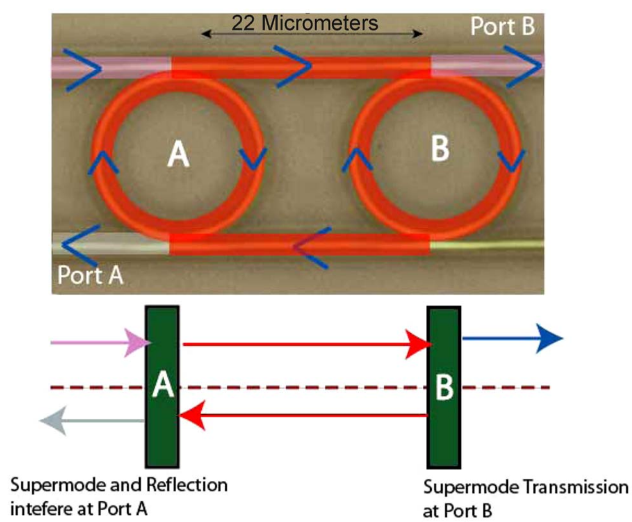

Fig. 2. (Color online) Formation of an induced absorption-like spectral feature line at Port A.

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structure is clad by a 3 μm thick SiO_2 layer deposited by plasma-enhanced chemical vapor deposition.

We measured a pulse advance of 85 ps at the output port at the absorptionlike spectral range [see Fig. 3(b)]. The experimental setup to measure the optical advance is shown in Fig. 4. A continuous wave light from a tunable laser source modulated at rf frequency (500 MHz) is coupled into the device. We estimate the relative group delay by comparing the probe and the output in the time domain. The time advance of the optical signal can be tuned by tuning the absorptionlike spectral feature. The bandwidth can be tuned by shifting the resonance condition of one or both of the resonators. This may be accomplished through either thermal [11] or electrical [12] mechanisms. In this demonstration, we thermally tune one of the rings using an argon laser. Using an optical fiber, green argon laser light (514.5 nm) in the milliwatt power range is incident on one of the rings. As silicon absorbs the incident power, the temperature of the ring is locally modified to produce a redshift in the resonance through a thermo-optic effect. As the incident argon laser intensity is increased, the absorption super-mode quality factor is modified. As shown in Fig. 5(a), the bandwidth of the fast light spectral feature is modified as the power of the incident laser is increased. The measured optical pulse advance is shown in Fig. 5(b), where the pulse advance is tuned from 85 to 23 ps, corresponding to an effective group index range of −1158 to −312. Note that the maximum pulse advance is limited only by the maximum Q of the cavities, which in turn is limited by the fabrication process [13]. We measured a fractional advancement of 4.25%. Since we used a harmonically modulated signal to measure the negative delay, the measured advance here could in principle also be interpreted as a fractional delay of 95.75%. However, such a high fractional delay is ruled out, since the delay through a static resonating device is limited strongly by the bandwidth-delay product [11,14]. Note that the one pass time delay through half the circumference of the ring A is ~0.32 ps (with a waveguide group index ~4.5).

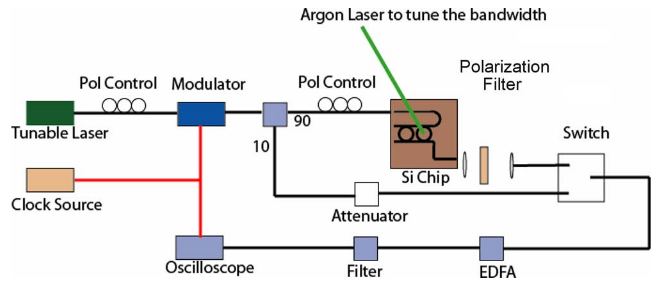

Fig. 4. (Color online) Experimental setup. The black lines represent optical fiber. Lines connecting modulator rf input and oscilloscope trigger input represent coaxial cables. A high speed electro-optic modulator generates a sinusoidal probe beam of 500 MHz. Light is coupled to the device and compared with a reference arm to determine the delay or advance. An argon laser beam at 514.5 nm is used to thermally tune the structure to vary the bandwidth of the induced absorption feature.

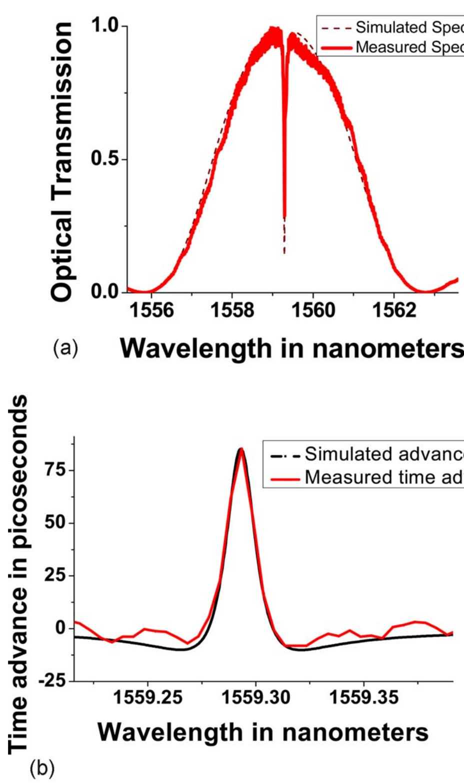

Fig. 3. (Color online) (a) All optical analog to EIA. An optical analog to EIA is created when light from the super mode formed between the reflectors coherently cancels the light coupled into port A (in Fig. 2). The sharpness of the spectral feature is controlled by the bandwidth of the super mode, which is limited only by the intrinsic quality factor in silicon. (b) Optical advance through the device measured at the induced absorption spectral feature.

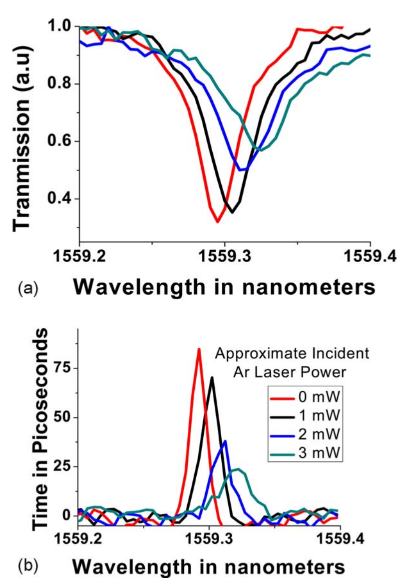

Fig. 5. (Color online) Measured tunable optical advance through the device. The reflectivity of the mirrors is frequency sensitive and can be controlled by the tuning of one or both of the reflectors. The tunable bandwidth of the spectral feature is shown in (a). The measured tunable optical pulse advance is shown in (b). The tuning of the reflectors was done here using a 514.5 nm argon laser incident on the device.

Hence, the measured peak pulse advance is 257 times larger than the one pass travel time through the ring from the input to the output waveguide.

In contrast to the traditional methods, the nominal operating temperature for the above technique can span hundreds of Kelvin, corresponding to hundreds of nanometers tuning range of the nominal operating wavelength. The nominal operating temperature can be designed to be between a few Kelvin to ~700 K, limited only by the thermally generated free carrier concentration. The nominal operating wavelength can be chosen to be anywhere in the 1300–5500 nm region of transparency in silicon. The operating bandwidth and the maximum pulse advance can be chosen by controlling the quality factor of the optical cavity, which can be designed with quality factors between 10^2 and 10^6 by controlling the losses arising from the bending radius, scattering losses, and surface conditions [13]. We also note that even though the fractional advancement of the pulses is comparable to earlier methods owing to the bandwidth-delay limit [14], the operating bandwidth is fundamentally higher than earlier methods, which are constrained by the material electronic energy states [1–5].

In conclusion, we have shown tunable superluminal propagation on a silicon substrate using coherent interaction between optical microcavities. We demonstrated generation of 85 ps time advanced signals. We also showed that the negative group index can be tuned between −1158 and −312. In contrast to earlier approaches [1–9] the proposed technique does not require gain media or specific energy levels and works at room temperature in an integrated silicon microscale device. The ability to advance optical pulses in a solid-state highly scalable silicon microscale system could open up a wide array of control techniques for high-performance micro-optical information technology [6].

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