

# Direct measurement of tunable optical delays on chip analogue to electromagnetically induced transparency

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**Abstract:** Direct time-domain measurement of tunable optical delay in a silicon resonating structure is presented. The structure is composed by a double-ring resonator, whose spectrum has a narrow transparency peak with low group velocity analogous to that in electromagnetically induced transparency. Effective group indices from 90 to 290 are obtained by tuning the resonator thermally. The measurements agree well with the theoretical analysis.

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OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators.

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Optical integration on chip has shown great progress in recent years with various optical devices being demonstrated on silicon [1-11], however, a high performance optical buffer on chip, a necessary component for optical information processing remains to be demonstrated. In order to buffer optical information on chip, where the device dimensions are required to be small, the speed of light has to be significantly reduced. Slowing of light in silicon waveguides induced by stimulated Raman scattering effect has been demonstrated using strong pump pulses [12]. Delays using on-chip components that are passive (i.e., where no pump source is needed) were recently measured in photonic crystals [13,14]. In these structures, however, the transmission decreases with the delay due to the intrinsic band structure of the crystal. Here in contrast, we show optical delays in a passive integrated structure where the fundamental tradeoff between the transmission and the delay is not present. This integrated structure is based on our recent demonstration [15] of an on-chip analogue to the electromagnetically induced transparency (EIT) systems [16,17] based on coherent interference between coupled resonators [18-27]. We measure effective group indices ranging from 90 to 290 using by thermally tuning such structure.

Figure 1(a) shows a top-view microscopy image of the device fabricated on the silicon-on-insulator (SOI) platform. It consists of a pair of silicon ring resonators with diameter of 10  $\mu\text{m}$  coupled to a pair of parallel silicon strip waveguides. Both the waveguide coupled to the rings and the one forming the rings have a width of 450 nm and a height of 250 nm. The center-to-center (CTC) distance between the straight waveguide and the rings is 610 nm, and the CTC distance between the rings is 15.69  $\mu\text{m}$ . A small difference in perimeter ( $\sim 8$  nm) is introduced to slightly detune the two ring resonances. The waveguides and rings are defined on silicon using electron-beam lithography followed by reactive ion plasma etching. The resulting structure is covered by a 3- $\mu\text{m}$ -thick  $\text{SiO}_2$  upper-cladding deposited by plasma-enhanced chemical vapor deposition, yielding silicon waveguides and rings surrounded on all sides by oxide.

The structure presents a high-Q resonant mode when the low-Q resonances of both ring resonators couple coherently. The black line in Fig. 1(b) shows the normalized transmission spectrum for the quasi-TM mode (dominant electric field perpendicular to the substrate) of the

double-ring resonator measured with a tunable laser. The spectrum shows a narrow transmission peak inside a broader dip, similar to the transmission spectrum of an EIT system. When both ring resonators are out of resonance, light passes through the waveguide without coupling to the ring resonators, and the transmission is high. When light is coupled into one of the ring resonators, the resonator acts like a mirror reflecting the light from one waveguide into the other waveguide. The transmission thus shows a dip with full-width-half-maximum (FWHM) of 4.4 nm. When light is coupled into both ring resonators, the two rings form a Fabry-Perot (FP)-like cavity with light traveling in the waveguides between the two rings following the direction of the arrows in Fig. 1(a). The transmission spectrum of the device shows a peak at the resonant wavelength of the FP-like mode ( $\lambda_{FP}$ ), as the characteristic of a FP cavity. The FWHM of the peak is  $\sim 0.13$  nm, corresponding to a quality-factor of  $Q = 11,900$ . This FWHM would support a bit-rate on the order of 16 Gbps [28]. Note that the double-ring resonator is still a traveling wave cavity with no back reflection into the input waveguide at any wavelength, which is in contrast to ordinary FP cavities.

Like in an EIT system, the narrow transmission peak in Fig. 1(b) is associated with a large optical delay. At the high-Q resonant wavelength of the FP mode  $\lambda_{FP}$ , light is trapped between the two ring resonators before being transmitted through the device, therefore experiences a large delay. This delay is determined by the reflectivity of the two ring resonators at  $\lambda_{FP}$ . The closer  $\lambda_{FP}$  is to the resonant wavelength of the two ring resonators  $\lambda_{R1}$  and  $\lambda_{R2}$ , the higher the reflectivity of the rings, and the higher the optical delay in the device. In an ideal device, where the cavity is lossless, theoretical model [15,23] show that the optical delay approaches infinite with the peak transmission equals 1 when  $\lambda_{FP} = \lambda_{R1} = \lambda_{R2}$ , since the FP cavity is completely isolated from the input and output waveguide, and light can be stored in the cavity forever. In the fabricated device, the maximal time light can be delayed is limited by the scattering loss in the waveguide.

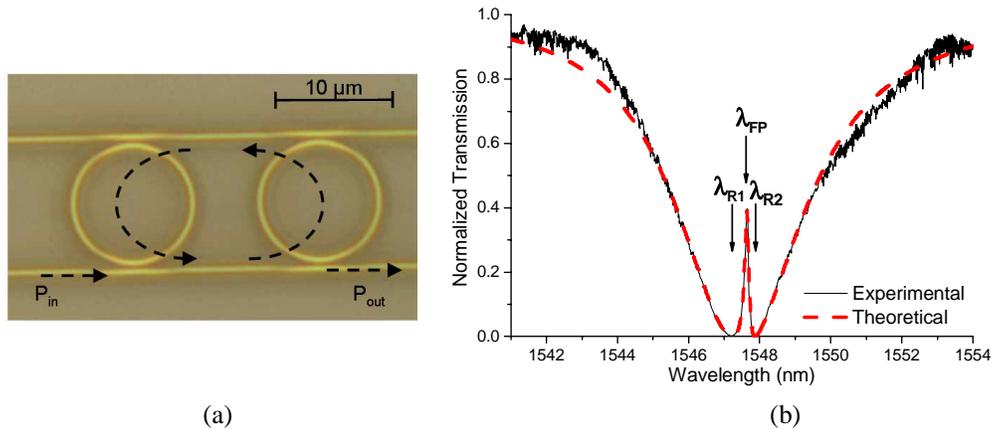


Fig. 1. (a) top-view microscopy image of the fabricated double-ring resonator. (b) normalized quasi-TM mode transmission spectrum of a double-ring resonator.

The measured transmission spectrum in Fig. 1(b) can be fitted well with theoretical model [15,23] when the scattering loss in the waveguides is considered. The dashed curve in Fig. 1(b) shows the calculated transmission spectrum when the power coupling coefficient between the waveguide and the rings is 15%, the detuning between the two ring resonances is  $\Delta\lambda_r = \lambda_{R2} - \lambda_{R1} = 0.65$  nm, the detuning between the FP mode and the center of the two ring resonances  $\Delta\lambda_{FP} = \lambda_{FP} - (\lambda_{R1} + \lambda_{R2})/2 = 0.1$  nm, and the propagation loss in the curved waveguide forming the ring is 8.0 dB/cm.

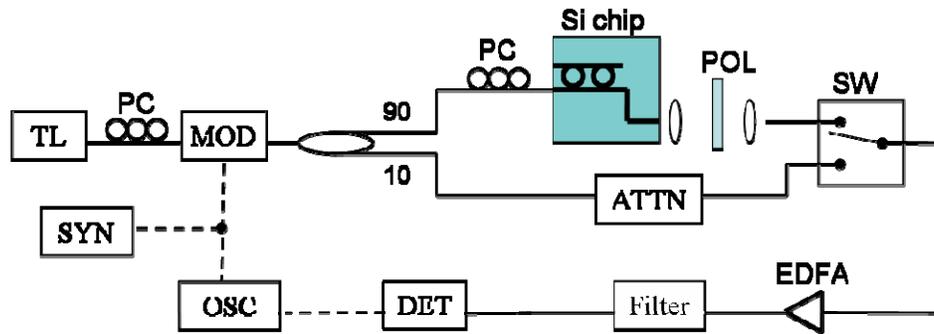


Fig. 2. Experimental setup. TL: tunable laser; MOD: optical amplitude modulator; PC: polarization controller; POL: polarizer; ATTN: attenuator; SW: fiber optical switch; EDFA: Erbium doped fiber amplifier; DET: optical detector; OSC: sampling oscilloscope; SYN: synthesizer. The thick solid lines represent optical fibers and waveguides, and the dashed lines represent coaxial RF connections.

The experimental setup to measure the optical delay in the device is shown in Fig. 2. CW light from a tunable laser is modulated by a 2 GHz sinusoidal signal. 10% of the modulated light is tapped off with a fiber coupler to be used as a reference for the delay measurement. The other 90% of light is sent into the silicon waveguide coupled to the double ring resonator. The output of the waveguide is collected into fiber with a lens and a collimator. An optical switch is used to send either the light from the device branch or the reference branch into the detection system, where light is amplified by an Erbium doped fiber amplifier, and the sinusoidal waveforms are recorded with a sampling oscilloscope. At each wavelength, the relative optical delay of the device is measured by comparing the phase of the sinusoidal waveforms from the device branch and the reference branch.

The measured delay spectrum is shown in Fig. 3 (black squares). At the center of the FP-like mode, the optical delay increases significantly due to multiple passes in the cavity, and the peak delay is measured to be 17.9 ps. Considering that the length of the device in the transmission direction is  $\sim 26 \mu\text{m}$ , this delay corresponds to an effective group index of 207, which is on the same of magnitude as that measured in the slow-light regime of photonic crystal waveguide [14]. The total length of the waveguides forming the resonator is  $94.2 \mu\text{m}$ , with a group index of  $\sim 4.4$ . The measured peak delay is 13 times the one-pass delay in these waveguides. The uncertainty of the delay measurement is estimated from multiple measurements to be  $\sim 0.5$  ps, except at the wavelengths where the transmission of the device is close to zero. The measured group delay spectrum shows some ripples outside of the ring resonances. These ripples are caused by the weak FP cavity formed by the reflections at the edges of the chip. The solid line in Fig. 3 shows the theoretical group delay calculated using the same parameters as used to fit the transmission spectrum in Fig. 1(b). One can see that the simulation agrees well with the experimental results. Note that the waveguide coupled to the double-ring resonator has a group velocity dispersion of  $0.11 \text{ ps}/(\text{nm}\cdot\text{cm})$  (obtained from simulation with a full-vectorial finite-difference mode solver) and a total length of 7 mm. The dispersion of the waveguide introduces a slight tilt in the measured delay spectrum ( $\sim 0.2$  ps across the span in Fig. 3). This effect has been taken into account in the calculation.

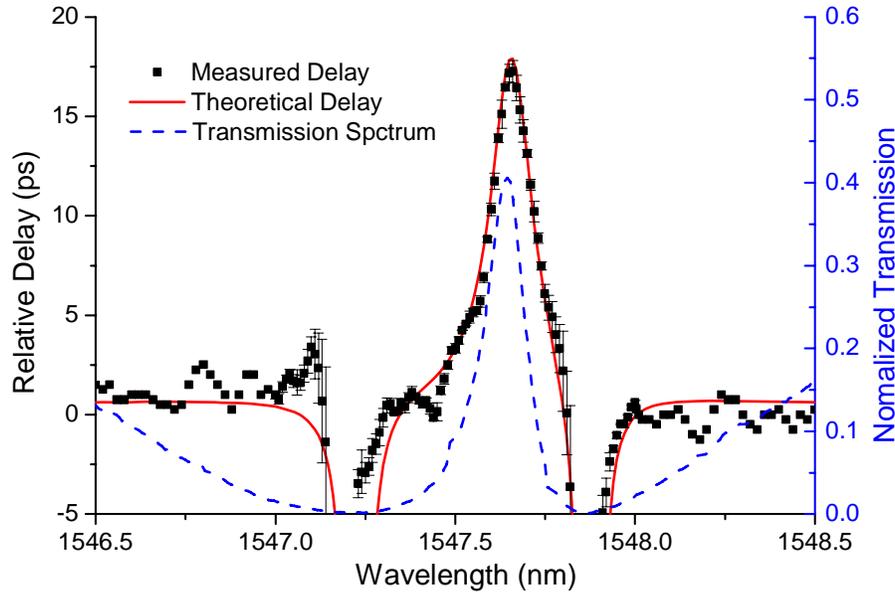


Fig. 3. Relative optical delay of the device. The red solid line shows the theoretical delay spectrum. The black squares show the measured delays. Multiple measurements are made between the wavelength of 1547 nm and 1548 nm, from which the error bars are obtained. The blue dashed line shows the measured transmission spectrum, which is associated with the right y-axis.

The peak delay is highly dependent on the detuning between the two ring resonators. In order to show variable delays, we tune the resonance of each resonator thermally. Green laser with optical power on the order of mW from an Argon laser is coupled into an optical fiber and is incident on one of the ring resonators from out-of-plane. The pump laser is absorbed by silicon and creates a local temperature increase so that the ring resonator on which the pump laser is incident has a higher temperature than the other one. Temperature increase induces an increase of the refractive index of silicon [29] and a red-shift of the resonance of the ring resonators. By changing the position and power of the pumping laser, the detuning between the two rings  $\Delta\lambda_R$  can be controlled. If the pump laser is aimed at ring 1,  $\lambda_{R1}$  increases more than  $\lambda_{R2}$ , therefore  $\Delta\lambda_R$  reduces, which induces a narrowing of the FP mode and an increase in the optical delay. This is shown as the green triangles and blue diamonds in Fig. 4, where the measured peak optical delay is increased from 17.9 ps to 25.0 ps, corresponding to an increase of effective group index from 207 to 290. As the optical delay increases, the height of the transmission peak reduces, because, as light spends more time in the cavity, more power is lost from scattering in the resonators. Note that the heating affects not only the ring but also the straight waveguide connecting the rings; however we verify experimentally that its effect is negligible on the transmission spectrum and the delay. If the pump laser is aimed at ring 2,  $\lambda_{R2}$  increases more than  $\lambda_{R1}$ , therefore  $\Delta\lambda_R$  increases, and the peak delay decreases, as shown by the red hollow triangles and purple circles in Fig. 4. The peak effective group index reduces from 207 to 90. From the green triangles and blue diamonds in Fig. 4(a), one can also observe that the transmission peak becomes more non-symmetrical as  $\Delta\lambda_R$  decreases. This is because the detuning of the FP mode  $\Delta\lambda_{FP} = 0.1$  nm has negligible change when the resonances are tuned. Therefore the relative detuning of the FP mode  $\Delta\lambda_{FP} / \Delta\lambda_R$  becomes more significant as  $\Delta\lambda_R$  decreases, which causes not only the asymmetry, but also a further drop of height of the transmission peak.

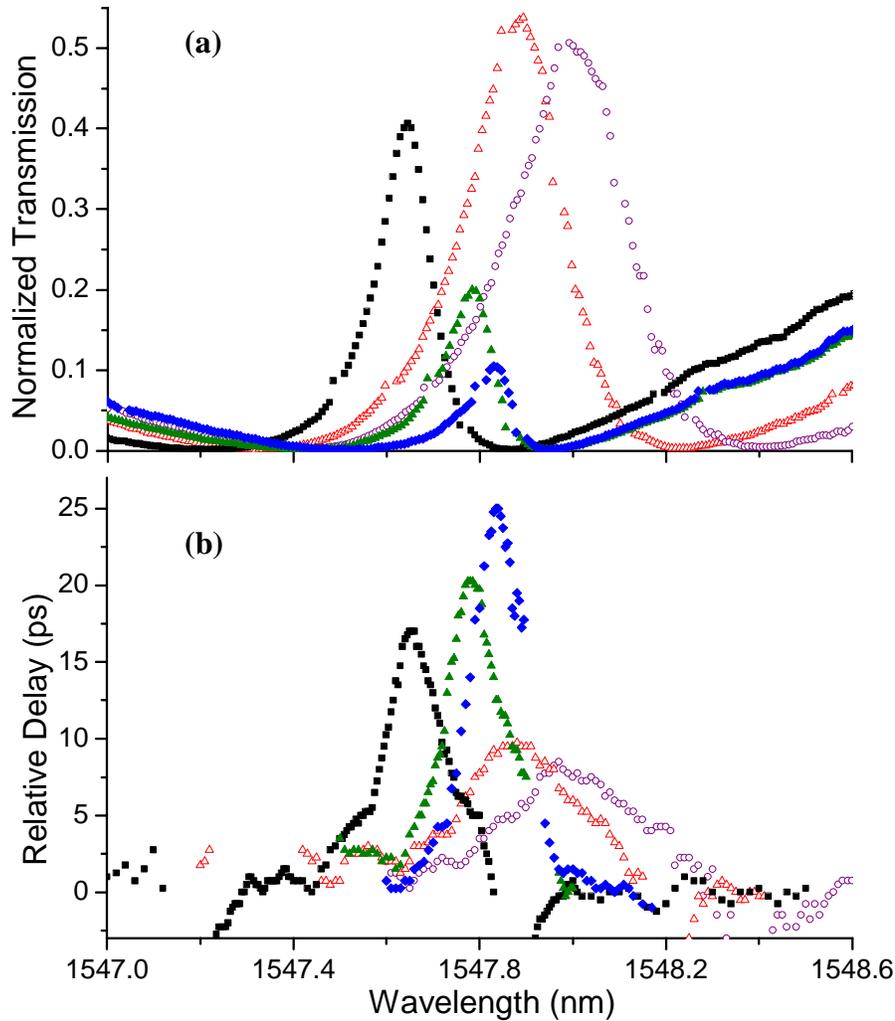


Fig. 4. Thermal tuning of the transmission and optical delay of the double-ring resonator. (a): normalized power transmission spectrum; (b): relative delay spectrum. Black squares: neither ring is heated; green triangles and blue diamonds: ring 1 is heated; red hollow triangles and purple circles: ring 2 is heated. The delay measurements close to the transmission minimum is unreliable, therefore is not shown in the figure.

In conclusion, we have shown experimentally tunable optical delay in an on-chip resonating structure. The delay is experimentally limited only by the scattering losses due to side-wall roughness of the waveguide and the detuning of the FP resonance from the center of the two ring resonance ( $\Delta\lambda_{FP} \neq 0$ ). Suppose the loss of the strip waveguide can be decreased 8 dB/cm to 0.8 dB/cm [30], simulations show that a 200-ps optical delay (corresponding to a group index of 2300) can be achieved with less than 3 dB attenuation using the double-ring resonator with  $\Delta\lambda_{FP} = 0$ .

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