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Widely Tunable Slow-light Delay Line Using Parametric-amplification Assisted Silicon Microring Resonator

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Abstract *We propose a widely tunable slow-light delay element based on silicon microring resonator assisted by parametric amplification. This scheme provides flexible adjustment of the delay time and bandwidth to adapt to different data rates.*

Introduction

On-chip slow-light delay line based on silicon-on-insulator (SOI) platform is an important candidate technology for future integrated telecommunication and computer systems due to its small footprint, and compatibility with the IC manufacturing. Several SOI based slow light mechanisms have been investigated experimentally and numerically, including microring resonator [1][2], photonic band gap structures [3] and Stimulated Raman Scattering (SRS) induced slow light [4][5]. Microring resonator based on-chip slow-light devices show advantages in relatively simple structure and large delay compared to other slow-light mechanisms. Another merit of microring resonator is its enhanced nonlinear effect due to the increased intra-resonator intensity and effective path length [6].in InP and GaAs / GaAlAs based microring resonator [7].

Telecommunication applications require that the slow-light elements have large delay-tuning range with variable bandwidth adapted to different data rates while achieving maximum delay. Most of the previous methods realized tunable delay by tuning the resonance spectrum using electro-optic or thermo-optic methods, which increase the manufacturing complexity. Recently, a method to achieve tunable delay based on SRS in microring resonator was proposed [5], however, the operating wavelength is not within telecommunication window.

Here we propose an SOI wire waveguide based microring resonator assisted by the parametric amplification. We find that even a weak round-trip parametric gain is sufficient to compensate the round-trip loss so that the transmission spectrum can be continuously tuned from a deep notch to unit gain, thus the effective bandwidth and the delay can be adjusted according to the data rate of the signal. In addition, we quantify the system performance of the return-to-zero (RZ) signals passing through the slow-light element using a new figure of merit (FOM).

Theory and model

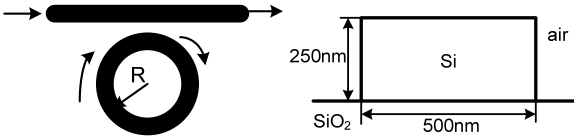

Fig. 1 single side coupled microring resonator and its vertical structure

In our study, we consider a single side coupled SOI-wire based microring resonator with a width of 500 nm and a height of 250 nm (Fig. 1). This waveguide supports a TE mode and the effective mode area is estimated to be 0.12μm^2. The effective index is about 2.54 at 1550 nm and the corresponding group index is 4.024. We assume that free carrier absorption effect is negligible by employing certain techniques such as applying an external electric field or introducing non-radiative centers [8]. A signal and a pump with optical frequencies ω_s and ω_p at the two resonant frequencies of the resonator are launched into the bus waveguide, another wave denoted as idler would be generated at the frequency $\omega_i = 2\omega_p - \omega_s$, which is also at the resonant frequency. The transfer function of a ring resonator can be written as [6]:

$$T(\omega)=\frac{t-a\exp(i\phi)}{1-t\exp(i\phi)} \tag{1}$$

where $t=\sqrt{1-r^2}$ is the transmission coefficient; *a* contains the per-turn loss, parametric gain and two photon absorption (TPA) induced loss, *Φ* contains both the linear and the amplification-induced nonlinear phase shifts. The typical TPA coefficient and nonlinear index of refraction are about 7×10^{-14} cm^2/W and 0.45 cm/GW. As the pump intensity is much larger than the signal intensity, there is only SPM, TPA effect and linear loss for the pump while the signal experiences additional parametric amplification and XPM induced by the pump.

Design of the widely tunable slow-light element

To design such a tunable slow-light element, some important characteristics of the resonator should be taken into account, including the delay tuning range, the largest achievable bandwidth and the pump power required to tune the gain spectrum from a deep notch to unit gain. These characteristics are determined by the combination of the resonator parameters such as the coupling coefficient r, the circumference length L, and the linear loss of the resonator. As the largest achievable bandwidth is mainly determined by the coupling coefficient r and the circumference length L, we first fix the coupling coefficient r to be 0.35 and the circumference length L to be 130 um in order to obtain a relatively large bandwidth. Therefore the signal and the pump wavelengths are located at two resonances of 1530.7 nm and 1576.8 nm, respectively. We plot the pump power coupled in the ring versus the input pump power by varying the linear loss (Fig. 2). We find that resonator with smaller linear loss has larger intracavity pump power at the same input pump power, which facilitates the generation of parametric gain however limits the maximum delay. We choose the linear loss to be 6/cm in the following simulations. Both the resonant wavelengths of the pump and the signal are red shifted due to the SPM effect and the XPM effect, respectively, which are shown in Fig. 3(a). Fig. 3(b) depicts the typical signal spectrum when the intracavity power is 6 W, 11 W and 18.68 W, respectively.

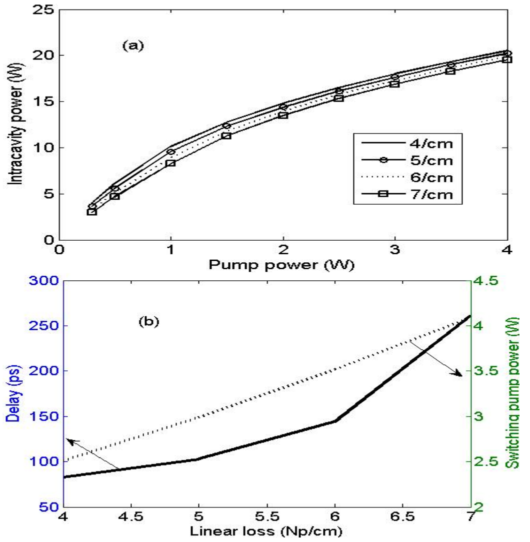

Fig. 2 (a) Intracavity power vs. input pump power when the linear loss is 4/cm, 5/cm, 6/cm and 7/cm. (b) Maximum delay and switching pump power vs. linear loss.

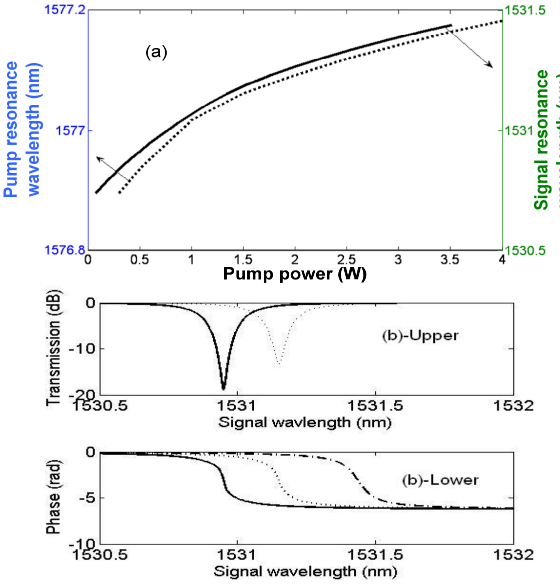

Fig. 3 (a) pump and signal resonance wavelength vs. the input pump power. (b) Signal spectrum when the intracavity power is 6W (solid), 11W (dashed) and 18.68W (dot-dashed).

One can obtain the delay of the slow-light element by deriving the phase-frequency curve. The 3-dB bandwidth of the transmission spectrum is much wider than the delay bandwidth. Therefore, we use the 3-dB bandwidth of the delay-frequency curve to find out the optimum data rate so that the output signal does not suffer much distortion.

We plot the maximum delay, the bandwidth and their product versus the input pump power in Fig. 4. We find an increase in the delay when the pump power is low, due to the fact that TPA exceeds parametric gain when the pump power is low and vice versa when the pump power is high. Fig. 4 shows that the the largest delay reaches a maximum of ~150ps when the pump power is ~0.6 W. Further increasing the pump power leads to a saturation of the delay to ~50 ps. The trends of the bandwidth and the delay-bandwidth product variation are opposite to that of the maximum delay. The delay can be tuned from 53 ps with a bandwidth of ~15 GHz to about 150 ps with a bandwidth of ~2 GHz.

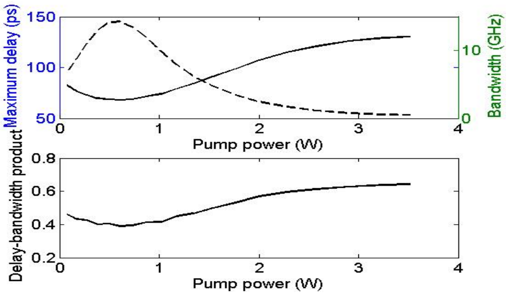

Fig. 4-Upper: Maximum delay and bandwidth vs. the pump power; 4-Lower: delay-bandwidth product vs.pump power.

System performance of the slow-light element

As the parametric-amplification assisted microring resonator is a dispersive medium, the output signal is distorted, including broadening caused by the group velocity dispersion, and asymmetric oscillation caused by the third order dispersion. Here we use a FOM defined as the average difference between the normalized output RZ pulse and the input RZ pulse to quantify the distortion induced by the slow-light element. Fig. 5 plots this FOM and the delay time for different data rates when the intracavity power is 6 W, 11 W and 18.68 W, respectively. The RZ pulses are 33% duty-cycle Gaussian shape with a length of 2^7-1 pseudo random bit sequence (PRBS) as used in [9]. From these curves, one can choose the suitable operating condition (pump power) to satisfy different delay and signal-quality requirements. For comparison, we also show the relation between the largest accommodated data rate and the delay as well as the corresponding FOM by detuning the resonance spectrum. The advantage of the parametric-amplification assisted tunable slow-light resonator over the detuning method is evident in terms of tuning range and delay time with low distortion especially at high data rate.

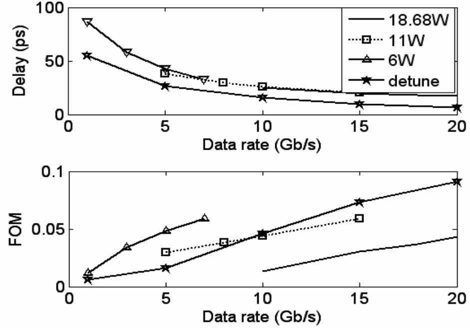

Fig. 5 Delay (upper) and distortion FOM (lower) vs. data rate, and comparison with the method of shifting the signal wavelength.

Conclusions

We have investigated parametric amplification in microring resonator and proposed an optically tunable slow-light element based on this mechanism. Simulations show that large delay ranging from ~18 ps to ~90 ps for data rates from 20 Gb/s to 1 Gb/s with low signal distortion can be achieved.

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