Tunable wideband optical delay line based on balanced coupled resonator structures

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An optical tunable delay line based on a side-coupled integrated spaced sequence of resonator (SCISSOR) structure in which pairs of resonances are tuned in opposite directions around the signal frequency is proposed and analyzed. It is shown that this balanced SCISSOR design mitigates the deleterious effects of group delay dispersion and provides both wide bandwidth and continuously tunable long delays without distortion. © 2009 Optical Society of America

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Tunable optical delay lines have important applications in the areas of optical communications, data processing, and microwave photonics [1–3]. A number of different approaches to optical delay have been implemented using such media as atomic vapors [4], optical fibers amplifiers [5,6], and others; however, on-chip all optical delay lines using photonic crystals [7] and coupled resonators [8–10] are potentially most suitable for practical applications owing to their compact size and ability to be integrated with electronics. The ability to obtain a large tunable delay is typically based on the existence of a sharp resonance, whether this resonance is of intrinsic atomic nature or is artificially imposed by the design of a photonic structure. Unfortunately, strong resonances are also inherently very dispersive, i.e., they are characterized by a strong group delay dispersion (GDD) [11,12]. For optical buffers in digital systems the GDD is manifested as a signal distortion and an increased intersymbol interference that limits the buffer capacity, while in the delay lines used in phased array systems, the GDD is manifested in the spatial domain as an angular broadening of the RF beam emitted by the antenna ("squinting"). Different methods have been proposed to reduce the GDD [13]; however, these methods also greatly increase the complexity. In this Letter we propose what we believe to be a new method to compensate for the GDD of coupled resonators and thus attain tunable optical delay lines characterized by a wide bandwidth, a long tunable delay, and a low distortion. These attributes are required for "true-time-delay" optical delay lines for use in broadband phased array systems.

Delay lines based on coupled resonators exist in two basic designs: coupled resonator optical waveguides (CROWs) [14] and side-coupled integrated spaced sequence of resonators (SCISSORs) [15]. While CROW delay lines have been implemented [10], much longer delays have been achieved using SCISSOR structures [9], primarily because the inevitable spread of resonator parameters in fabricated CROW devices causes a localization and a significant reduction in performance [16,17]. SCISSOR structures are not so strongly affected by fabrication variations and, in fact, these effects can be compensated. The phase shift in a SCISSOR structure [Fig. 1(a)] with N rings can be written as

$$\tan\left(\frac{\Phi}{N}\right)=\frac{\kappa^2\sin(\omega-\omega_r)\tau}{(1+\rho^2)\cos(\omega-\omega_r)\tau-2\rho}, \quad (1)$$

where τ is a round trip time, $\omega_r=2m\pi\tau^{-1}$ is the resonance angular frequency, κ is the coupling coefficient, and $\rho=\sqrt{1-\kappa^2}$. The group (or time) delay in a SCISSOR structure can then be written as

$$T_d(\omega)=\frac{\partial\Phi(\omega)}{\partial\omega}=T_{d0}-N\beta_3(\omega-\omega_r)^2+N\beta_5(\omega-\omega_r)^4+\cdots, \quad (2)$$

where $T_{d0}=N\tau(1+\rho)/(1-\rho)$ is the on-resonance delay, while $\beta_3=\tau^3\rho(1+\rho)/(1-\rho)^3$ and $\beta_5=\tau^5\rho(1+\rho)(1+10\rho+\rho^2)/12(1-\rho)^5$ are the terms for the higher-order GDD per ring. In Fig. 2 curve (a), the spectrum of group delay (GD) per ring $T_{d1}(\omega)$ is shown for the rings with $\tau=0.22$ ps (achieved with 30 μm circumference Si on SiO_2 resonators in [9]) and $\kappa=0.25$. To ascertain the negative impact of the GDD, consider a signal with bandwidth B shown schematically in Fig. 2; the GDD $\delta T_d(B)\sim N\beta_3B^2$ for this signal cannot exceed B^{-1}, which as shown in [12] leads to a rather simple condition for the delay–bandwidth product (DBP) $T_{d0}B\le N^{2/3}/3$, meaning that to attain a mod-

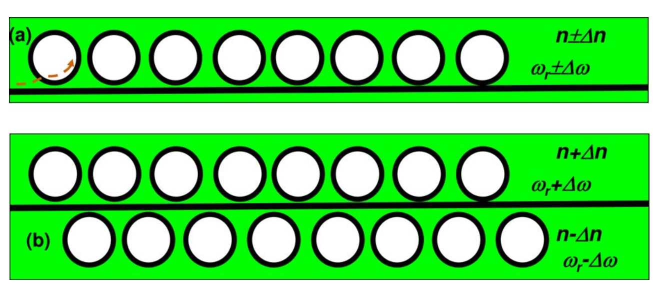

Fig. 1. (Color online) (a) SCISSOR tunable delay line. (b) Balanced SCISSOR tunable delay line.

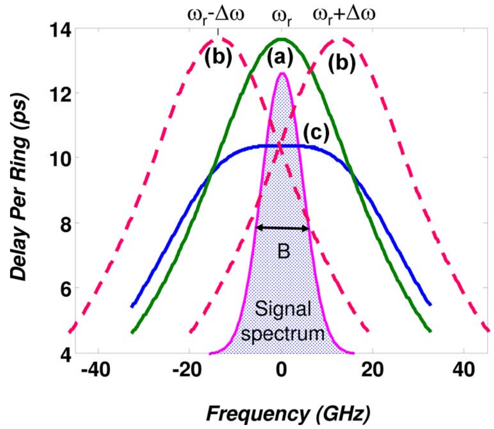

Fig. 2. (Color online) GD per ring spectra for (a) SCISSOR delay line, (b) up and down shifted SCISSOR delay lines, and (c) balanced SCISSOR delay line. Also shown is a digital optical signal power spectrum.

est "fixed" DBP of 10, at least 100 resonators are required.

"Tunable" delay, as required by many applications, is obtained from a SCISSOR structure by varying the resonant frequency ω_r. Shifting the resonant frequency up or down [Fig. 2 curve (b)] by the amount of $\Delta\omega \sim (\Delta n/n)\omega$, where Δn is the change in the rings' effective index, causes a change in the delay time $\Delta T_{d0}=NT_{d1}(\omega\pm\Delta\omega)-NT_{d1}(\omega\pm\Delta\omega)=N\beta_3\Delta\omega^2$. Unfortunately, with an off-resonance position of the signal, the GDD becomes a linear function of the bandwidth, $\delta T_d(B)=2N\beta_3\Delta\omega B$, and a restriction on the attainable tunable DBP $\Delta T_{d0}B \le \Delta\omega/2B \sim (\Delta n/n)(\omega/2B)$ is found. This indicates that, for 10 GHz bandwidth and about 0.01% change in the effective refractive index, a tunable DBP larger than unity cannot be achieved, which makes the delay line unfit for a phased array system with a large number of elements. Alternatively, an attempt could be made to tune coupling coefficient κ to vary delay; however, this approach is far more difficult to implement.

A way to achieve the tunability and at the same time to expand the bandwidth of a SCISSOR structure is now described. This is achieved by taking advantage of the fact that the third- and the fifth-order dispersions in Eq. (2) have opposite signs. In the structure shown in Fig. 1(b), one half of rings have their resonant frequencies shifted up by a small amount $\Delta\omega$ relative to the central signal frequency ω_0, while the resonance frequencies of the other half are shifted down by the same amount, i.e., $\omega_{1,2}=\omega_r\pm\Delta\omega$. This structure is named the "balanced SCISSOR." In Fig. 1(b) the up- and the down-shifted rings are located on opposite sides of the same bus because this is potentially the simplest way to implement the shift using the thermal- or the carrier-induced index change $\pm\Delta n$ on the two sides of the central bus.

In Fig. 2 in addition to the already mentioned shifted spectra $T_{d1}(\omega\pm\Delta\omega)$ for the "upper" and the "lower" rings drawn by dashed curve (b), the resulting combined mean delay $\bar{T}_{d1}=T_{d1}(\omega+\Delta\omega)/2+T_{d1}(\omega-\Delta\omega)/2$ is shown by curve (c), which is significantly flattened over the bandwidth of the signal B. The detuning $\Delta\nu=(2\pi)^{-1}\Delta\omega$ in Fig. 2 curve (c) was chosen to be 13 GHz.

To provide an analytical estimate of the device performance, an expression for the GD in the balanced SCISSOR is developed using the power series approach

$$T_d(\omega)=T_{d0}-N\Delta\omega^2[\beta_3-\beta_5\Delta\omega^2]-N[\beta_3-6\beta_5\Delta\omega^2]\times(\omega-\omega_r)^2+N[\beta_5-15\beta_7\Delta\omega^2](\omega-\omega_r)^4+\cdots. \quad (3)$$

The term quadratic in $\omega-\omega_r$ vanishes for a detuning $\Delta\omega_0=(\beta_3/6\beta_5)^{1/2}\approx(1-\rho)/\sqrt{6}\tau$, which for resonators considered in our numerical example amounts to $\Delta\nu_0=10$ GHz. Using this design essentially eliminates third-order dispersion with only a slight penalty of about 15% reduction in the total delay. What is more exciting, however, is the fact that by changing $\Delta\omega$ a tunable delay can be achieved. Differentiating Eq. (3) with respect to detuning $\Delta\omega$,

$$\left.\frac{\mathrm{d}T_d}{\mathrm{d}\Delta\omega}\right|_{\Delta\omega_0}=-\frac{4}{3}N\beta_3\Delta\omega_0=-\frac{4}{3\sqrt{6}}T_d\frac{\rho\tau}{1-\rho}, \quad (4)$$

and then

$$\Delta T_d=-\frac{2}{3\sqrt{3}}\frac{\rho\omega\tau}{1-\rho}\frac{\Delta n}{n}T_d. \quad (5)$$

For rings with $\tau=0.22$ ps and $\kappa=0.25$, $\Delta T_d/T_d\sim 3\times10^3\Delta n/n$ is obtained. Therefore, changing the refractive index by 0.01% can change the delay by more than 10%. To test these analytical results, numerical analysis of the balanced SCISSOR was performed with the aforementioned parameters and the detuning of the two sets of resonators varied from 11.5 to 17 GHz. The results shown in Fig. 3(a) indicate that a tunable delay of about 2 ps per ring can be achieved as the overall shape of the GD spectra changes.

At larger detuning a slight "camelback" shaped response is obtained. The flattened spectrum obtained at smaller detuning is suitable for a digital signal with its single lobe spectrum. For RF photonics, a typical signal has a RF carrier of frequency ν_{RF} modulated with RF bandwidth B_{RF}, which has a typical double sideband spectrum [shown in Fig. 3(a)], and for such a signal a slight camelback shaped spectrum of the GD may actually be optimal.

The value of the maximum GD per ring as a function of the index change (for an effective index of about 2.2) is shown in Fig. 3(b), and these results are consistent with the rough estimate obtained before—a reasonably, small (less than 10^{-3}) index change can accomplish a fairly large fractional change in the delay time. Therefore, it appears that the main restriction on the delay is not the limited ability to change the index but still the GDD.

Figure 4 shows the results from numerical modeling of the propagation of a RF signal through the balanced SCISSOR tunable delay line of Fig. 1(b) with $N=50$ rings. The RF signal is a 100 ps long burst of

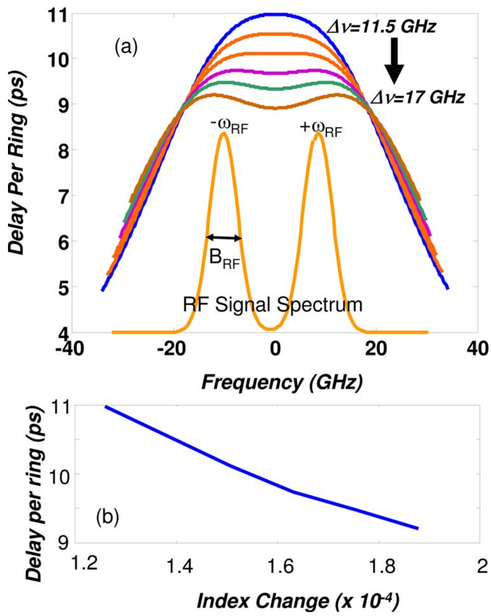

Fig. 3. (Color online) (a) GD spectra of balanced SCISSOR delay line for different values of detuning $\Delta\nu$. (b) Delay per ring as a function of index change.

the RF carrier with a frequency of $\nu_{RF}=8.8$ GHz; its spectrum is shown in Fig. 3(a). This signal is used to modulate the intensity of a 200 THz optical carrier, which then passes through the optical delay line and is detected at the other end using an ac-coupled photodetector, from which the delayed RF signal emerges. These results show that, with a modest change in the refractive index, low distortion tunable delays of about 100 ps (from 450 to 550 ps) can be

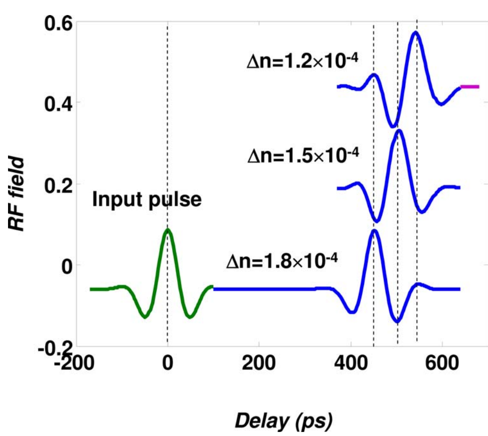

Fig. 4. (Color online) Tunable delay of RF pulses using balanced SCISSOR with 50 rings.

achieved, corresponding to more than 2π phase shift for the 8.8 GHz RF carrier. Since the total optical bandwidth B of the double sideband modulated signal is about 25 GHz, the tunable DBP is equal to a respectable value of 2.5. Low distortion indicates that even longer tunable delays can be obtained with a larger number of rings. In the end, the optical loss will be the ultimate limitation. Using the data from [8] (2.9 dB/cm) and the fact that the ratio of the tunable to the fixed delay in Fig. 3(b) is $\Delta T_d/T_d \sim 0.18$, we estimate the loss per 100 ps of the tunable delay to be about 22.5 dB, which is similar to the one actually observed in [8] with 56 rings. Therefore, the increased tunable delay will follow when the fabrication techniques improve. In conclusion, we have proposed a tunable optical delay line, the balanced SCISSOR, in which long tunable delays of wide bandwidth analog and digital signals can be achieved with small variations in the effective refraction index and these delays are not compromised by the signal distortion.

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