2 bit Continuously Tunable Slow Wave Delay Line at 2.5 Gbit/s

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Abstract: A continuously tunable time delay from zero to 800ps has been experimentally achieved on a 2.5Gbit/s signal with a Slow Wave Delay Line realized with coupled ring resonators is Silicon Oxinitride technology. The overall insertion loss is 8 dB and the footprint is less than 2.9 mm^2.

Summary

In this contribution we report both the spectral and time domain characterization of tunable slow wave delay lines (SWDL) realized with directly-coupled ring-resonators in SiON (Silicon Oxinitride) technology. We claim that the presented experimental results represent the state of the art of tunable delay in optical domain. A continuously tunable delay from zero to 800ps has been achieved on a 2.5 Gbit/s NRZ signal, corresponding to a fractional delay of 2 bit.

The architecture of the delay line is shown in Fig. 1. It comprises two ring-based cascaded structures coupled to the same bus.

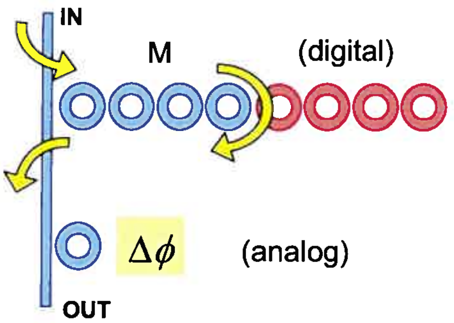

Fig. 1: Scheme of a continuously tunable delay line including a 'digital' or discrete tunable section and an 'analog' or continuously tunable delay.

The input signal enters the first structure and propagates along the ring chain until an out-of-resonance ring is found. At this point the light is reflected and propagates backward to the bus where it arrives from with a delay T_d=2M/πB, where B is the bandwidth of the structure and M is the number of rings tuned at resonance. The folded layout allows an easy and complete reconfiguration of the delay line as well as a reduction of the overall dimensions. This chain induces a 'digital' or discrete delay with a resolution equal to the time delay induced by the single ring (2/πB). The second structure is simply a ring phase shifter that induces a continuously variable delay ('analog') depending on the detuning between the signal and its resonant frequency. The two cascaded structures can therefore induce a continuously variable delay from zero to the maximum value.

Fig. 2 is a photograph of the initial section of an integrated realized SWDL.

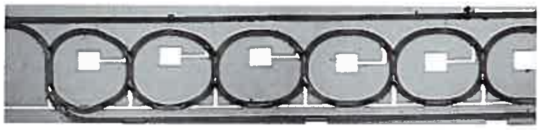

Fig. 2: Photograph of the first rings of a slow wave delay line realized with directly coupled ring resonators. The diameter of the rings is approximately 1.24 mm, corresponding to a FSR=50GHz.

The input waveguide is on the top left and the output port on the bottom right of the photograph. The different shape of the first rings is because of the apodization of the coupling coefficients of the directional couplers, in order to achieve a flat intensity spectral response as well as a ripple free group delay characteristic. All the rings have the same nominal resonance. An heater is placed on each ring to control the resonant frequency and the electric pads are clearly visible the middle of the rings. The delay line can be reconfigured at the typical velocity of a thermocontroller, that is well below 1 ms, simply by changing the voltage applied to the heater.

A 2.2 by 2.2μm square waveguide in SiON with 4.4% index contrast has been employed to realize the devices. These waveguides can be easily coupled with small core optical fibers with an insertion loss of 0.2dB per facet. The present waveguide attenuation is 0.35dB/cm but an attenuation of 0.15dB/cm has been recently achieved at 1550nm. The 4.4% index contrast guarantees a minimum bending radius of 300 μm with negligible radiation losses, corresponding to ring resonators with a FSR of 100 GHz. This is a limitation only to the minimum achievable footprint and does not limit neither the group delay per ring (equal to 2/πB) nor the insertion loss per ring (equal to IL_r=cα/πBn_g, being n_g the group index of the waveguide).

Fig. 3 shows both the intensity and delay spectral responses of a SWDL with FSR=50 GHz, useful bandwidth of 2.5 GHz and finesse 16 (slowing ratio S=10). Continuous lines refer to experimental measurements whereas dashed lines are the simulated responses of the nominal structure.

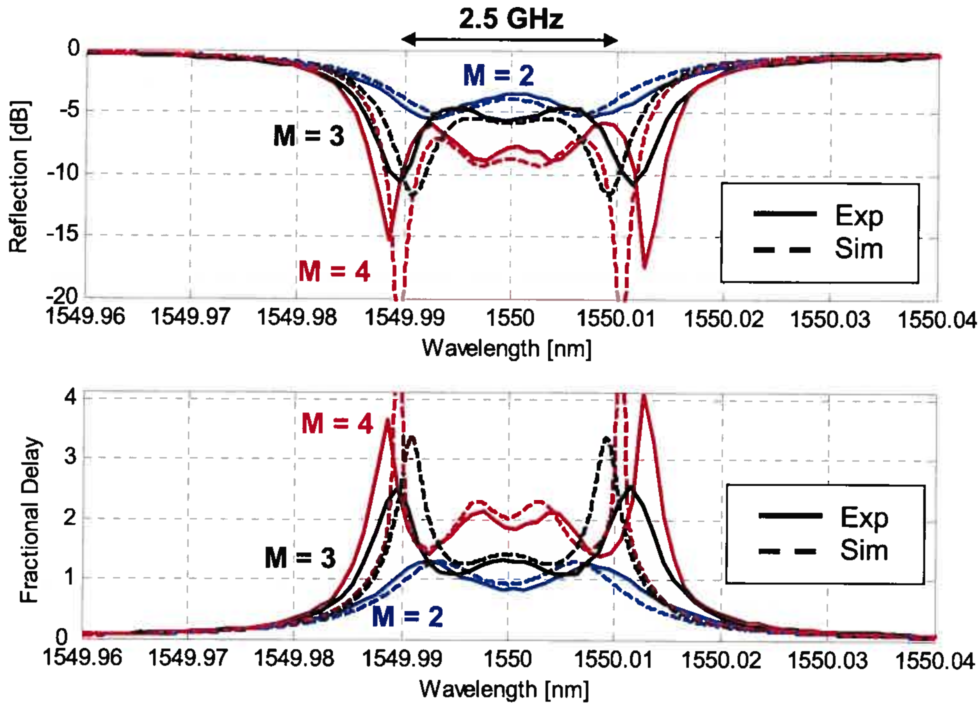

Fig. 3: Spectral intensity and group delay characteristic of a SWDL with M=2, 3, 4 tuned rings. The delay is normalized to 2.5Gbit/s NRZ pulse width.

The agreement is excellent, apart the peaks at the edges of the passing bands that are very critical with respect to the coupling coefficients and to the detuning. These, however, do not impact on the pulse shape because are outside the used band. The group delay is normalized to the NRZ 2.5Gbit/s pulse width. Our folded SWDL with four rings in resonance induces a delay equal to 2 bit lengths (800 ps) with an insertion loss lower than 8 dB, one of the best experimental results to author knowledge [1], [2], [3]. As figure of merit, the usually used group delay to insertion loss ratio results to be 100 ps/dB, achieved in a structure with a footprint of 2.9 mm^2, that is 276 ps/mm^2.

Note that the theoretical limit on the insertion loss per unit delay is $IL/T_d = c\alpha/n_g$=7dB/ns, not very far from the measured result (10dB/ns).

In Ref. [2] Vlasov presents a fractional delay of 1.7 bit at 3 Gbit/s with negligible distortion and longer delays but with noticeable distortion. However, these delays are obtained with another ring based architecture (APF) that is not fully tunable. In Ref.[3], instead, a CROW with 12 rings is presented but the induced delay is 110ps over a bandwith of 17 GHz and the figure of merit is only 2.5 ps/dB.

By increasing the number M of tuned rings, both the delay and the insertion loss increase but the intensity spectral shape remains roughly the same obtained with four rings.

The spectral characteristic shown in Fig. 3 has been achieved by tuning the various ring separately. A Peltier was inserted below the chip and the small thermal crosstalk between the rings compensated during the reconfiguration of the structure. To investigate the impact in the time domain of the frequency misalignments we have measured the induced time delay and the pulse distortion on a 2.5 Gbit/s NRZ data stream. To this end a SWDL with FSR=50GHz and bandwidth B=6.25 GHz, that is a finesse equal to 8 (slowing ration S=5) was used.

The measured eye diagrams at the output of the SWDL are shown in Fig. 4 for a delay line with 0, 1, 2 and 3 tuned rings, respectively.

The input signal is rather sharp and can be described with a supergaussian of order 5, that is a pulse with a bandwidth much larger than the useful bandwidth of the delay line. Despite the distortion of the leading and trailing pulse edges clearly visible in Fig. 4, the eye remains well open, with a small intersymbol interference and only slightly attenuated (the scale of the pictures are identical). These distortions will almost disappear if a smoother input pulse is used, as an example by filtering the electric signal sent to the electro-optical modulator. Simulations, not shown here for brevity, are in perfect agreement with time domain measurements.

The best way to tune the various rings to the correct position is in the time domain by maximizing the eye opening rather than impose a flat intensity spectral response. In this way also the group delay characteristic is optimized and the pulse shape well preserved.

The continuous delay is achieved with a single phase shifter with a FSR of 50 GHz. By changing the signal to ring resonance detuning the delay is varied from

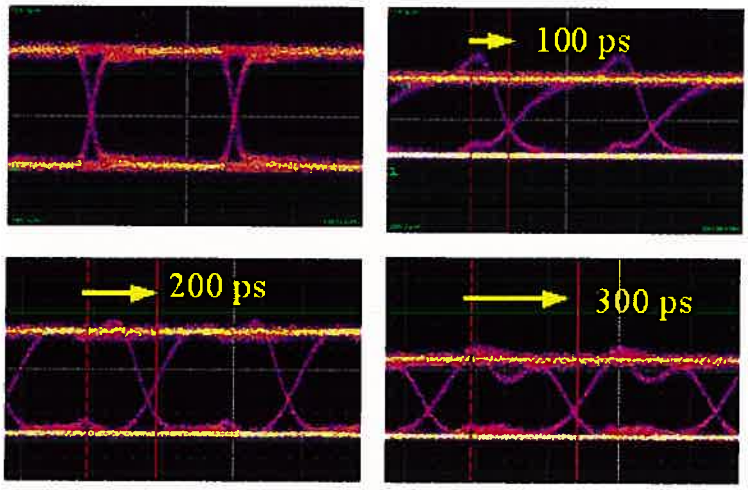

Fig. 4: 2.5Gbit/s eye pattern delayed by a SWDL with *M* rings tuned to resonance. A total delay of 300 ps is induced without significant pulse distortion.

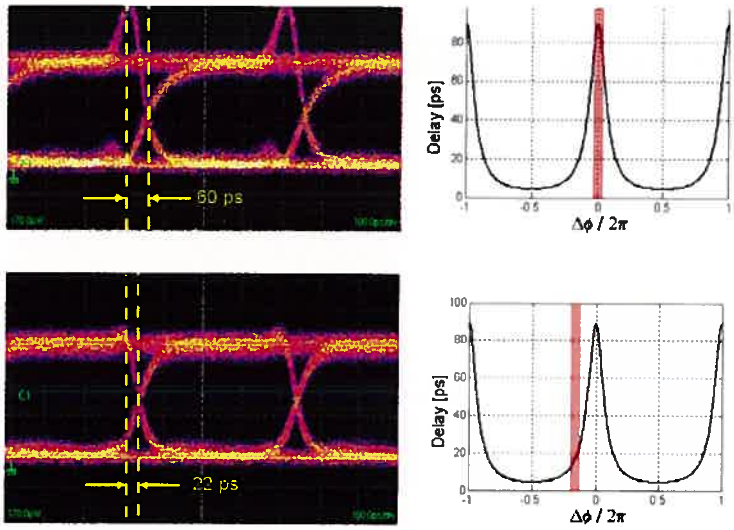

Fig. 5: 2.5Gbit/s eye pattern delayed by a single ring phase shifter tuned at resonance and detuned by 0.2 FSR.

zero to the roundtrip time delay of the ring. Fig. 5 shows a 2.5 Gbit/s pulse that undergo a delay of 60 ps, obtained close to the resonance and of 22 ps, when detuned by 0.2 FSR. The distortion of the trailing edge is evident but the eye aperture remains unaffected. Clearly this overshoot disappears with smoother pulse shapes.
In conclusion, we have shown the potentialities of a fully tunable delay line realized with large rings in glass material. Although the footprint of structures realized with such a technology is far away to be comparable with Silicon based SWDLs [2], the weak attenuation, the easy tuneability and their simplicity and flexibility appoint these structure as very promising for the implementation of reasonable delays with acceptable insertion losses.

Acknowledgments
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References

1 F. Morichetti et al., "Tunable Slow wave Optical Delay Lines", OSA Topical Meeting on Slow and Fast Light, paper MB2, July 2006.
2 F. Xia, L. Sekaric and Y. Vlasov, "Ultracompact optical buffers on a silicon chip", Nature Photonics 1, 65-71, 2006.
3 J.K. Poon, L.Z. Zhu, G.A. DeRose, A. Yariv, "Transmission and group delay of microring coupled-resonator optical waveguide", Optics Letters, 31, 4, 456,2006..4 R.G.Heideman et al, Photonic West, 2006.