Fast Thermal Switching of Wideband Optical Delay Line With No Long-Term Transient

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***Abstract*— We present results for a broad bandwidth continuously tunable optical delay line based on the balanced side-coupled integrated space sequence of resonators scheme. A tunable delay of up to 345 ps is obtained without distortion of the optical signal. Fast thermal switching speed under 10 μs is achieved without any measurable long-term transient by utilizing a novel balanced thermal tuning scheme.**

***Index Terms*— Complementary metal–oxide–semiconductor (CMOS) compatible, microresonators, optical delay lines, phased arrays, switching transients.**

I. Introduction

The goal of this research is to create a practical optical true-time-delay (TTD) device for phased array systems, providing continuously tunable optical delay for broadband optical signals (10GHz), and switching time under 10μs for fast beam steering of an electronically tuned phased array antenna [1]. Previous approaches for optical TTD include dispersive optical fibers and tunable lasers [2,3], Bragg grating prisms [4] and tunable Bragg gratings [5], but delays were too short for practical systems. CMOS compatible microresonators [6-8] offer compact solutions, modulation and filtering [9], but have relatively narrow bandwidth and high group velocity dispersion [10, 11]. Previous work by the authors has shown novel techniques [12, 13] and initial measurements [14, 15] to overcome these limitations. Melloni [16] produced hybrid digital/analog delay devices using coupled resonator optical waveguide (CROW) and photonic crystal structures, Zhuang [17] created a beam-forming network based on optical ring resonators. This letter provides new results for a practical TTD device, including our first measurements of the switching speed. A potential application is a phased array 30-40GHz radar / communications system, requiring 200ps tunable delay. At lower frequencies, e.g. X-Band, over 300ps is required.

Initial results [14] had multiple TTD devices on one chip to support polishing for testing. This work creates individual devices with etched facets to eliminate polishing and support packaging. A future goal is to integrate all photonic devices in a phased array system onto a single photonic circuit; low-noise laser, linearized modulator, TTD device, and detector, that can be fabricated in a high-volume, low-cost CMOS foundry.

Manuscript received July 29, 2011; revised November 21, 2011; accepted December 20, 2011. Date of publication December 23, 2011; date of current version March 2, 2012. This work was supported in part by a DARPA SBIR Program Highly-Integrable Microresonators with the Fast Tunable Group Delay for Broadband RF True Time Delay under Contract W31P4Q-09-C-0298.

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Digital Object Identifier 10.1109/LPT.2011.2181495

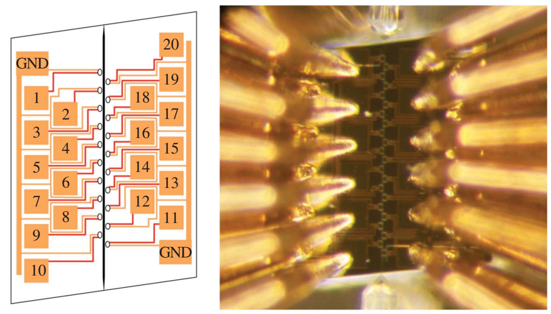

Fig. 1. Schematic and photograph of true time delay device.

II. Balanced SCISSOR Device

Devices in this letter use silicon on insulator (SOI) waveguides and microresonator structures, with waveguide dimensions of 250μm $\times$ 500μm. A schematic design of a 20 microresonator device is shown in Fig. 1, together with a photograph of a device, which includes a single waveguide $\sim$900μm long, with tapers at both ends to expand the beam and provide high efficiency coupling to a lensed fiber. Input and output ends of the device are etched at an angle of 8° to eliminate optical reflections and improve system performance. The device has 20 racetrack shaped microresonators, 10 on either side of the waveguide, with radius of 7μm and 5μm straight section providing a coupling coefficient of $\sim$0.4. Large tunable delays are best achieved using thermal tuning, since a large index change can be achieved without introducing additional loss, however, the thermal switching time can be long as it takes time to dissipate heat in the chip. Additional longer time constants occur in standard thermal tuning schemes from time constants associated with the submount, heatsink, etc. - the balanced thermal switching approach used in this work, in which overall heating to the chip does not change, eliminates all long term transients. A nichrome microheater is placed on top of each microresonator, with a similar size as the microresonator to enable fast tuning speed [18]. Carrier injection, while providing fast (ns) initial switching, causes an additional increase in optical loss while tuning, and long term thermal transients from heating of the device [19].

The device includes contact pads for each microresonator for probing (Fig. 1) and/or wirebonding to facilitate packaging.

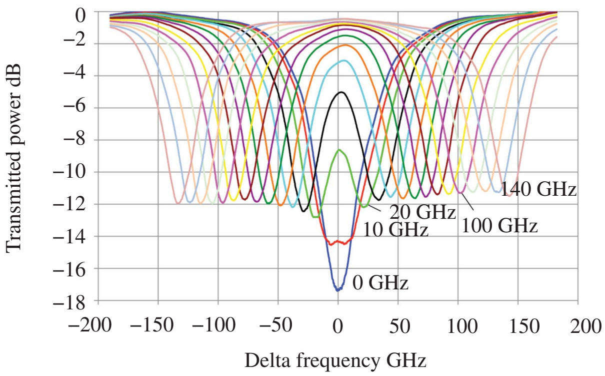

Fig. 2. Measured transmission spectra of Balanced SCISSOR versus detuning.

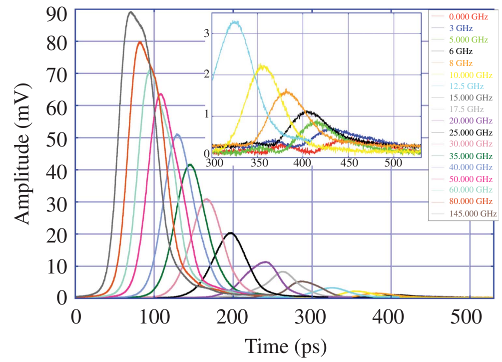

Fig. 3. Wideband optical pulse from TTD device for different detuning values from 0 to 145 GHz; inset shows zoom-in on low detuning values.

Devices with different numbers of microresonators and coupling coefficients were incorporated into a 6 silicon wafer design and fabricated at the Cornell Nanofabrication facility.

Experiments used a device with 20 tunable microresonators. The device was operated in the Balanced SCISSOR mode [12, 14]. Operation can be explained by considering the measured transmission spectra for the device, shown in Fig. 2. The 20 microresonators are split into 2 sets of 10; one set is tuned up in frequency, while the other set is tuned down by the same frequency, from a starting position where all 20 are aligned with the optical signal at 0GHz. The minimum transmission occurs when all microresonators are aligned at 0GHz (−17.2dB), providing the maximum delay through a SCISSOR structure, however, the bandwidth is smallest and distortion highest. When the sets are detuned by ±10GHz a reduced loss (reduced delay) with a broader flat response occurs, providing a larger bandwidth. The overall tuning response of the Balanced SCISSOR can be seen in Fig. 2 from the set of spectra with detuning increased in ±10GHz steps; the loss (delay) at the signal varying from a large value to a small one, with increasing bandwidth, as the detuning is increased from 0 to 140GHz. The maximum loss at 0GHz is compressed in these measurements (expect 2× loss per set, ∼24dB) due to the limited dynamic range of the OSA used.

III. Experimental Results

The device was characterized using a broadband ASE source at 1550nm passed through a polarizer to obtain TE polarized light, and coupled into the device using a lensed PM singlemode fiber. A lensed singlemode fiber was aligned to the output of the device, and connected to an optical spectrum analyzer (OSA) to measure the transmission spectra for a variety of microresonator bias voltages. The fiber-to-fiber coupling loss was ∼10dB, higher than expected, due to issues with the angled facet etch on this device run. Coupling losses as low as 1dB/facet are expected from an optimized device.

Extensive tuning characteristics of each microresonator were measured under computer control, and the zero bias wavelength and tuning slope (proportional to V^2 - for resistive heating) stored to file for use in tuning experiments.

To measure tunable delay together with the effects of 3rd order dispersion and bandwidth, key parameters for these devices, a broadband optical pulse of ∼45ps FWHM (10.5 GHz), with 1GHz repetition rate at 1553nm, was used. This wavelength allowed the 2 sets of microresonators to be initially tuned (heated) to align with the signal, and then one set reduced in frequency (heated) while the other increased in frequency (reduced heating) and the required detuning range achieved. The output of the TTD device was amplified using a semiconductor optical amplifier to show the feasibility of optical amplification using a device that could be heterogeneously integrated with the TTD device. For phased array systems, measurements of third order intercept and SFDR are often used, which would show the full effects of the TTD device on link performance, however, as the TTD device is a linear device, it is not expected to directly degrade SFDR.

Measurements of the optical pulses from the device when operated in the Balanced SCISSOR scheme, shown in Fig. 3, were taken on a 50GHz oscilloscope with a 70GHz detector. The inset shows an expanded view of pulses for small detuning frequencies, where the pulse amplitude is smallest. The two smallest detuning frequencies, 0GHz and 3GHz provide distorted pulse waveforms, due to the narrow width of the response (see Fig. 2), however, for 5GHz the pulse shape is good, indicating low distortion. When the detuning frequency is increased, the delay reduces and the pulse amplitude increases, as the loss is proportional to delay. The maximum tunable delay with low distortion (5GHz to 145GHz) is 345ps. At the largest detuning frequencies, 80 and 145GHz, the pulses show trailing shoulders, however, these are believed to be from detector saturation at these high power levels, especially as the pulses see little effect from the microresonators at these large detuning frequencies.

A plot of the delay and peak pulse amplitude versus detuning frequency is shown in Fig. 4a. The two (different color) points at lowest detuning are those with distorted output waveforms. The shape of the delay versus detuning curve can be seen, with significantly larger delay change seen at smaller detunings, saturating at higher values. Using this data, the change in attenuation versus change in delay is plotted in Fig. 4b. As expected from the Balanced SCISSOR model, a fairly linear characteristic is found, with a slope of 0.06dB/ps. Lower loss versus delay is preferable, and work is underway to reduce the loss through optimized waveguide and microresonator designs. In a phased array system the loss versus delay must be compensated by gain, electronic

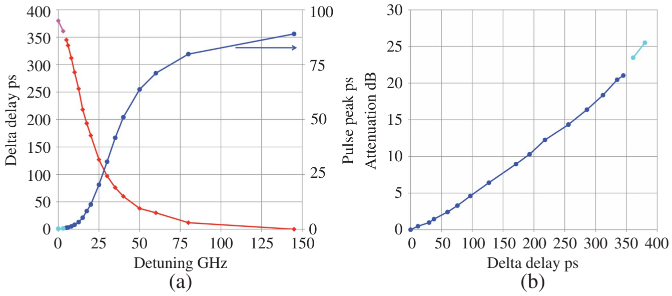

Fig. 4. (a) Plot of delay and pulse amplitude versus detuning frequency. (b) Attenuation (dB) versus delta delay.

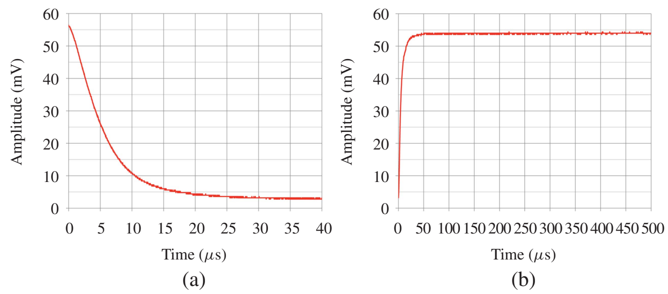

Fig. 5. Switching transients. (a) 10GHz–50GHz. (b) 50GHz–10GHz detuning.

or optical, in order to provide both controllable amplitude and delay for the beamforming process.

Tuning transient measurements were taken by switching all microresonators from the voltage settings for one detuning frequency to those for a second detuning frequency in a synchronized way, with all electrical switching transients taking place in under 1μs. The measured change in output power versus time is used to represent the change in delay versus time. Two measurements of switching transients are included in Fig. 5, for transients between 10GHz and 50GHz detuning, the first with a fast (μs) timescale to show the fast speed of switching, and the transient in the opposite direction on a longer timescale to validate that there is no long term response. Measurements taken with a much longer timescale of 1s provide the same flat, non-changing response after the initial fast transient. Long-term transients are often found in thermal tuned devices due to long thermal time constants associated with submounts, heatsinks, mechanical mounts and the electronic feedback loop to control temperature. The lack of any measurable long term transient in this device is due to the balanced thermal approach employed, in which the heating increase to one set of microresonators is exactly matched by the heating reduction in the other set, keeping the total device heating constant. Values for the switching speed taken when switching between various different sets of detunings produced switching times between 5.9μs and 7.2μs (20:80%).

IV. Conclusion

TTD devices have been developed for broad bandwidth optical time delay with continuous tuning of the delay and fast thermal switching. The Balanced SCISSOR scheme provides broad bandwidth and low distortion; the balanced thermal approach provides fast thermal switching times with no long-term switching transient. Results for a device including 20 microresonators show a maximum tunable delay of 345ps with low distortion of a 45ps (10.5GHz) optical pulse. Additionally, fast thermal switching times of 5.9μs to 7.2μs (20:80%) are found, with no measurable long-term switching transient. These devices are ideally suited for electronically scanned phased array systems supporting multiple simultaneous beams.

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