Optical time division multiplexer on silicon chip


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Abstract: In this work, we experimentally demonstrate a novel broadband optical time division multiplexer (OTDM) on a silicon chip. The fabricated devices generate 20 Gb/s and 40 Gb/s signals starting from a 5 Gb/s input signal. The proposed design has a small footprint of 1mmx1mm. The system is inherently broadband with a bandwidth of over 100nm making it suitable for high-speed optical networks on chip.

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References and links
1. Introduction

Recent innovations and breakthroughs in silicon photonics are paving the way for the realization of high speed optical interconnects fabricated on a CMOS chip. In order to realize high bandwidth links some form of multiplexing scheme will be required to meet the bandwidth requirements for both intra-chip and on-chip communications [1]. The leading multiplexing scheme is wavelength division multiplexing (WDM), where multiple wavelength channels are used to transmit information. Numerous WDM devices and systems have been demonstrated on a silicon chip as seen in just a few examples in References [2–6]. However, an inherent challenge with WDM is that the bit-rate of each wavelength channel is limited by the speed of each individual modulator. Since the modulators are likely to use on-chip electronic drivers, this channel bit-rate will likely be limited to no more than 10Gbit/s, thus requiring many precisely tuned wavelength channels to reach aggregated high data rates. In order to achieve significantly higher data rates in each channel, here we propose and demonstrate a simple scheme for time-multiplexing optical data [7–10] to high data rates from several slowly modulated paths. In the following sections, we explain the operation principle of our device and demonstrate the simple generation of 20 Gb/s and 40 Gb/s from a 5 Gb/s input using our optical time-division multiplexer. This scheme is inherently passive and enables ultra high bit rates. In addition, with the recent demonstration of large bandwidth WDM components (>60 GHz) on a Silicon chip, such as switches [11] and interleavers [12], our OTDM device can be seamlessly integrated into a WDM system.

2. Operation principle and design

Our optical time division multiplexer (OTDM) operates by splitting an input pulse-train operating at a slow rate into multiple paths, each with a different delay. These delayed signals are then recombined into one output at an effectively higher data-rate. The delay between each path inherently determines the final bit rate. Consequently, any arbitrarily high bit rate can be achieved by controlling the number of paths the input signal is split over and the delay difference between each path. A schematic of our OTDM is seen in Fig. 1. It starts with a $1:N$ splitter that splits the input signal into $N$ channels. Each of these channels is delayed by a multiple of a path-length difference $\Delta L$, or equivalent to a time of $T_{NB} = 1/(NB)$ where $B$ is the bit-rate of the input signal. The channels are then recombined into a high bit rate composite channel using an $N:1$ combiner. For example, if the data source operates at 5 Gb/s and eight paths are used, the bit-rate of the photonic link will be 40 Gb/s using our OTDM device. One limitation of our approach is that the input signal must be pulsed and the duration of the individual pulses must be significantly less than the final bit-period $T_{NB}$. However, with the demonstration of stable on-chip mode locked laser sources, pulse durations of less than a picosecond are possible enabling >100 Gb/s bit-rates [13,14].

The final bit-rate is only dictated by the relative time-delay between each path. This time delay in an SOI platform is determined by the speed of the propagating signal, which is reduced from the speed of light by the group index of the mode ($v = c/n_g$). In order to calculate the group index, we used a full vectorial 3-D mode solver to calculate the change in effective index of a waveguide with dimensions of 600 nm x 250 nm as seen in Fig. 2.
These dimensions were chosen in order to minimize the loss from the etched sidewalls while achieving high mode confinement and single mode operation at wavelength of 1550nm, as seen in the inset of Fig. 2. From the effective index, the group index \( n_g \) for different wavelengths is calculated using \( n_g = n_{\text{eff}} - \frac{\lambda \, d n_{\text{eff}}}{d \lambda} \), where \( n_{\text{eff}} \) is the effective refractive index of the mode and \( \lambda \) is the carrier wavelength, as plotted in Fig. 2. At a wavelength of \( \sim 1.55 \, \mu m \) the group index is \( n_g = 4.058 \) which corresponds to a path length difference of \( \Delta L = c \cdot \frac{T_{\text{diff}}}{n_g} \), where \( c \) is speed of light in free space. Therefore, starting from a 5 Gb/s input pulse-rate, a 20 Gb/s rate can be realized, for example, by splitting the signal into four paths with a 50 picoseconds delay difference or an equivalent length difference of \( \Delta L \sim 3.694 \, \text{mm} \). While this is a significant length the actual footprint can be considerably minimized by looping this length into a spiral. In addition, the length can be further reduced by using schemes to increase the group index as proposed elsewhere [15–18]. Lastly, we see in Fig. 2 that the group index is relatively constant and only varies by \( \Delta n_g = 0.0095 \) over a 100 nm bandwidth. This corresponds to only a 117 fs variation in the bit-period, which is negligible for all but ultra-high bit rates.

3. Fabrication

Based on the simulation results, we fabricated the proposed multiplexer on an SOI platform as shown in a scanning electron microscope (SEM) image in Fig. 3. A negative, high-resolution,
electron-beam photoresist XR-1541 was spin-coated to form a ~100 nm-thick masking layer. Next, the structure was patterned using electron-beam lithography then transferred to the silicon layer using chlorine-based inductively coupled plasma reactive ion etching. Finally, the devices were clad with ~2 um silicon dioxide. The structure shown in Fig. 3 generates 20 Gb/s rates starting from 5 Gb/s signal. We observe that the footprint of the entire device is less than 1mm² and was achieved by spiraling the individual delay elements (ΔL = 3.694 mm) into a footprint of only ~150 μm. Higher bit rates of 40 Gb/s were achieved by connecting two of the 20 Gb/s devices in parallel with a 1.846 mm path length difference between them (~25 ps delay). The propagation loss of these fabricated waveguides was measured to be ~3 dB/cm, which is low enough to achieve multiplexing of the 5 Gb/s input signals used here. Lastly, to improve the coupling to/from the chip, nanotapered couplers were used [19].

![Fig. 3. A top-view scanning electron microscopy (SEM) image for 20 Gb/s OTDM. Magnified images of the spiral with length ΔL = 3.694mm and the 1:4 Y-splitter are shown.](image)

4. Experimental results

Figure 4 shows the generation of 20 Gb/s signals using our 5 Gb/s to 20 Gb/s OTDM device. The device was tested with 200 fs pulses from a Ti:Sapphire pumped Optical Parametric Oscillator (OPO) at a wavelength of 1550 nm and a repetition rate of 76 MHz. The output was detected using a high-speed photodetector and oscilloscope (~30 GHz bandwidth). We see from this input that four clear pulses (P1, P2, P3, and P4) are produced by our OTDM with a ~50 ps separation between each of them, corresponding to a 20 Gb/s bit-rate. We also see that the pulse amplitudes decrease. We determined that the decay is exponential and, consequently, attribute it to the inherent propagation loss of the waveguides. From the path length difference and amplitude decay, we determined the propagation loss of the waveguides is ~3 dB/cm. This loss is comparable to other Si nanophotonic waveguides and could be reduced using techniques such as etchless waveguides [20]. Lastly, we note that the oscillations in the waveform are due to the inherent detector response as verified by measuring pulses directly from the laser source.
Fig. 4. Time multiplexing of four pulses using a single pulse from a Ti:Sapphire laser. The separation between each consecutive pulses is 50 ps. The inset shows the detector response for the input Ti:Sapphire pulse.

In Fig. 4 only one sequence of 20 Gb/s pulses is shown due to the low repetition rate of the input source. In order to demonstrate continuous generation of 20 Gb/s signals, we constructed a mode-locked fiber-ring laser that operates at ~5 Gb/s and is seen in Fig. 5. The laser is realized by driving an electro-optic modulator with a pulsed pattern generator operating at 9.63 GHz. A loop of single mode fibers with a 50/50 coupler is used to provide feedback and out-couple the laser pulses. An erbium doped fiber amplifier (EDFA) is used as the gain medium. The laser generates pulses of duration ~40 ps that repeat every ~200 ps. The output of the laser was then amplified using an EDFA before going to the chip. A polarization controller is used to launch a TE mode into the waveguide. Finally, the signal at the output was traced using a photodetector module in a high-speed oscilloscope. The results are seen in Fig. 6 where we observe continuous generation of 20 Gb/s pulses from a 5 Gb/s source.

Fig. 5. Experimental setup used to test the devices with fiber-ring mode locked laser schematic.

Fig. 6. Results of continuous generation of 20 Gb/s pulses from a 5 Gb/s source.
Fig. 6. a) The input stream of pulses at 5 Gb/s from a fiber-ring mode locked laser. b) 20 Gb/s TDM signal at the output of the device.

We also tested a 40 Gb/s OTDM device as seen in Fig. 7. Here, the Ti:sapphire pumped OPO was used to test the 40 Gb/s device performance since the pulse duration of the mode-locked laser could not be reduced to less than 40 ps. We see in Fig. 7 that the OTDM device produces eight pulses (P1-P8) with a separation of 25 ps between consecutive pulses. We see that these pulses are not as clear as in the 20 Gb/s case, which we attribute to the slow response of our photodetector and oscilloscope. The oscilloscope is limited to a 30 GHz bandwidth, which is significantly less than the 40 Gb/s we tried to measure here.

Fig. 7. The output signal from the 40 Gb/s device using a single pulse input from a Ti:Sapphire laser. The inset shows the detector response for the input Ti:Sapphire pulse.

5. Discussion and conclusion

In this work, we demonstrated for the first time, OTDM on a silicon ship with a very compact size ~1 mm x 1 mm and a propagation loss of ~3 dB/cm. Both 20 Gb/s and 40 Gb/s signals were generated from a 5 Gb/s source. While here we have only demonstrated rate multiplication, our OTDM device can be adapted to efficiently generate arbitrary digital signals by integrating electro-optic modulators into each of the N individual paths as seen in Fig. 8. Our approach has the distinct advantage that inherently slow modulators operating at
the same bit-rate as the input pulse train (i.e., 5 Gb/s) can be used to achieve very high overall bit-rates at a single wavelength. This is unlike a previous demonstration of a pulse rate multiplexer based on a silicon ring resonator where it would be impossible to modulate individual bit-positions without very high-speed modulators [10]. While the size of our device is large, the total path length difference at a 5 Gb/s input rate is approximately ~12 mm; with further improvements in slow light photonic structures and 3-D integration it will be possible to shrink the size of our OTDM significantly [15–18,21]. Lastly, further improvements in measurement of the pulse train and loss should allow for the generation of ultra high speed 160 Gb/s OTDM signals, which will play a key role for high-speed optical networks on chip [1].

Fig. 8. Schematic of full OTDM multiplexer with the integration of EO modulator in each channel. Each EO modulator is used to switch the pulses on/off. The modulated pulses are recombined at an effectively higher bit-rate.

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