Improvement of input power dynamic range for 20 Gbit/s optical WDM switch nodes using an integrated Michelson wavelength converter

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Total number of authors: 11

Published in:
Optical Fiber Communication. OFC 97., Conference on

Link to article, DOI:
10.1109/OFC.1997.719862

Publication date:
1997

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):

**ThD**
8:30–10:00am
Room C241

**All-Optical Switching**
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**High-speed optical logic**

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All-optical switches and logic gates have been studied for many years, primarily because of their potential for high-speed operation. High-speed operation has been demonstrated in optical AND (demultiplexing) gates. For example, researchers at NTT have demonstrated all-optical demultiplexing of 100 Gbit/s data streams using a variety of optical switching elements. Still, all-optical bit-wise logic has not been demonstrated above 40 Gbit/s. However, rapid advances in the demonstrated switching speeds of optical logic gates are expected in the near future.

All-optical logic gates take advantage of the intensity-dependent transmission or the intensity-dependent refractive index (or both) of optical waveguides. Typically, short optical pulses are used to induce these nonlinearities because they have high peak powers and dissipate relatively small amounts of heat. Therefore soliton or short pulse communication systems, (with BZ signaling formats) will benefit most from the availability of all-optical logic gates. However, the simplest (utilizing a single waveguide) optical logic gates, NOT gates based on cross-gain saturation in active semiconductor waveguides, are compatible with NRZ signaling formats as well. Another simple (single waveguide) logic gate is the all-optical AND gate based on four-wave mixing. Such gates have been used as demultiplexers, wavelength converters, and synchronizers in recent experiments.

To achieve logic operations other than AND and NOT, interferometric switches, based on the intensity-dependent refractive-index effects in waveguides are necessary. To date, most interferometric switches have been based on the nonlinear optical mirror or NOLM. Using either a fiber or an active semiconductor nonlinearity, AND, NOT, and XOR operation have been demonstrated. In addition, OR and NOR functionality have been demonstrated in an ultrafast nonlinear single-arm interferometer (UNI). With this increased functionality comes complexity. In general, interferometric switches are more complicated to fabricate than single waveguide switches, they can be difficult to stabilize, and they require three input beams, the two logical inputs and a clock beam. Also, these devices are not, in general, cascadable. Recently, Mach-Zehnder interferometer and UNI configurations have been demonstrated that are cascadable. Still, without the use of optical amplifiers and filters, the fanout for these gates is low, limited by device loss and by the accumulation of amplified spontaneous emission noise.

The ultimate speed of all-optical logic gates is limited by the recovery time of the transmission and/or index nonlinearities responsible for the switching. That recovery time can be as short as the duration of the pulses doing the switching, as in the case of fiber-based switches, or as long as the carrier temperature equilibration time (approximately 1 ps), as in the case of active semiconductor-based switches. Semiconductor-based switches are attractive because they are ultimately integrable and have large nonlinear coefficients, facilitating smaller device dimensions. However, due to the nonlinear absorption effects accompanying the nonlinear index changes, it is unlikely that nonlinear waveguide lengths, using conventional semiconductor materials, can be reduced much below a hundred microns. Therefore, optical logic gates will not compete with electronic gates in terms of density on a chip. Also, without careful design, the semiconductor-based switching devices can be limited by carrier population and thermal effects to operation speeds of a few gigahertz.

With all these difficulties and drawbacks, optical logic gates are still attractive components for many applications. Any simple (small gate count) processor, such as an address recognition circuit or an encryption circuit, can be run at ultrahigh data rates using optical logic. Optical gates can be used as ultra precise phase comparators in electro-optic phase-lock loops and synchronization circuits. Recently, optical gates have been used to generate microwave signals with high fractional bandwidth. It is clear that as the speed and reliability of optical logic gates improve, new circuits and applications will be demonstrated.

throughput and easier management, as well as wavelength reuse. Furthermore, semiconductor optical amplifiers (SOAs) are attractive for space switching in the nodes because they offer short switching times (~1 ns), compensate for loss and, very importantly, have the high on-off ratios of 40–50 dB that are required to overcome cross talk induced penalty. One disadvantage of the SOA gates is their limited input power dynamic range and, thus, limited cascadability caused by noise and gain saturation. We show that even at a high bit-rate of 20 Gbit/s the latter imperfection can be compensated by the extinction ratio enhancing capability of interferometric wavelength converters (IWCs). Consequently, the input power dynamic range for switch blocks using IWCs together with SOA gates can be improved compared to switch blocks without IWCs. This is especially important at high bit rates where the cascadability of the SOA gates decreases. Here, more than 15 dB improvement of the input power dynamic range is achieved at 20 Gbit/s using a high-speed Michelson interferometer (MI) wavelength converter after the SOA gate compared to the SOA gate alone.

The experimental setup shown in Fig. 1 is used to measure the input power dynamic range for the SOA gate and for the gate followed by an MI wavelength converter. Light at 1555 nm is externally modulated at 20 Gbit/s before coupled to a 450-µm-long SOA gate (operated at a fiber-to-fiber gain of 22 dB). Following the SOA gate an erbium-doped fiber amplifier (EDFA) in saturation boosts the signal to a power level of ~6 dBm before entering the receiver or wavelength converter. The converter is an integrated MI based on an all-active multiple quantum well structure that converts from 1555 to 1560 nm using 9 dBm of input power at 1560 nm.

In Fig. 2 the regenerating capability of the interferometric wavelength converter is illustrated by eye diagrams at: (a) the input of the SOA gate, (b) output of the SOA gate and (c) after the wavelength converter (c) for a relatively high input power of -3 dBm to the SOA gate. Due to gain saturation, the SOA gate clearly distorts the input signal leading to an extinction ratio of only 8 dB at the output compared to 12 dB at the input. However, when passing the interferometric wavelength converter

**ThD2 Fig. 1.** 20 Gbit/s experimental setup for input power dynamic range measurements of SOA gate and SOA gate followed by an integrated all-active Michelson interferometer (MI) wavelength converter.

**ThD2 Fig. 2.** 20 Gbit/s eye diagrams at: (a) the input of the SOA gate at 1555 nm, (b) output of the SOA gate at 1555 nm and after the Michelson interferometer wavelength converter at 1560 nm. The input power to the SOA gate is ~3 dBm.

**ThD2 Fig. 3.** Power penalty (@BER = 10^-9) at 20 Gbit/s as function of the input power to the SOA gate. The curve indicated by (○○○) is measured after the SOA gate while the curve given by (●●●) is measured after the SOA gate and MI wavelength converter.
Optical buffers storing single packets of optical data are important components for ultrahigh-speed multi-access time-division multiplexing (TDM) networks. Data packets must be stored while users wait for access to the network and while received packets are rate-converted to interface with slower speed electronics in the node. Optical packet storage has been demonstrated at data rates of 10 Gbit/s to the network and while received packets are rate-converted to interface with slower speed electronics in the node. With slower speed electronics in the node, optical packet storage has been demonstrated at data rates of 10 Gbit/s to the network and while received packets are rate-converted to interface with slower speed electronics in the node. However, without the converter an input power dynamic range of 12 dB is found while the input power dynamic range with the converter is increased by more than 15 dB.

Part of this work was carried out within ACTS research program No. 043 KEOPS.


**Figure 1.** Experimental setup. EDFA: erbium-doped fiber amplifier; SMF-DS: dispersion shifted fiber; PC: polarization controller.

**Figure 2.** 50-GHz digital sampling oscilloscope display of a portion of the input data packet detected by a 45-GHz bandwidth photodiode. The optical pulses are 3 ps in duration and have a center wavelength of 1553 nm.

The signal is regenerated and the extinction ratio enhanced to 10 dB. As seen in Fig. 3, this reduces the power penalty (@BER = 10^-3) from 1.8 dB after the SOA gate to about 0.4 dB after the wavelength converter. From Fig. 3, the important role of the 20-Gbit/s interferometric wavelength converter as a regenerating device in optical WDM switch nodes is obvious. Without the converter an input power dynamic range of ~12 dB is found while the input power dynamic range with the converter is increased by more than 15 dB.

**Figure 3.** Time-domain display of the output of the buffer showing single 3-ps optical pulses stored for more than 300 circulations.

In conclusion, I have demonstrated the loading and unloading of a 40-Gbit/s data packet in an active fiber loop buffer. I believe this is the highest speed loading and unloading of an optical buffer to date.