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ULTRAFAST ALL-OPTICAL DEMULTIPLEXERS FOR OTDMA NETWORKS

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In this paper we report the demonstration of all-optical self-clocked time-demultiplexing and packet routing using two demultiplexers the TOAD and the CPMZ. For the TOAD the clock and data were polarization multiplexed. The TOAD was used to demultiplexed OTDM data at 0.25 Tb/s. The required switching energy was only 800 fJ. A polarization filter was used to separate the clock signal from demultiplexed data at the output port of the TOAD. We have also demonstrated a newly developed all-optical switch called CPMZ, which is based on a nonlinear Mach-Zehnder interferometer. The CPMZ is a polarization and wavelength insensitive demultiplexer because, unlike the TOAD, it does not require any polarization or wavelength filter at the output port to separate the demultiplexed data from the clock signal.

1.Introduction

Optical time division multiplexed (OTDM) networks have been proposed [1] which have the potential to carry Tb/s aggregate throughputs on a single wavelength channel for micro- and local-area interconnect applications. In OTDM, a time period of length T is divided into a frame comprised of $N = T/\tau$ time slots, each of duration τ, where the i^{th} slot corresponds to the i^{th} transmitter address. The time frame may be defined by an optical clock with period T and pulse duration which is less than τ. If picosecond optical pulses from a modelocked laser are used to generate the clock, then the ODTM system may have up to Tb/s aggregate throughput. The maximum number of channels permitted is, in turn, determined by the repetition rate of the laser. In such ODTM networks ultrafast all-optical demultiplexers are essential.

Optical time division multiplexing (OTDM) is promising technique for utilizing the an enormous optical fiber transmission capacity, which is in the tens of terahertz. For OTDM, each user is assigned to one particular time slot i within a time frame. This assignment is permanent during transmission and reception of the information. For the reception of incoming information, it is necessary to demultiplex data from desire time slot within the time frame. Currently an increase of the capacity of the OTDM systems is strongly limited by the speed of the available opto-electronic demultiplexers. This causes the bottleneck at the receiving end. In order to overcome this bottleneck it is necessary to avoid opto-electronic devices in ultra fast OTDM systems by employing all-optical devices for the demultiplexing and also other critical processing.

In addition to the ultra fast all-optical switching performance, some other characteristics are strongly desired if real implementation such optical switching devices should take a place. Some of those are the long term stable operation with a low control pulse energy, very high contrast ratio, low crosstalk, single wavelength and polarization independent operation, and the possibility of small scale integration with other electronic components of the communication system. The previously demonstrated all-optical devices [2-11] can not fulfill most of the above requirements. However recently developed two interferometric switching devices based on Sagnac and Mach-Zehnder are promising to fulfill most of the requirements. The device based on the Sagnac is called the Terahertz Optical Asymmetric Demultiplexer (TOAD) [12, 13] and the Mach-Zehnder is Symmetric Mach-Zehnder (SMZ) [15, 16]. The TOAD demonstrated a 4 ps switching window using a 800 fJ of control pulse energy, and SMZ a 8 ps with a 11 pJ. The principle of these devices is the fast turn on and off operation possible either by the special geometrical position of the strong nonlinear optical element or by the two control pulses to do the independent switching operation.

In addition to already demonstrated Mach-Zehnder, these are two additional possible configurations, which are based on the different propagation directions for the control and data pulses inside the arms of the interferometer. One of the configurations duplicates the performance of the TOAD, but another one is very promising to fulfill all of the above requirement. Here we present the demonstration of the Mach-Zehnder all-optical switch by counter-propagating the control pulses with respect to the data pulses so called Colliding Pulse Mach-Zehnder (CPMZ). The CPMZ operation as an ultra-fast all-optical and polarization insensitive gate is described and 10 ps switching window is reported with only 650 fJ required switching energy. We also report the demonstration of all-optical time-demultiplexing using the TOAD. The TOAD was used to demultiplex three consequent data pulses with 4 ps separation. Only 800 fJ switching energy was required. Non-polarization preserving single mode optical fiber was used to carry polarization multiplexed clock and data.

2. Terahertz Optical Asymmetric Demultiplexer

The TOAD (Fig. 1) is composed of a small optical loop mirror, a nonlinear element (NLE), and intraloop 2 × 2 coupler which injects control pulses into the nonlinear element. When a train of closely spaced OTDM signal pulses enter the TOAD, each pulse splits into equal clockwise (CW) and counterclockwise (CCW) components which counter propagate around the loop and arrive at the NLE at slightly different times as determined by the offset, Dx, of the near edge of the NLE from the midpoint of the loop. The control pulse arrives at the NLE just before the CCW component of the signal pulse which is to be demultiplexed, but just after its CW counter propagating complement and induces nonlinearities in the NLE which cause the two components to experience different losses and phase shifts, and consequently recombine and exit the loop at the output port. All other OTDM signal pulses, (for which the counter propagating components do not straddle the control pulse arrival at the NLE) exit the loop at the input port.

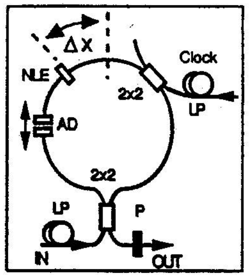

Fig. 1. Terahertz Optical Asymmetric Demultiplexer

The experimental setup demonstration of demultiplexing ability of the TOAD is shown in Fig. 2. The NLE and intraloop coupler were on the same side of the loop center. The length of optical fiber used for the loop was less than 1 m long. The NLE was a 500 μm long, DC-biased semiconductor optical amplifier (SOA), with an injection current of 35 mA. The offset Δx was set using an adjustable delay, AD, to minimize the length of the switching window. In this case the AD was composed of a small grin rod-air gap-grin rod combination, with one grin rod on a mechanical translation stage. Loop polarization controllers, LP, and an in-line analyzer, P, were used to discriminate the signal and control pulses at the TOAD output. The SOA inside of the TOAD (see Fig. 1) was set asymmetrically about the loop center with one end approximately 100 μm from the loop midpoint, and the other end approximately 400 μm from the midpoint. Channel 1 (CH 1) and channel 3 (CH 3) use an adjustable delay to position a 1 ps signal pulse in a 4 ps time slot, adjacent to the 1 ps signal pulse in channel 2 (CH 2). All three channels are set equal in intensity by a variable neutral density filters, NDF, at the CH 1 and CH 3 inputs. The 100 MHz repetition rate of the mode-locked laser determines the 10 ns duration of the ODTM frame. Loop polarizers set the clock and data into orthogonal polarization states, and a polarization combiner was then used to polarization multiplex the clock and the data onto a common transmission line. This is the self-clocking feature of the system. Any changes in the length of the transmission line are not critical, since the clock's placement within the TDM frame is not changed. Using an adjustable delay, AD1, the clock pulse was positioned in an arbitrary OTDM time slot, i (see timing diagram in Fig. 3a). As shown in Fig. 3a, maximum of 2500 channels can be accommodated by this time frame.

Before entering the demultiplexer (the TOAD), the clock and the multiplexed data pulses were first separated by a polarization beam splitter, PS. The data were injected into he TOAD input port, while the clock was directed through an adjustable delay, AD_C, and into the TOAD control port. By positioning the clock relative to the OTDM data frame using AD_C, data in a particular slot was demultiplexed and appeared at the TOAD output port. This is shown schematically in Fig. 3b-c, where slots 1 and 4 are

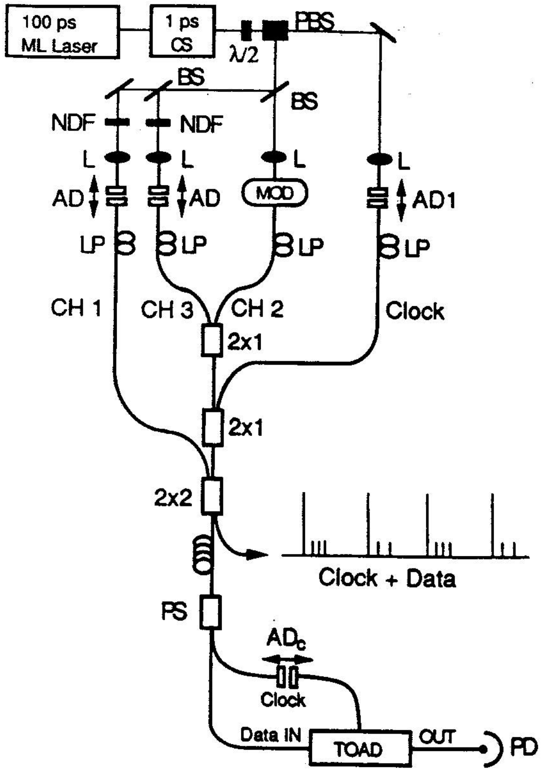

Fig. 2. Experimental setup.

selectively demultiplexed.

The ability of the TOAD to function as a ultrafast all-optical demultiplexer is shown in Fig. 4.

This result was obtained using a time resolution technique. Fig. 4. shows the TOAD output as a result of scanning a clock pulse over time slots 1, 2 and 3 to demultiplex DATA from CH1, CH2 and CH3. In this case all three channels were set to carry the same DATA "1". Fig. 3d-e are oscilloscope photographs and show the output of the TOAD when the clock pulse has been synchronized to demultiplex CH1 and CH4, respectively.

3. All-optical Address Recognition and Self-routing of Photonic Packets with Two Bit Addressing

In ultra-high speed networks individual address bits are spaced only picoseconds apart, and address recognition can be made by an ultra-fast demultiplexer which allows the packet to be routed without any opto-electronic conversion. One low-power device capable of performing the critical operation of reading address bits in an optically compressed packet header is the Terahertz Optical Asymmetric Demultiplexer (TOAD) [18].

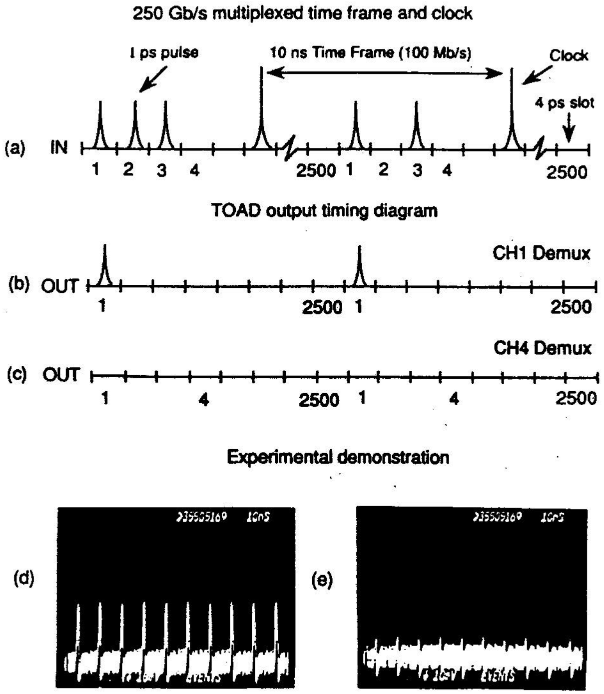

Fig. 3. 250 Gb/s OTDM timing diagram; 3a) 250 Gb/s multiplexed time frame and clock, 3b-c) demultiplexed CH1 and CH4; experimental demonstration of all-optical self-clocked demultiplexing of OTDM data at 250 Gb/s; 3d-e) demultiplexed CH1 and CH4, respectively.

To demonstrate all-optical address recognition and self-routing of photonic packets, one node of a network of 2 × 2 switches was used (see Fig. 5b). Packets, with 4 ps bit periods, were composed of a large amplitude leading clock pulse, a three bit header, and an empty payload. The switching node consists of an electro-optic switching element SW (e. g. 2 × 2 $LiNbO_3$ cross-bar switch) in a switched (cross) or unswitched (bar) state, an ultra-fast all-optical address recognition unit, routing controller which sets the state of the switching element, and an optical buffer that matches the delay of the input packed to the processing delay of the routing controller. Before entering the buffer a portion (10%) of the packed was split off and sent to the address recognition unit (two TOADs) to read two bits packed destination address. Demultiplexed address bits were sent to a routing controller which set the state of the 2 × 2 switch to a cross or bar state. Packets with destination address "11" were made to exit output port 2, while

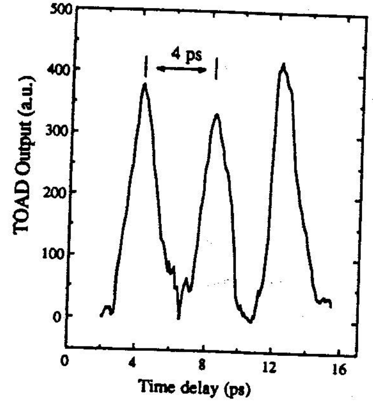

Fig. 4. Experimental demonstration of 250 Gb/s demultiplexing ability of the TOAD.

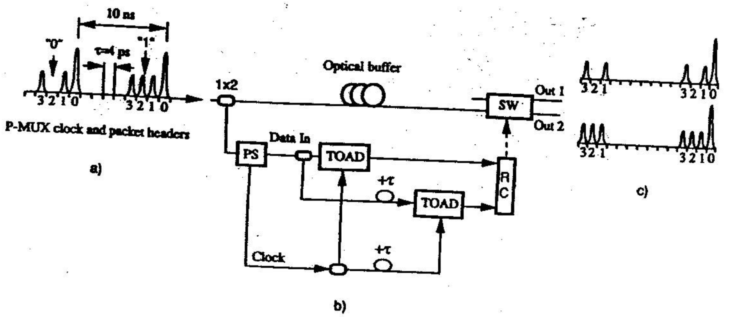

Fig. 5. Self-routing of the photonic packet. a) Node input; b) Switching node diagram; c) Node output: routed photonic packets; output 1-packets with destination address "10", output 2-packets with destination address "11".

packets with destination address "10" were made to exit output port 1. Fig. 5a shows the input multiplexed high intensity clock and two packets: "1110...0" and "1010...0".

Fig. 5c is a timing diagram of the output of the routing switch, SW, when the clock pulse has been synchronized to simultaneously demultiplex address bits 1(always "1") and 2("1" or "0"). When both address bits 1 and 2 are ("1") packets are routed to port 2. However, when bit 1 is "1" and bit 2 is "0" the packet is always routed to port 1. The experimental results are shown in Fig. 6-8.

In conclusion, these data demonstrate the all-optical processing and self-routing of a photonic packet without the need for any opto-electronic conversion for a case of two bit addressing. The address bit rate was 0.25 Tb/s (4 ps spacing between address bits). BER measurements of the set switching state were made by modulating bit 2 with a pseudorandom bit stream and monitoring the bit-error rate at the switching element. BERs of less than 10^{-9} were measured. This optically-transparent self-routing switching node can serve as a modular building block for 2-connected optical mesh networks.

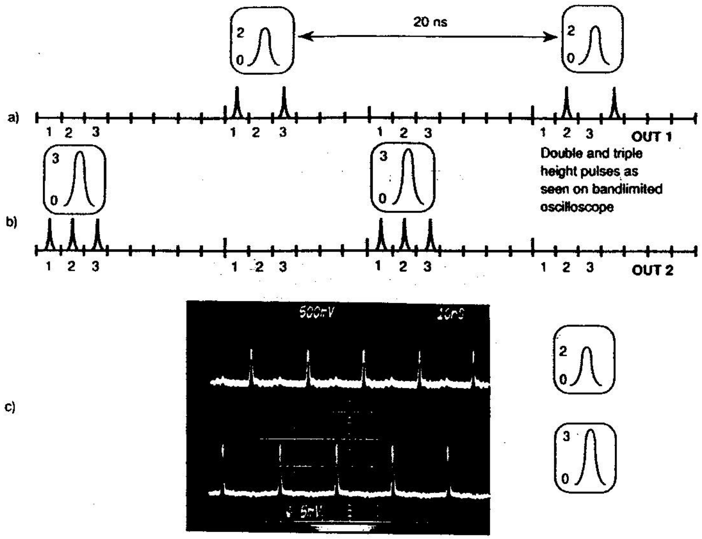

Fig. 6. Output of port 1 (OUT 1) and 2 (OUT 2) of the routing switch SW when simultaneously sampled bits number Two and Three are "1" and "0" or ("1" and "1") resp.: a) and b) timing diagram; Experimental demonstration: c) oscilloscope photograph of both outputs of the routing switch SW when demultiplexed address bits Two and Three are "10" upper trace and "11" lower trace.

4. Colliding Pulse Mach-Zehnder

The colliding pulse Mach-Zehnder is also excellent candidate for optical TDMA[19] The configuration of the experimentally demonstrated system using optical fibers is shown in Fig. 9. Two -3 dB 2×2 couplers provide the splitting and the recombination of the optical pulses for the Mach-Zehnder interferometer. The length of the arm in the Mach-Zehnder is adjusted by two adjustable time delay units to make the output very close to a complete interference at both outputs - one is the constructive and other destructive. The time delay unit is constructed with a pair of GRIN rod lenses on the x-y-z translators. One of the GRIN rod on one of the time delay unit is on the piezo-translator (PZT) stage to provide an ultra-fine adjustment much below the wavelength. Since the length of the arm in the Mach-Zehnder can not be maintained due to the instability of the fiber, a dynamic stabilization technique is used to maintain the constant interference condition by reading the output and adjust the PZT. The requirement of the same polarization for the maximum interference is maintained by the two loop polarizers inside the arms. Inside the Mach-Zehnder, two almost identical

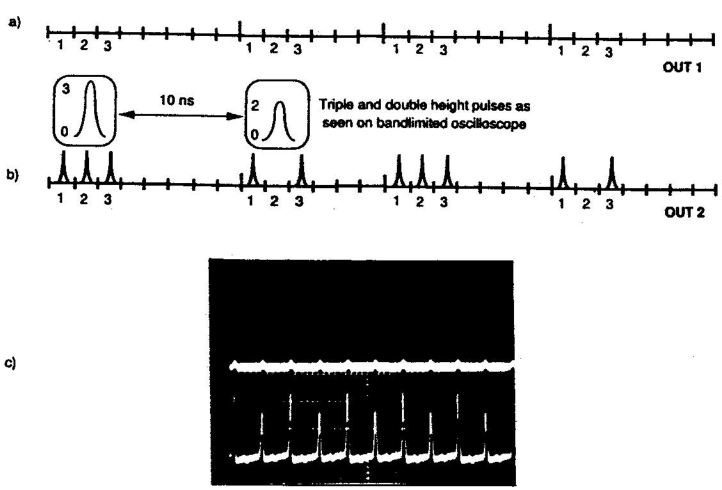

Fig. 7. Output of port 1 (OUT 1) and 2 (OUT 2) of the routing switch SW when simultaneously sampled bits number Two and Three are "1" and "0" or ("1" and "1") resp.: a) and b) timing diagram; Experimental demonstration: c) oscilloscope photograph of both outputs of the routing switch SW when demultiplexed address bits Two and Three are "10" upper trace and "11" lower trace.

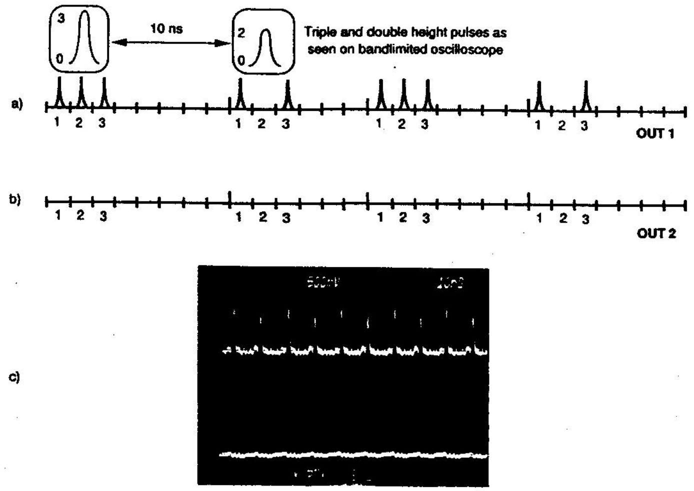

Fig. 8. Output of port 1 (OUT 1) and 2 (OUT 2) of the routing switch SW when bits number Two and Three are not sampled: a) and b) timing diagram; Experimental demonstration: c) oscilloscope photograph of both outputs of the routing switch SW.

semiconductor optical amplifiers (BT&D SOA 3200) are placed to provide the necessary

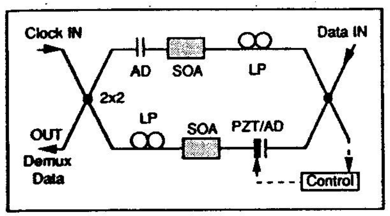

Fig. 9. Colliding Pulse Mach-Zehnder.

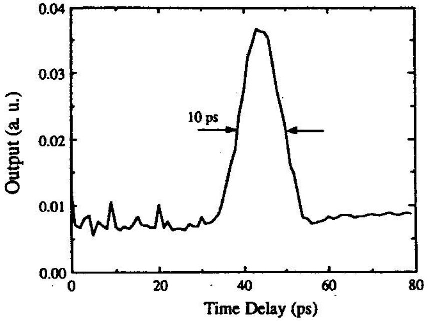

Fig. 10. 10 ps switching window.

optical nonlinearity for the switching. Here the control pulse is injected from the front of the Mach-Zehnder, and the data is injected from the back. The experimental result of 10 ps switching window by 0.65 pJ of control pulse energy at 1.313 μm is shown in Fig. 10. This has been obtained by delaying the control pulse with respect to the data pulse before both pulses coupled into the Mach-Zehnder. The temporal pulse width is about 2 ps. The demonstrated switching window of 10 ps is the minimum time but optimum output signal condition for the 500 μm long InGaAsP SOA which has an index of refraction of about 3.3. Since the counter-propagation geometry of control and data pulses, the time delay required for both pulses of arrive at the both ends is about 11 ps which is twice larger than the pulse transit time trough the SOA. In this demonstrated system, the contrast ratio between the switch on and off is about 5:1, however the ratio can be increased dramatically. The contrast ratio of only 5:1 is due to the different amount of loss at each arm of the interferometer and gain at the SOA's, therefore a complete interference at the output port could not have been achieved.

5. Conclusion

In conclusion, we report the demonstration of all-optical self-clocked time - demultiplexing and packed routing using two demultiplexers the TOAD and the CPMZ. For the TOAD the clock and data were polarization multiplexed.

The TOAD was used to demultiplexed OTDM data at 0.25 Tb/s. The required switching energy was only 800 fJ. A polarization filter was used to separate the clock signal from demultiplexed data at the output port of the TOAD.

We have also demonstrated a newly developed all-optical switch, which is based on a nonlinear Mach-Zehnder interferometer. The CPMZ is a polarization and wavelength insensitive demultiplexer because, unlike the TOAD, it does not require any polarization or wavelength filter at the output port to separate the demultiplexed data from the clock signal. This is a very important feature of this newly proposed switch. Because the CPMZ is based on SOAs, the data signal output can be larger than the data input. Therefore the number of switches that can be cascaded is limited by amplifier noise rather than power loss. The CPMZ can be integrated on a single substrate by fabricating the Mach-Zehnder waveguide structure together with the SOAs. It is expected that this integrated version of the CPMZ will not require active stabilization.

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