Demonstration of an All-Optical Simultaneous Wavelength Converting/Space-Switching Cross-Point Device

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***Abstract*—An integrated device consisting of two cascaded 2 × 2 crosspoint switches has been utilized to demonstrate a highly functional integrated routing and wavelength converting switch architecture at a data rate of 2.488 Gb/s. This allows simultaneous space switching and wavelength conversion of optical signals in wavelength-division multiplexed (WDM) networks. Eye diagrams and bit-error-rate (BER) curves are displayed for wavelength conversion and simultaneous routing of a separate signal.**

I. Introduction

THERE has been much recent interest in wavelength conversion within wavelength-division multiplexed (WDM) networks [1]. Here wavelength conversion has several potential applications which include enacting fast link restoration, allowing flexible system evolution, interfacing different networks and providing more efficient network management (where wavelengths are assigned on a local rather than a global level). Many different techniques for wavelength conversion have been demonstrated using diode lasers and diode laser amplifiers [2]. However, several applications which require wavelength conversion also involve space switching. For example, link restoration is of great interest where a signal traveling between network nodes must be rerouted on the link failure of an original path 1 via a second path 2. To avoid contention with existing traffic on path 2, wavelength conversion is used to convert the signal to a redundant wavelength and then to convert it back when it reaches the destination node and switch it spatially to the appropriate port for retransmission. As such schemes use a space switch to provide the rerouting followed by a wavelength converter, there is interest in examining the integration of these functions on a single chip. Previous reported work has centred on chip designs to achieve optimum performance at only one of these functions [3] or on utilizing discrete devices to solve wavelength contention problems [4]. Specific tailoring of individual SOA's for the two separate functions within an integrated chip matrix would prove technologically very difficult in terms of growth. This is because ideally SOA's for wavelength conversion require structures with high confinement factors and long active regions, whereas for space switching short amplifiers with low confinement factors are the optimum. To incorporate both optimum SOA structures on one chip would require several regrowth steps which increases production time and complexity and would most likely reduce the functionality of the switch architecture.

This letter demonstrates experimentally for the first time that at a data rate of 2.5 Gb/s the two functions can be performed simultaneously with a crosspoint matrix of identical SOA's by optimization of SOA bias currents and optical input powers. Achieving both functions on one small, integrated device offers advantages over the usage of separate components such as lower loss, easier temperature control and packaging and potentially lower cost devices. The switch also can be used for time division switching at rates of over 1 Gb/s, suitable for packet switched applications.

II. Device Description

The wavelength converting space switch used in the following experiments consists of two cascaded 2 × 2 monolithic InGaAsP–InP optical cross-point switches [5] that use active/passive integration to allow low loss waveguides, splitters, total internal reflection (TIR) mirrors and amplifiers to be incorporated on the same chip (Fig. 1). The first switch consists of two input ridge waveguides which each branch at a 1 × 2 power splitter, so that the four resulting waveguides can be separately switched between blocking and transmission using integrated 500-mm-long polarization sensitive (TM sees ~2 dB more gain [5]) semiconductor optical amplifiers (SOA's). Alternate waveguides are then coupled together to complete the crosspoint switch, and this is then connected to a second one whose structure is the mirror image of the first section. The cascading of two devices affords greater variety in the way the wavelength conversion function can be applied (Fig. 2) and also incorporates two SOA's in a given route through the chip which increases the available gain. A downside of this is an increase in the amount of spontaneous emission produced. Current biasing of a single SOA at 200 mA provides 24 dB of on-chip gain [5] to counteract the losses incurred from the mirrors, power splitters, waveguides and coupling. An unbiased SOA acts as an efficient absorber, curtailing the passage of light through that particular route and producing

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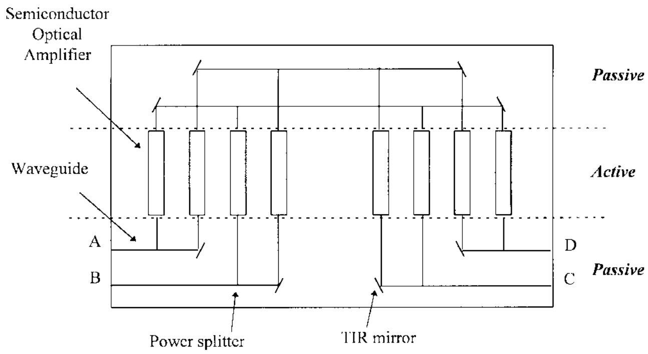

Fig. 1. Schematic of the optical cross-point switch.

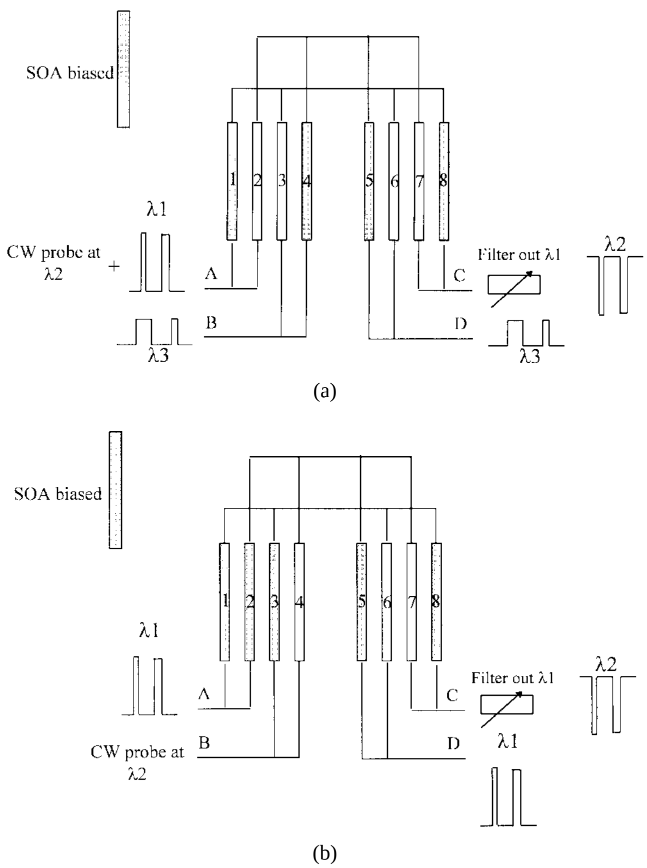

Fig. 2. Schematic showing an example of how the cross-point switch can have increased functionality by incorporating wavelength conversion. (a) By injecting the probe beam with the pump beam into the same waveguide, freeing up another waveguide for routing another signal. (b) By injecting the probe beam into a different waveguide to the pump, offering increased functionality.

low crosstalk levels (< -45 dB). Under normal operating conditions (i.e., high-input powers) and with the two SOA's in a particular route each biased at 200 mA, the device functions with around 8-dB fiber-to-fiber loss for a wavelength at the gain peak. It should be noted that the cross-point switch has the added advantage of being small, measuring only 1.2 mm $\times$ 2.5 mm.

Fig. 2(a) illustrates an example of the inherent functionality that this optoelectronic circuit offers. By driving SOA's 1 and 8, a signal at $\lambda 1$ can be simply routed from A to C. If wavelength conversion of $\lambda 1$ is required because of contention

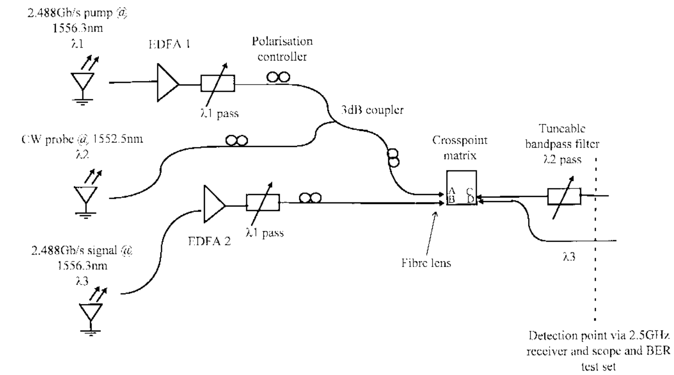

Fig. 3. Schematic of experimental apparatus.

further on in the network, a CW probe beam at $\lambda 2$ can also be injected at A allowing wavelength conversion by cross-gain modulation (XPM) [6] in SOA's 1 and 8 to take place. Input B is, therefore, left free for routing another signal at $\lambda 3$ to output D. Alternatively, the CW probe beam could be injected at input B as in Fig. 2(b) allowing a "broadcast and select" type operation to take place whereby $\lambda 1$ can be transmitted from A to C due to SOA's 1 and 8 and *also* transmitted from A to D by having SOA's 2 and 5 on as well. Wavelength conversion could then take place from $\lambda 1$ to $\lambda 2$ for either (or both) of outputs C and D by biasing either (or both) of SOA's 3 and 4 (conversion would take place in SOA's 8 and 5, respectively). This latter approach offers higher flexibility with regard to output wavelength combinations but uses up more input waveguides in the process.

It can, therefore, be seen that virtually any combination of input and output wavelengths can be accommodated by appropriate SOA biasing and filtering on the outputs. Thus, this integrated device shows the functionality required to allow link restoration to take place.

III. Experimental Setup

Here, an experimental example of one of the possible functions allowed with this architecture is demonstrated whereby wavelength conversion and routing of one signal in conjunction with simultaneous routing of another signal at a different wavelength is shown. The experimental setup is displayed schematically in Fig. 3 and corresponds to the arrangement of Fig. 2(a). Temperature controlled distributed feedback (DFB) lasers are used as optical sources. The pump, a 2.488 Gb/s $2^7 - 1$ pseudorandom bit sequence (PRBS) nonreturn-to-zero (NRZ) signal at 1556.3 nm $(\lambda 1)$ is injected into an EDFA for amplification and then combined with a continuous-wave (CW) probe at 1552.5 nm $(\lambda 2)$ using a fiber coupler. A tunable bandpass filter is used to remove amplified spontaneous emission from the EDFA. Polarization controllers after all the signal lasers are used to set the input signal polarizations to TM for maximum gain. The resulting light is then coupled into the device at A via a lensed fiber. The average in-fiber injected powers are $+6.5$ dBm and -2 dBm for $\lambda 1$ and $\lambda 2$, respectively. SOA's 1, 8, 4, and 5 are biased at 180, 130, 135, and 196 mA, respectively after optimization and minimization of power penalty. Amplifiers 1 and 8 allow

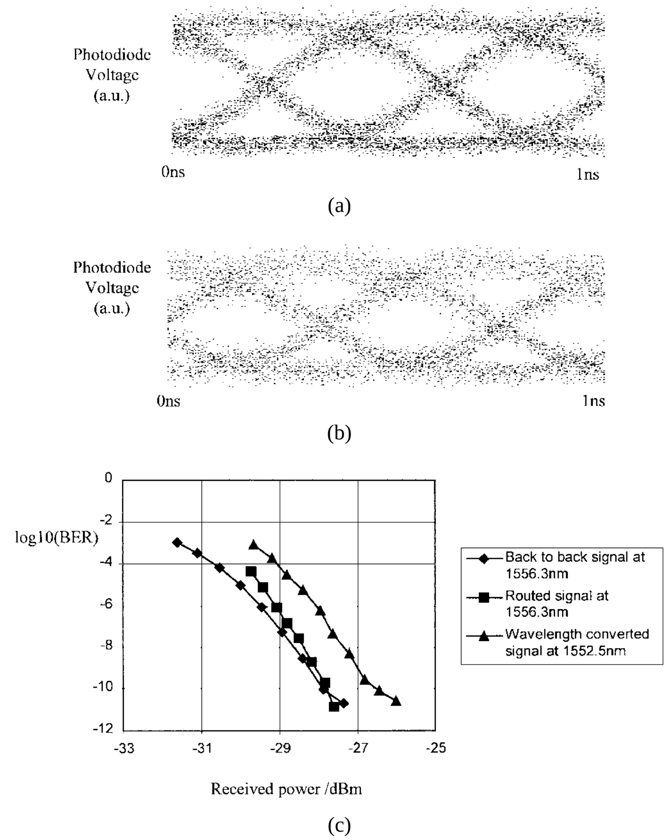

Fig. 4. (a) AC coupled eye diagram of routed 2.488-Gb/s PRBS NRZ signal at 1556.3 nm. (b) AC coupled eye diagram of wavelength converted beam at 1552.5 nm. (c) Plot showing BER curves for optimized routed and wavelength converted signals at above wavelengths.

wavelength conversion of the data at the pump wavelength onto the probe and routing to output C. Here, a 1-nm optical bandpass filter is used to remove the pump light at $\lambda 1$. A 2.5-GHz receiver was used to examine the received light in conjunction with a fast oscilloscope and bit-error-rate (BER) test kit. Simultaneously, another patterned signal at 2.488 Gb/s and wavelength 1556.3 nm $(\lambda 3)$ is injected into B via a second EDFA, bandpass filter and a lensed fiber and routed to output D via amplifiers 4 and 5. The average in-fiber power of this signal was $+6$ dBm.

IV. Results

Fig. 4(a) and (b) shows example eye diagrams for the routed signal $(\lambda 3)$ at output D and the wavelength converted signal $(\lambda 2)$ at output C. The converted signal is inverted, a characteristic of the cross-gain saturation method of wavelength conversion. By biasing of different SOA's (1, 6, and 4, 7) the outputs were switched between D and C. By using appropriate output filter tuning and SOA bias currents, any combination of $\lambda 1$, $\lambda 2$, and $\lambda 3$ at either output C or D was achievable.

Fig. 4(c) shows the optimum performance in terms of BER curves for these wavelengths. It can be seen that the purely routed signal sees a very small ($<$0.5 dB) power penalty for a 10^{-9} sensitivity. The converted signal suffers a higher penalty ($\sim$1.5 dB) which is most likely due to a reduction in extinction ratio at these input power levels (coupling losses and power splitter/mirror losses reduce the actual input power into the first SOA). It is thought that higher input powers would improve this performance.

Wavelength conversion at data rates of 10–20 Gb/s should also be possible at higher input optical powers to allow the effective gain conversion lifetime in the SOA to be reduced [7]. The crosspoint allows different data rates to be switched as well as allowing the conversion of both RZ and NRZ data. The switch can also allow time division switching at rates of up to 1 Gb/s.

V. Conclusion

Wavelength conversion, switching and routing using a single integrated photonic device have been demonstrated simultaneously for the first time at the data rate of 2.488 Gb/s. The size of the device should be scaleable to a higher number of inputs and outputs. This will also allow the approach to be used more widely within future WDM switching nodes.

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