NOVEL WAVELENGTH-FORMAT CONVERTER FOR FUTURE LAMBDA-NNI

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Abstract: Submarine cable networks may be required to connect to terrestrial networks without costly OE/EO conversions. Due to the differences in fibers and repeaters, it is likely that at a gateway node signals with different wavelengths and different modulation formats will need to be connected transparently using all-optical wavelength and modulation conversions. We have developed a semiconductor optical amplifier Mach-Zehnder interferometer (SOA-MZI) and confirmed experimentally successful wavelength conversion over a 30 nm range. We have also demonstrated error-free all-optical conversion from OOK to BPSK/QPSK modulations. The proposed transparent conversion techniques can play a key role for future all-optical networks.

1 INTRODUCTION

With increasing demands for cost-effective, low latency connections, optical network-network interfaces (NNI) have attracted much attention, and are already employed in some terrestrial networks. Photonic Cross Connect (PXC) and multi-degree Reconfigurable Optical Add/Drop Multiplexing (ROADM), which are key technologies in wavelength routing, will increase the demand for optical NNIs In the near future, submarine cable networks may be required to connect to terrestrial DWDM networks without costly OE/EO conversions.

Due to the differences in fibers and repeaters, the wavelength assignments of submarine DWDM systems are not always identical to their terrestrial counterparts: While 0.4 or 0.8 nm wavelength spacing at the ITU-T grid over C and L band is common in terrestrial DWDM, those of 0.3 or 0.6 nm over C-band are also common in submarine systems. Moreover, the modulation formats can also be different because of the different transmission distances and environmental conditions. Indeed, we ourselves have employed Chirped RZ-OOK (Return to Zero On/Off Keying) or RZ-OOK in some submarine cable systems. Also DPSK (Differential Phase Shift Keying) and DQPSK (Differential Quadrature PSK) have been extensively studied for the next generation of long-haul systems, while conventional NRZ-OOK is thought to be in the majority in terrestrial metro areas. Therefore, as illustrated in Fig. 1, it is likely that at a gateway node between a submarine cable and a terrestrial network, signals with different wavelengths and different modulation formats will need to be connected transparently via optical NNIs, using all-optical wavelength and modulation format converters.

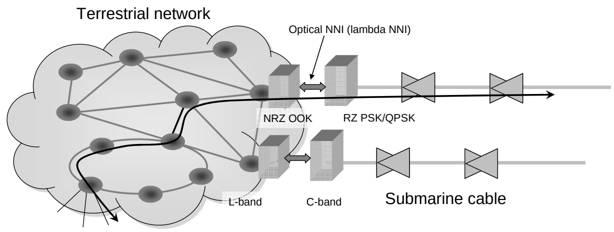


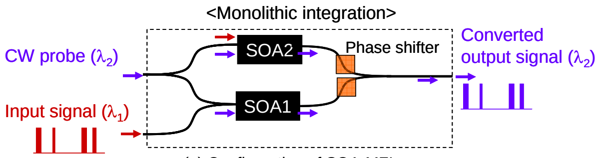
Figure 1: All optical wavelength / modulation format conversion at network gateways

To achieve optical wavelength conversion, numerous devices and methods have been proposed and demonstrated [1-2]. Among them, a semiconductor chip with a Mach-Zehnder interferometer having a semiconductor optical amplifier (MZI-SOA) in each of its two arms seems to be one of the most successful solutions because of its small size, low cost, energy efficiency and capability to be integrated with other components [1-2]. In addition, it is technically feasible for MZI-SOAs to provide more complex photonic signal processing, i.e., optical retiming, optical demultiplexing, optical reshaping, and modulation format conversion [3-6].

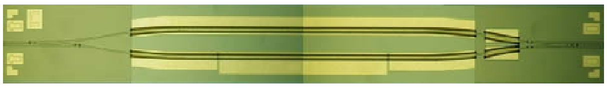
The most critical drawback of the MZI-SOA is the limitation on its operating bit rate determined by the interaction between the photons and the charge carriers. We have developed a high-speed, polarization-insensitive SOA-MZI by optimizing the active layer configuration. In this paper, we demonstrate experimental wavelength conversion and all-optical modulation conversion from OOK to BPSK/ QPSK by using the high-speed SOA-MZI we developed. We also discuss its impact on future submarine cable networks.

2 SOA-MZI DEVICE

Figure 2(a) shows the configuration of an SOA-MZI, in which SOAs are located in each arm and are connected by passive waveguides and multi-mode interference (MMI) couplers. The peak gain wavelength of the SOAs is 1.55 μm, and the band-gap wavelength of the passive waveguides is 1.3 μm so that the signals propagate without massive loss. SOA1 is biased with sufficient forward current to supply the required gain. Firstly, modulated signal light (OOK) at wavelength □1 is amplified at SOA1. This amplification process consumes charge carriers and inversely modulates the carrier density of SOA1. As a result, the refractive index of SOA1 is changed by □1 so that the □2 signal is phase modulated in SOA1 by what is called cross-phase modulation (XPM). Because the phase modulation is converted to amplitude modulation due to the interferometer configuration, the data carried by wavelength □1 (signal light) is transferred to the probe light at wavelength □2.



(a) Configuration of SOA-MZI



(b) Photograph of the chip (4.8 mm x 0.75 mm).

Figure 2: (a) Configuration of the SOA-MZI monolithically integrated wavelength converter chip, (b) Top view of the fabricated wavelength converter chip.

In order to achieve high speed wavelength conversion, the dimensions of the SOA active waveguide and the carrier density were carefully designed by numerical simulations to have a short gain recovery time suitable for 40 Gbps operation. Figure 2(b) shows the top view of the fabricated wavelength converter chip. Figure 3 shows the cross-section view of the active SOA waveguide. The 0.6 µm x 0.2 mm rectangular SOA waveguide was fabricated by the high-precision wafer-process [7]. The monolithic chip was mounted in a butterfly module and coupled with pigtail fibers [8].

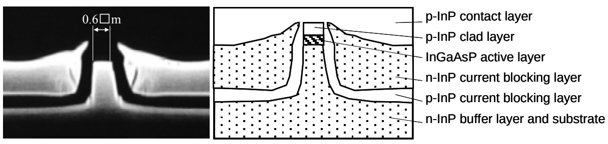


Figure 3: Cross-sectional SEM photographs of the active SOA waveguide.

3 WAVELENGTH CONVERSION

We conducted wavelength conversion experiments at 40 Gbps using the SOA-MZI module we developed. Figure 4 shows the wavelength-converted eye patterns for various probe wavelengths. Clear eye openings were obtained in the wavelength range from 1530 nm to 1565 nm. The measured power penalty was 2.5 dB for the wavelength conversion of 40 Gbps NRZ (PRBS 231–1) from 1547 nm to 1535 nm.

The narrow active SOA waveguide enhanced the polarization insensitivity of the InGaAsP active layer. The polarization dependent gain at 600 mA drive current was only 0.9 dB(p-p), and extinction ratios higher than 10 dB was obtained for both vertical and horizontal polarizations [7].

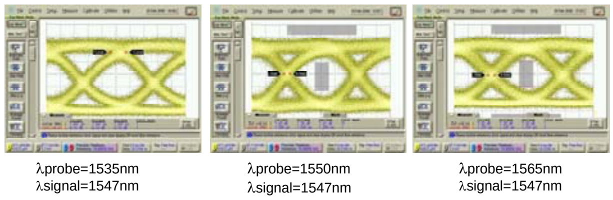


Figure 4: Wavelength-converted eye patterns at 40 Gbps. The wavelengths of the CW probe light were (a) 1535 nm, (b) 1550 nm, and (c) 1565 nm. The input signal wavelength was 1547 nm.

We also experimentally confirmed wavelength conversion at both 10 Gbps and 40 Gbps with reduced OSNR with the same bias condition for both bit rates [9]. Bit-rate independence is one of the benefits of the SOA-MZI configuration.

4 MODULATION FORMAT CONVERSION

So far various methods of modulation format conversion have been investigated [10-13] for future all-optical transport networks where different modulation formats may be selectively used depending on the network size and capacity. We have also proposed a novel all-optical modulation format conversion from OOK to BPSK/QPSK using SOA-MZIs [3]. Figure 5 shows the schematic diagram of the proposed OOK to BPSK converter. NRZ-OOK signal pulses are launched into the upper arm of the MZI as control pulses. An RZ-clock pulse sequence at □1 is launched into both arms of the MZI as probe pulses. In SOA#1, the charge carrier density is altered by the control pulse, and the phase and amplitude of the probe pulse after passing through SOA#1 are also changed. E1 and E2 are the amplitudes of the probe pulses after passing through SOA#1 when the control pulse is absent (corresponding to “0”) and present (corresponding to “1”), respectively. By adjusting SOA#2 current and the SOA-based-phase shifter, an NRZ-OOK data signal can be converted to an RZ-BPSK data signal as shown in Figure 5. The assist light at □2 is launched to suppress the rapid change in charge carriers which would cause frequency chirp and amplitude fluctuations. We note that the converted signal is not DPSK but BPSK, so that coherent detection or differential detection with an electrical decoder is necessary.

We confirmed the OOK/BPSK modulation format conversion experimentally by using a 1560.6 nm signal light modulated with 10.7 Gbps PRBS 231-1 OOK data and 1570.4 nm RZ pulses with 1574.2 nm assist light. Figure 6 shows the obtained bit-error rates (BER) of the converted signal. The received sensitivity of the converted signal was improved by 2.9 dB compared to the back-to-back case at BER=10-9, thanks to the balanced detection. The insets show the clear eye opening following the balanced receiver and the optical spectrum of the converted signal.

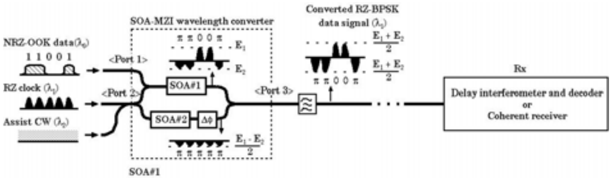


Figure 5: Schematic diagram of OOK/BPSK format conversion

The OOK/BPSK converter can be developed into an OOK/QPSK converter by using two SOA-MZIs as shown in Figure 7. We also verified the principle of OOK/QPSK conversion at 10.7 Gbps. The measured eye diagram and optical spectrum of the converted signals are shown in Figure 8.

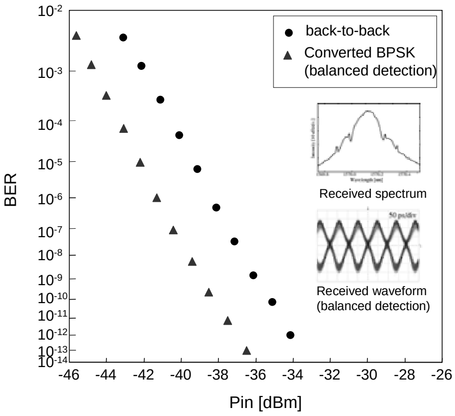


Figure 6:Performance of the OOK/BPSK conversion. Inset are the optical spectrum of the converted signal and the eye diagram of the electrical signal at the receiver

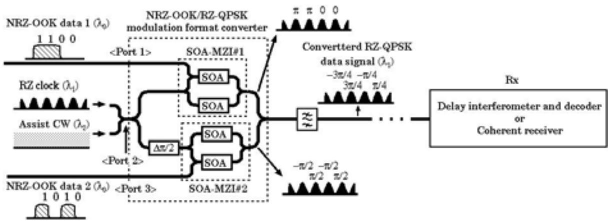
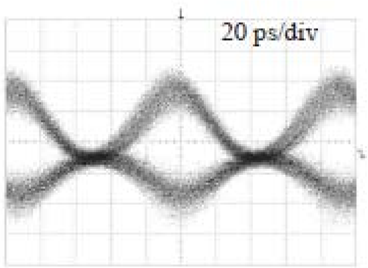
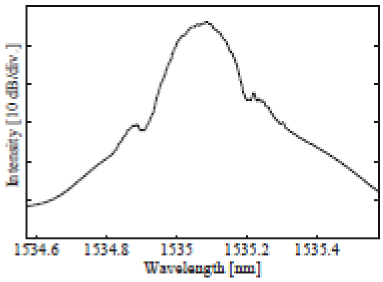


Figure 7:Schematic diagram of OOK/QPSK format conversion



(a)



(b)

Figure 8: Performance of the OOK/QPSK format conversion. (a) Eye diagram of the electrical signal at the receiver, (b) Optical spectrum of the converted signal

5 CONCLUSION

Monolithic SOA-MZI modules with an optimized InGaAsP active layer were developed for wavelength and modulation format conversion. We experimentally confirmed wavelength conversion of 40Gbps NRZ signals over the full C band, and OOK to BPSK/QPSK modulation format conversion at 10 Gbps. We believe that wavelength and modulation format conversion techniques will expand the applicability of optical NNI to submarine cable networks, and that high-speed SOA-MZI devices can be key components for such applications.

4. ACKNOWLEDGEMENT

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