

160 Gbit/s error-free all-optical demultiplexing using monolithically integrated band gap shifted Mach-Zehnder interferometer (GS-MZI)

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Abstract: Error-free all-optical demultiplexing is demonstrated with a monolithically integrated switch for 160 Gbit/s data stream. The switch comprises ‘band gap shifted’ semiconductor optical amplifiers, monolithically integrated within a symmetric Mach-Zehnder interferometer.

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1. Introduction

In OTDM systems, semiconductor optical amplifiers (SOAs) based interferometric switches have been proposed and investigated for all-optical demultiplexing in a number of publications [1-9]. In these concepts, the cross-phase modulation (XPM) due to the gain-saturation nonlinearity in SOAs provides the differential phase shift required for interferometric switching. The devices based on symmetric Mach-Zehnder interferometer (MZI) configuration provide higher flexibility and short switching windows. The monolithically integrated ones are very attractive compared to the hybrid solutions because of their compactness and stability. Error-free demultiplexing beyond 100 Gbit/s has been achieved first with hybrid-integrated MZI [5] at 168 Gbit/s and with hybrid GT-MZI [6] at 160 Gbit/s.

In this work, we report on 160 Gbit/s error-free all-optical demultiplexing by using a monolithically integrated Mach-Zehnder interferometer with ‘band gap shifted’ (GS) SOAs [7].

2. Experimental details

Fig. 1 illustrates the experimental setup of monolithically integrated GS-MZI switch in its application as a 160 Gbit/s to 10 Gbit/s all-optical demultiplexer. The key components of this interferometric switch are the two GS-SOAs integrated within its branches. The gain maximum of the SOAs is at a wavelength of 1.5 μm far from the data wavelength, which is at 1560 nm. The experimental comparison of the GS-MZI switch with the conventional MZI, regarding its better linearity, better contrast ratio and a higher phase shift can be found in [7].

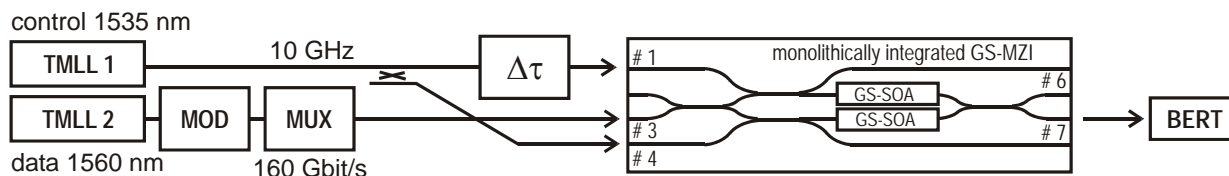


Fig. 1: Experimental setup for 160 Gbit/s all-optical demultiplexing using the GS-MZI.

The optical pulses for both control and data signals are generated by tunable mode-locked lasers (TMLL) [10]. These optical sources provide sech^2 -pulses of 1.3 ps width (FWHM) at a repetition rate of 10 GHz. The wavelength of the control signal (TMLL1) is set to $\lambda_{\text{control}} = 1535$ nm within the gain region of the GS-SOAs, where conventional erbium doped fiber amplifiers still can be used for amplification. The wavelength of the data signal (TMLL2) is set to $\lambda_{\text{data}} = 1560$ nm. The 10 GHz pulse train from TMLL2 is intensity modulated with a pseudo random bit sequence ($\text{PRBS} = 2^7 - 1$) to form the RZ data signal. It is then passively multiplexed by a fiber delay line multiplexer (4 stages) to a 160 Gbit/s single polarization data stream and coupled into the GS-switch at port #3. To ensure a multiplexed PRBS data stream, the bit sequences are shifted against each other by $(2^7 - 1)/2^n$ bit periods with $n = 1, 2, 3, 4$.

The interferometer is balanced by proper adjustment of the injection currents of the SOAs to provide no data transmission to the port #7 in the absence of control pulses. The control signal at 10 GHz is injected into the ports #1 and #4 in the additional arms of the symmetric MZI. The average power in control arms #1 and #4 is $P_{\text{control1}} = 15.5$ dBm and $P_{\text{control2}} = 17.7$ dBm, respectively. Thus the SOAs become saturated separately at different times which are defined by an external optical delay line. This time delay $\Delta\tau$ determines a gating window in which the data pulses are switched to the port #7 of the integrated switch. The injected average power into the data input port #3 is $P_{\text{data}} = 5.5$ dBm.

3. Results and discussion

Fig. 2 shows switching windows with different widths for the GS-MZI switch. Instead of the data pulses the unmodulated 10 GHz pulse train is used. The window width is varied by changing the time delay $\Delta\tau$ between the control pulses in both additional input arms of the GS-MZI. The minimum achievable window width (FWHM) is 3 ps, the highest contrast values about 27 dB. For the demultiplexing experiments a window width of about 6 ps with a contrast of about 22 dB is chosen.

Fig. 3 shows experimental results of the switched output power versus the data input power. Over a range of 20 dB linear dependence is observed. This dynamic range is limited by amplified spontaneous emission for low input power and by gain saturation of SOA for high input power. In this linear range, the switching performance of GS-demultiplexer is independent on the data input power.

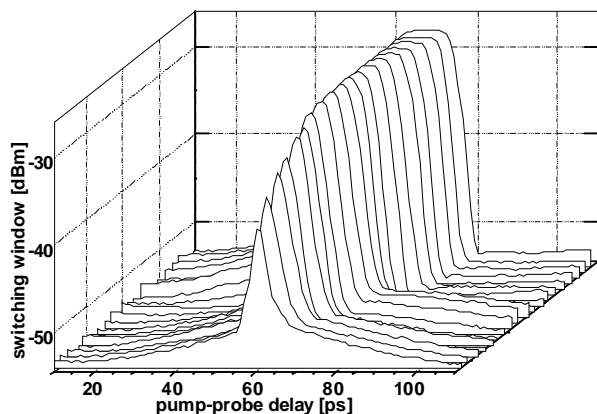


Fig. 2: Switching windows with different widths for GS-MZI switch.

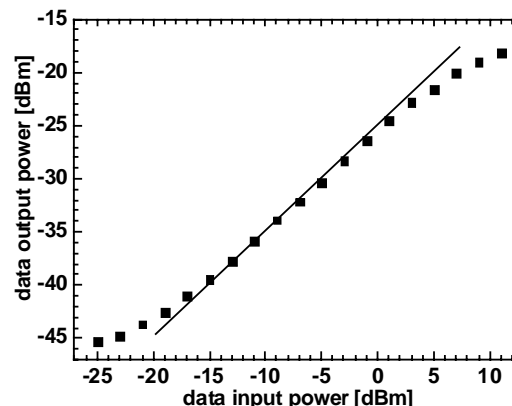


Fig. 3: Dependence of switching dynamics on data input power.

To investigate the performance of the monolithically integrated GS-MZI switch, the bit error rate (BER) for 160 to 10 Gbit/s and 80 to 10 Gbit/s all-optical demultiplexing is measured.

Fig. 4 illustrates the BER performances of the system in a back-to-back arrangement and in an all-optical demultiplexing experiment from 80 to 10 Gbit/s and 160 to 10 Gbit/s by using the GS-MZI switch. The received optical power is measured at the 10 Gbit/s receiver.

For the back-to-back curve the unmultiplexed 10 Gbit/s signal is used. Error-free operation is obtained in both cases, 80 to 10 Gbit/s and 160 to 10 Gbit/s all-optical demultiplexing, respectively.

For 80 Gbit/s demultiplexing, the BER performance is excellent. The small power penalty of 1 dB ($\text{BER} = 10^{-9}$), which we attribute to the slightly decreased signal-to-noise ratio, is due to the loss of the device (about 20 dB), which can be reduced by improved fiber-chip coupling.

For 160 Gbit/s demultiplexing the power penalty at a BER of 10^{-9} is about 3.5 dB. An indication of an error floor at 10^{-11} is observed, which is mainly due to the jitter in the control pulse source. However, for all the 16 channels (under unchanged operation conditions), error-free operation ($\text{PRBS} = 2^7-1$) is obtained with a BER less than 10^{-9} . Fig. 5 illustrates the system penalty of all OTDM channels for a BER less than 10^{-9} . The variation in the system penalty for different channels is due to the losses in the passive fiber delay line multiplexer.

To investigate the influence of the optical control pulses and the external optical delay (Δt) on the switching performance, the VPIcomponentMaker™ [11] is used for simulations. 3 ps (FWHM) pulses of sech^2 -shape at 160 Gbit/s are used as data stream. We investigated the extinction ratio of the demultiplexed optical data signal for different widths (FWHM) of control pulses (sech^2) and for different widths of the switching windows. Fig. 6 depicts the simulation results for 160 to 10 Gbit/s demultiplexing. The extinction ratio degrades by 10 dB with increased width of the control pulse from 0.5 ps to 3 ps. This demonstrates the strong enhancement by very short pulses for demultiplexing processes of the MZI-type demultiplexer.

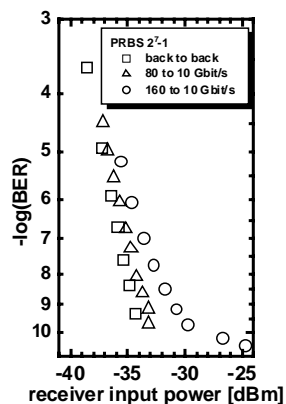


Fig. 4: BER performance with GS-MZI switch.

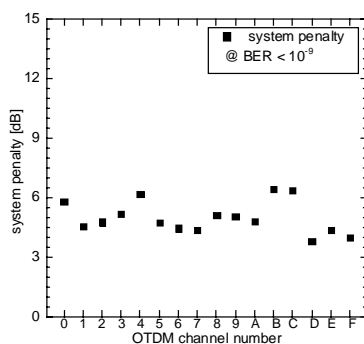


Fig. 5: System penalty for the 16 OTDM channels.

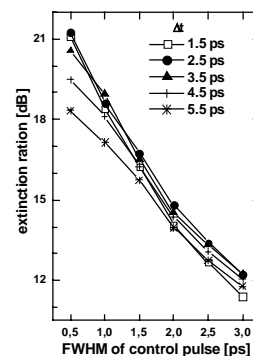


Fig. 6: Dependence of demultiplexed signal on the control pulse- and switching window widths.

4. Conclusion

Error-free all-optical demultiplexing of 160 Gbit/s data signals to 10 Gbit/s was performed with monolithically integrated Mach-Zehnder interferometer comprising ‘band gap shifted’ SOAs. The GS-MZI is a compact and stable device providing switching windows with a high contrast and short window width. By using shorter control pulses and reducing the jitter of the pulse sources, demultiplexing from even higher data rates can be expected.

5. References

- [1] M. Eiselt: Optical loop mirror with semiconductor laser amplifier, *Electron. Lett.*, vol. 28, pp. 1505-1507, 1992.
- [2] J.P. Sokoloff, P.R. Prucnal, I. Glesk, M. Kane: A terahertz optical asymmetric demultiplexer (TOAD), *IEEE Photon. Technol. Lett.*, vol. 5, pp. 787-790, 1993.
- [3] E. Jahn, N. Agrawal, M. Arbert, H.-J. Ehrke, D. Franke, R. Ludwig, W. Pieper, H.G. Weber, C.M. Weinert: 40 Gbit/s all-optical demultiplexing using a monolithically integrated Mach-Zehnder interferometer with semiconductor laser amplifiers, *Electron. Lett.*, vol. 31, pp. 1857-1858, 1995.
- [4] R. Hess, M. Caraccia-Gross, W. Vogt, E. Gamber, P.A. Besse, M. Duell, E. Gini, H. Melchior, B. Mikkelsen, M. Vaa, K.S. Jepsen, K.E. Stubkaer, S. Bouchole: All-optical demultiplexing 80 to 10 Gb/s signals with monolithic integrated high performance Mach-Zehnder interferometer, *IEEE Photon. Technol. Lett.*, vol. 10, pp. 165-167, 1998.
- [5] S. Nakamura, Y. Ueno, K. Tajima, J. Sasaki, T. Sugimoto, T. Kato, T. Shimoda, M. Itoh, H. Hatakeyama, T. Tamanuki, T. Sasaki: Demultiplexing of 168 Gb/s data pulses with hybrid-integrated symmetric Mach-Zehnder all-optical switch, *IEEE Photon. Technol. Lett.*, vol. 12, pp. 425-427, 2000.
- [6] S. Diez, C. Schubert, R. Ludwig, H.-J. Ehrke, U. Feiste, C. Schmidt, H.G. Weber: 160 Gbit/s all-optical demultiplexer using hybrid gain-transparent SOA Mach-Zehnder, *Electron. Lett.*, vol. 36, pp. 1484-1485, 2000.
- [7] T. Tekin, M. Schlak, W. Brinker, B. Maul, R. Molt: Monolithically integrated MZI comprising band gap shifted SOAs: a new switching scheme for generic all-optical signal processing, *Proc. of ECOC'00*, vol. 3, pp. 123-124, 2000.
- [8] C. Schubert, S. Diez, J. Berger, R. Ludwig, U. Feiste, H. G. Weber, G. Toptchiyski, K. Petermann, V. Krajinovic: 160 Gb/s all-optical demultiplexing using a gain-transparent ultrafast-nonlinear interferometer (GT-UNI), *IEEE Photon. Technol. Lett.*, vol. 13, pp. 475-477, 2001.
- [9] T. Tekin, M. Schlak, W. Brinker, J. Berger, C. Schubert, B. Maul, R. Molt: Ultrafast all-optical demultiplexing performance of monolithically integrated band gap shifted Mach-Zehnder interferometer, *Proc. of ECOC'01*, vol. 4, pp. 504-505, 2001.
- [10] R. Ludwig, S. Diez, A. Ehrhardt, L. Küller, W. Pieper, H.G. Weber: A tunable femtosecond modelocked semiconductor laser for applications in OTDM systems, *IEICE Trans. Electron.*, E81-C(2), pp. 140-145, 1998.
- [11] <http://www.VPIsystems.com>.