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320-to-10 Gbit/s all-optical demultiplexing using sum-frequency generation in PPLN waveguide

F. Gomez-Agis, C.M. Okonkwo, A. Albores-Mejia, E. Tangdiongga and H.J.S. Dorren

A 320-to-10 Gbit/s all-optical demultiplexer based on sum-frequency generation in a periodically-poled lithium niobate (PPLN) waveguide is demonstrated. A bit-error-rate of 10^{-9} is achieved with a power penalty of 1.5 dB.

Introduction: All-optical demultiplexing (AOD) is an essential function in optical time-division multiplexed (OTDM) systems, which serves to extract base-rate channels from a time-multiplexed high-bit-rate signal. AODs based on high nonlinear fibres [1] and semiconductor optical amplifiers [2] have been demonstrated at 320 Gbit/s. The first type offers the potential for ultrafast operation based on the femtosecond-scale time-response of the Kerr nonlinearity, the switching response of which is limited by the pulse width of the control pulse and the walk-off between the signal and the control pulses owing to the fibre length. The latter is limited by the switching performance owing to residual slow recovery times and losses by optical filtering.

Interest in periodically-poled lithium niobate (PPLN) as an ultrafast switching device resides in the femtosecond-scale response of the $\chi^{(2)}$ nonlinearity, low noise, compactness and high conversion efficiency at low optical powers. A first demonstration using PPLN as an AOD has been carried out at 160 Gbit/s by exploiting a second-order cascaded nonlinear effect [3]. The control signal, located in the C-band, is first frequency-doubled by second-harmonic (SH) generation. Subsequently, the upconverted signal acts on the data pulses via difference-frequency generation (DFG) extracting the selected channel in the C-band. Nevertheless, the maximum allowed bit-rate is limited by the broadening effect induced on the control pulses owing to the group-velocity mismatch (GVM) between the fundamental wavelength and its SH. A second demonstration consisted of adding/dropping a 10 Gbit/s tributary from an aggregated 320 Gbit/s signal by exploiting the sum/difference-frequency generation and pump depletion effects [4] employing high optical powers. However, no characterisation of the PPLN as an AOD was carried out. In this Letter, we present a demultiplexing scheme based on sum-frequency generation (SFG) where the maximum allowed operating bit-rate is mainly controlled by the pulsewidth of the control pulse. The broadening effect introduced by GVM does not act on the control pulse but on the extracted channel. This scheme allows error-free operation at 320 Gbit/s using moderate optical powers.

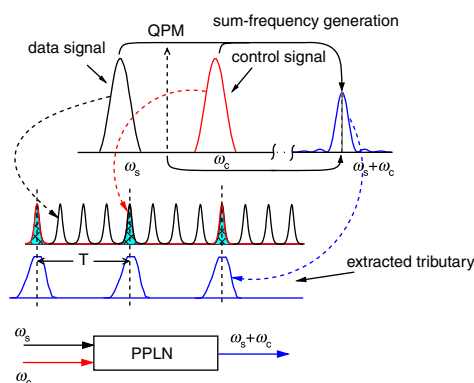


Fig. 1 SFG-based all-optical demultiplexing concept

Principle of operation: The wavelengths associated with the data and control signals, schematically shown in Fig. 1, are assigned to fulfil the conditions for SFG in the PPLN satisfying the relation $\lambda_{SH}^{-1} = \lambda_s^{-1} + \lambda_c^{-1}$, where s and c denote the data and control signals, respectively, and λ_{SH} the wavelength of frequency-doubling of the PPLN. Normally, λ_{SH} is also called the quasi-phase matching (QPM) wavelength. The wavelengths ranges satisfying this relationship are within the transparency range of the material $0.35 \leq \lambda \leq 4 \mu\text{m}$. Both signals are coupled into the PPLN and by tuning an optical delay in the control signal path, a particular channel is selected. The interaction

area between the signals is upconverted to the visible region and corresponds to the extracted channel. The extracted signal in question presents no intra-channel interference owing to the existing separation between pulses that corresponds to the period of the extraction rate. Inter-channel interference is avoided by controlling the control pulse width. Finally, the extracted channels are detected by a photoreceiver to drive a bit-error-rate (BER) tester.

Experimental setup: A schematic of the experimental procedure is shown in Fig. 2. Optical pulses generated by a fibre modelocked laser (FMLL) with a pulse width of 1.5 ps at 1550 nm and 40 GHz repetition rate are amplitude modulated to form a $2^7 - 1$ return-to-zero on-off keying (RZ-OOK) PRBS stream. The pulses are compressed to 1 ps, tuned to 1559 nm and multiplexed by a fibre-based interleaver to form the 320 Gbit/s OTDM signal. The control signal has a pulsewidth of 2.5 ps at 1541 nm and 10 GHz repetition rate. To resolve the data signal in the optical demultiplexer, the pulses were compressed to 1.2 ps and tuned to 1533.6 nm. The timing jitter of the control signal after pulse compression obtained from phase-noise measurements is 45 fs. The wavelengths of the data and control signals which satisfy SFG are coupled into the PPLN with the corresponding average power of 11 and 10 dBm. To select a particular channel of the OTDM signal, a tunable optical-delay line is placed in the path of the control signal. At the output of the PPLN, the extracted channels downconverted to 773.1 nm are detected by a 12 GHz GaAs/pin photoreceiver for BER performance evaluation.

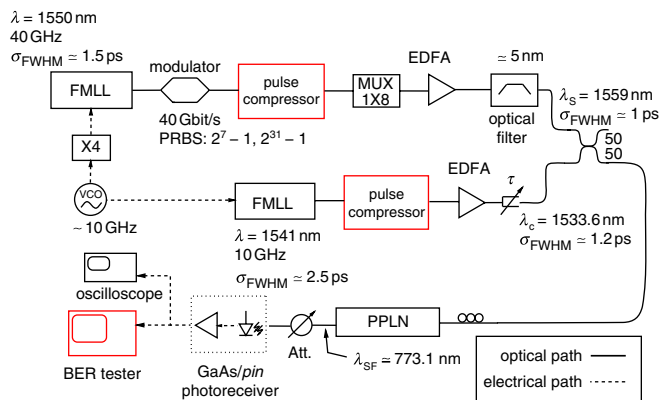


Fig. 2 PPLN-based all-optical demultiplexer

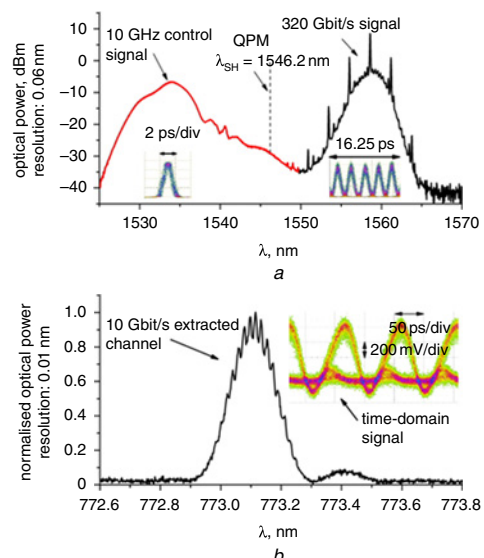


Fig. 3 Optical spectra at input of PPLN (Fig. 3a). 10 GHz control signal and 320 Gbit/s data signal. Optical spectrum of 10 Gbit/s extracted channel (Fig. 3b)

Inset: Eye-diagram of extracted channel

The PPLN consists of a temperature-controlled and pigtailed 30 mm waveguide, the QPM of which at 52°C peaks at 1546.2 nm ($\lambda_{SH} = 773.1 \text{ nm}$) with a normalised efficiency $\eta_{\text{norm}} = 214\% \text{W}^{-1}$. It holds a

GVM of 2.5 fs/mm between signals in the C-band and 0.3 ps/mm between SH and C-band signals.

Results: The spectra of the signals entering into the PPLN are shown in Fig. 3a. The spectrum of the control pulse together with the spectrum of the 320 Gbit/s OTDM signal are placed in a conjugate-sided fashion with respect to the QPM wavelength. The corresponding wavelengths were assigned not only to satisfy the SFG process but also to reduce the amount of noise at the QPM wavelength. When the SFG process is satisfied, the extracted channel is selected by tuning the optical delay. This implies an overlapping or cross-correlation between the pulses of the control and data signals, downconverting the target channel to λ_{SH} , the width of which is broadened from 1.2 to 10.2 ps ($1.2 \text{ ps} + 0.3 \text{ ps/mm} \times 30 \text{ mm}$) owing to the GVM. Since every 100 ps (the period of the control signal) a pulse is extracted, no intra-channel crosstalk is revealed. Fig. 3b shows the optical spectrum and time-domain trace of a 10 Gbit/s extracted channel. The width of the pulses is due to the combined effect of the impulse response of the photoreceiver and the oscilloscope. If the control pulses are not adequately compressed (as defined by the data bit-slot), inter-channel crosstalk will be experienced.

The BER performance of the PPLN-based demultiplexer is shown in Fig. 4. The circles illustrate error-free operation of a 10 Gbit/s single channel at 850 nm used as reference. The full and half-filled squares represent the best and worst case 320-to-10 Gbit/s demultiplexing performance. Error-free operation is achieved on all the channels with an average received optical power of -16.4 dBm . This value corresponds to an average power penalty of 2 dB with respect to the reference. This penalty is due to a reduced OSNR and to the responsivity of the photoreceiver which is optimised for 850 nm. The OSNR for the 320-to-10 Gbit/s case is 10.4 dB compared to 12 dB for the 160-to-10 Gbit/s case. BER curves for best and worst cases are also plotted in the same Figure. The attained average power penalty is less than 1.5 dB. Finally, Fig. 5 shows the BER performance of 10^{-9} for 320 and 160 Gbit/s demultiplexed signals. Corresponding average optical powers of -16 and -17 dBm were attained.

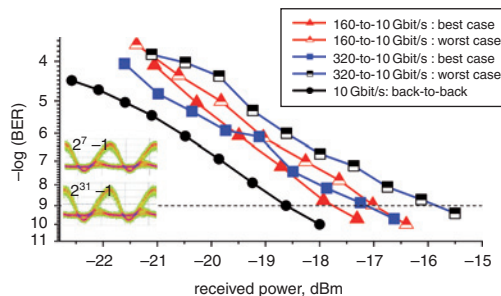


Fig. 4 BER curves of PPLN-based all-optical demultiplexer

Circles: single 10 Gbit/s channel; squares: 320-to-10 Gbit/s demultiplexing—best case; half-filled squares: 320-to-10 Gbit/s demultiplexing—worst case; triangles: 160-to-10 Gbit/s—best case; half-filled triangles: 160-to-10 Gbit/s—worst case

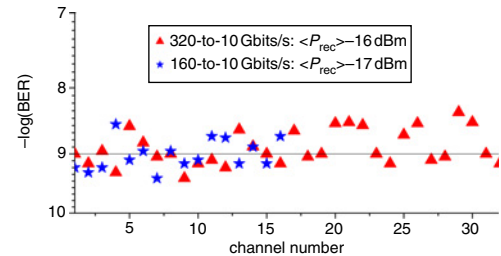


Fig. 5 BER performance of OTDM channels with fixed average power
Stars: 160-to-10 Gbit/s; triangles: 320-to-10 Gbit/s

Conclusions: A successful all-optical demultiplexing scheme for 320-to-10 Gbit/s employing a periodically-poled lithium niobate waveguide is presented. By exploiting the sum-frequency generation nonlinear process, the bit-rate is limited by the pulsewidth of the control pulse. Error-free operation is achieved for all the channels attaining an average power penalty of 2 dB. The results here outlined demonstrate the potential offered by PPLN waveguides in ultra-high-speed optical signal processing.

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One or more of the Figures in this Letter are available in colour online.

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