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Four-Wave-Mixing-Based Dual-Wavelength Conversion in a Semiconductor Optical Amplifier

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Abstract—The simultaneous wavelength conversion of two different formats or bit-rate optical signals, with low input power, is demonstrated in a highly nonlinear semiconductor optical amplifier with a single strong continuous-wave pump. For two amplitude-modulated signals of different bit rates, moderate penalties are obtained, and for the case of mixed amplitude and phase modulation at 10 Gb/s, practically penalty-free operation is achieved. In all cases, small difference (<1.1 dB) between single- and dual-channel operation is obtained, allowing asynchronous operation.

Index Terms—Nonlinear optics, optical frequency conversion, semiconductor optical amplifiers (SOAs).

I. INTRODUCTION

ALL-OPTICAL wavelength converters (AOWCs) are likely to become essential building blocks for future dynamic high-capacity optical networks [1]. Wavelength conversion is used as an alternative to unavailable photonic memories, trying to solve contention resolution, as well as for space switching in wavelength-routed networks [2]. In many switch implementations which include a wavelength converter it is considered a scarce resource, often shared between all possible inputs and outputs [3]. It is, therefore, desirable to utilize this resource as best as possible. The ideal wavelength converter should possess many properties, paramount among which are the following:

- 1) transparency to the modulation format and speed of the incoming data signal, so that the exact same component can be reused regardless of the incoming data signal;
- 2) compact form factor and integrable technology, so that the converter can be placed on a photonic integrated chip (PIC) together with other components such as switches and filters;
- 3) simultaneous and preferable asynchronous conversion of more than one signal.

Parametric converters based on degenerate four-wave mixing (FWM) using periodically poled LiNbO₃ devices [4] as well as highly nonlinear fiber (HNLF) [5] certainly offer transparent

converters, yet they do not allow PIC-like integration. Converters based on cross-gain and cross-phase modulation (XGM, XPM) in semiconductor optical amplifiers (SOAs) can be operated at very high speeds [6] and have great integration potential but offer a simple conversion mechanism only for a single amplitude modulated signal, although inclusion of SOAs in more elaborate setups has yielded a more generalized converter, suitable for either phase or amplitude modulated signal, yet still incapable of simultaneous conversion [7].

The use of SOAs with FWM has several demonstrations [8], [9]; in many of them, a strong optical data-carrier is converted to one or many (multicast) output carriers, achieving high efficiency FWM but with a single data pattern being copied each time. Multiple conversions using a single strong continuous-wave (CW) pump and multiple modulated carriers was suggested but only demonstrated for a single modulation format, at low bit rates and with considerable penalty [10]. Recently, we reported on initial results of penalty free simultaneous conversion of two 10-Gb/s data signals, one modulated in phase and the other in amplitude [11].

In this letter, we expand the concept of FWM-based simultaneous conversion and show that using this method, we obtain an integrable converter, which is transparent to both modulation format and modulation speed and can be operated in an asynchronous manner.

Three different test cases are explored. The case of two 10 Gb/s with different modulation format, phase-shift keying and amplitude-shift keying (PSK + ASK) is revisited followed by a complementary scenario of two different bit-rate channels using amplitude modulation, 20 + 10 Gb/s and 40 + 10 Gb/s. In all three cases, only small input powers are needed for the incoming data channels, most appropriate in cases where wavelength conversion is required to solve contention in an all-optical switching node [12]. The use of a strong CW pump clamps the optical gain, suppressing the normally occurring XGM. Practical penalty-free operation (<0.3 dB) is obtained for the case of two 10-Gb/s signals with different modulation format. When two amplitude-modulated signals with different bit rates are converted, a moderate penalty is found (maximum <4 dB). Most importantly for all the test cases is that only a small difference (<1.1 dB) between single- and dual-channel operation was measured, implying that the converter can also be used in an asynchronous fashion, as the introduction of a second channel has a minor effect over the conversion performance.

II. EXPERIMENTAL DEMONSTRATIONS

The key to the successful demonstration of simultaneous conversion of two independent data signals using FWM is proper power equalization of the input data signals as well as of the strong

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Fig. 1. Experimental setup for dual-channel (PSK + ASK) simultaneous lambda-conversion in a single SOA.

CW pump. Low optical power for the two input channels prevents deleterious FWM products from interfering with the input channels or with the converted products. However, higher input powers improve the optical signal-to-noise ratio (OSNR) of the converted channels, which is essential for error-free operation. Above the optimal input power levels, used in the experiments described below, any increase in the modulated inputs does not enhance the performance but decreases the FWM efficiency due to power splitting into the nondegenerated and secondary FWM products. Similar considerations are also applied to the choice of CW-pump power: the pump must be strong enough to clamp the gain, minimizing any XGM that might be introduced by intensity modulated data inputs, and to reduce the ASE floor.

The equalization process was carried out by monitoring the output eye patterns for residual XGM and bit-error rate (BER) for sufficient OSNR. This process was repeated for both single and dual conversion operation, so that final choice of power levels was a compromise between single and dual conversion. In some cases, single conversion performance could have been much better but also the performance difference between single and dual conversion would have been much larger. The choice of wavelengths (ITU channels) took into consideration the effect of unwanted conversion products between the pump and the data channels. In general, the most suitable arrangement of data channels and CW pump was found to be such that the data channels are up-converted and that the spacing between them is twice as that of the spacing between the CW pump and the data channel closest to it [CW at ITU(X), Data 1 at ITU(X-1), Data 2 at ITU(X-3)]. Implementation of down-conversion schemes (conversion to longer wavelengths) is not possible due inferior OSNR, up to 10 dB lower than that achieved for up-conversion, due to intrinsic higher ASE floor.

A. Mixed Modulation Formats 10 Gb/s (ASK + PSK)

Fig. 1 presents the experimental setup used for the case of PSK and ASK simultaneous conversion at a bit rate of 10 Gb/s in both channels.

The two laser sources at 1558.17 nm (−12 dBm) and 1556.55 nm (−17 dBm), ITU channels #24 and #26, were modulated with PSK and ASK, respectively, at a rate of 10 Gb/s (NRZ PRBS $2^{31} - 1$ data sequence) and combined at the SOA input with a much stronger CW signal at 1555.75 nm (channel #27). The polarization controllers (PCs) after the lasers were carefully adjusted to achieve the lowest insertion loss through the modulators, and the PCs just after them are used to align the polarization of the CW pump with the probe signals to maximize the FWM process. The SOA, ultranonlinear device with MQW

Fig. 2. Simultaneous lambda-conversion, 10 + 10 Gb/s (PSK + ASK): optical spectra for SOA input and output, DEMUX channels #28 and #30 (left); eye diagrams and BER curves for single and dual conversion operation.

structure (CIP), was biased at 500 mA, with a saturation output power of 15 dBm and small signal gain >30 dB. At the output, the converted channels were filtered by an ITU-grid DEMUX (100-GHz spacing). To enable the BER *versus* received optical power measurements in similar conditions, the back-to-back and the converted signals were amplified by a low noise EDFA (10-dB gain, 4-dB noise figure) and filtered again (1.5-nm window) to remove excessive ASE. The converted PSK signal was further processed by passing through a delayed interferometer (DI) to convert phase into amplitude modulation before detection. For the 10 + 10-Gb/s case, the BER measurements were taken using a 10-Gb/s APD receiver.

The optical spectrum at the SOA's input and output as well as the eye diagrams and the BER versus optical power at the receiver for the 10 + 10 Gb/s, ASK + PSK, are shown in Fig. 2. BER versus received optical power performance of a single converted channel is as good as the original data signal (back-to-back). Even in the presence of a second converted channel the observed degradation is within the measurement error and in any case does not exceed 0.3 dB.

The spectra at Fig. 2 (left) illustrates the required spectral positioning of input data channels and CW pump, as discussed before CW at ITU-grid channel #27, the ASK channel #26 PSK channel #24, avoiding interfering cross-channel products. The input PSK channel required more power (+5 dB) than the ASK channel since the FWM efficiency drops the further the signal is detuned from the CW pump. In any case, this penalty-free performance is obtained for low input peak powers (< −10 dBm) and a very modest −2-dBm CW pump.

B. Mixed Bit-Rate ASK (10 + 20 Gb/s, 10 + 40 Gb/s)

The setup used for mixed bit-rate ASK signals required several minor adaptations in comparison to the setup in Fig. 1. An amplitude modulator (AM) after L2 replaced the phase modulator (PM) and a 40-Gb/s PIN photodetector replaced the APD receiver for all measured BER curves (also for the 10-Gb/s channels). In addition, the selected wavelength channels were slightly shifted in the ITU grid, but maintaining relative positioning: the CW pump at channel #28 (1554.94 nm) and the two modulated carriers at channels #27 (1555.75 nm, L1) and #25 (1557.36 nm, L2). This shift was required to better align the outputs to a 200-GHz DEMUX used to filter the converted channels out. Fig. 3 shows the measured BER versus received power for NRZ converted channels at 10 and 20 Gb/s using a $2^{31} - 1$ -bit-long PRBS data sequence. Optimal input power levels for data carriers were found to be below −15 dBm and the CW pump was set at +7 dBm. Both positioning of the 10-

Fig. 3. Simultaneous lambda-conversion 20 + 10 Gb/s ASK: eye diagrams and BER curves of 20 (left) and 10 (right) Gb/s channels.

Fig. 4. Simultaneous lambda-conversion 40 + 10 Gb/s ASK: eye diagrams and BER curves of 40 (left) and 10 (right) Gb/s channels.

and 20-Gb/s input data channels with respect to the CW pump were tested: close to (conversion from channel #27 to channel #29) and apart (from channel #25 to channel #31). From Fig. 3, the 20-Gb/s channel presents error-free operation, with 1-dB degradation of required optical power at the receiver for the same BER performance when being the closest (100 GHz) to the CW probe.

When placed further away (300 GHz), the power penalty increases to 2 dB. A very small difference (0.1–0.3 dB) exists between single- and dual-channel operation modes. For the 10-Gb/s channel, when placed closer to the CW pump, a power penalty of 2 dB was measured for single conversion and an extra 1.1 dB in the dual-channel mode. When placed further away from the pump (ITU channel #25), a power penalty of 2.2-dB penalty was observed and when a second channel (channel #27) was turned ON simultaneously an error floor was observed around a BER $\sim 10^{-12}$; at a BER of 10^{-11} , a 4-dB penalty was obtained. The detected noise floor is mainly due the noise from spurious FWM over the converted channel and the limited OSNR.

For the 40 + 10 Gb/s case (Fig. 4), the converted 40-Gb/s channel shows an error floor above BER = 10^{-12} regardless of the presence of a second 10-Gb/s input channel. This noise floor is mostly the result of overshoots appearing at the higher ("1") bit level and the limited OSNR at the SOA's output.

A 4-dB total penalty was obtained at BER = 10^{-11} , with an added 1-dB penalty when the second channel is turned ON. The 10-Gb/s channel was measured to have a 4-dB penalty due mostly to noise over the high-level (see on inset in Fig. 4) with no difference between the single- and the dual-channel operation.

For the case of simultaneous conversion of 40- and 10-Gb/s channels it was impossible to switch the respective positions of 40- and 10-Gb/s channels since the obtainable FWM efficiency and OSNR for the 40 Gb/s, when placed further away from the CW pump, could not deliver error-free operation.

III. DISCUSSION AND CONCLUSION

We have demonstrated an all-optical wavelength converter based on FWM phenomenon in a single SOA and single CW pump capable of simultaneously converting two different data streams with low input powers. For mixed modulation formats at 10-Gb/s negligible penalty was obtained and for mixed bit rates at speeds up to 40-Gb/s moderate penalties were found, all with minor dependency on the introduction of a second simultaneously converted channel (< 1.1 dB). The ASK modulation did not result in XGM since the modulated signals at the SOA's input were more than 20 dB lower than the CW pump, insuring deep saturation of optical gain as well as allowing the desired degenerated FWM process to dominate. The CW and carrier's power should be optimize as a compromise between the FWM efficiency, ASE suppression, gain-clamping and the induced dynamic gain compression. Better performance could be obtained with lower noise SOAs, such as quantum-dot-based devices, or with a device enabling higher saturation power. In these cases, the strong optical gain and FWM efficiency should be maintained but the output OSNR improved. With the demonstrated minor degradation of power penalty when a second channel is introduced, the suggested scheme is suitable for many applications in all-optical routers, enabling asynchronous operation as well as operation with different modulation formats and bit rates up to 40 Gb/s.

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