Wideband All-Optical 3R WDM Regeneration Based on Dual-Pump Parametric Amplifier

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Abstract: Simultaneous all-optical 3R regeneration of WDM channels is demonstrated, based on dual-pump parametric amplification with sinusoidal modulated pumps. We observe receiver sensitivity improvement better than 1.5dB for five WDM channels modulated with 10Gb/s NRZ-OOK data.
OCIS codes: 190.4410 Nonlinear optics, parametric processes, 130.7405 Wavelength conversion devices

1. Introduction

3R regeneration of optical channels is an essential requirement in long-haul links. All-optical 3R techniques are of particular interest as regeneration based on optical-electrical-optical conversion is energy inefficient and limited in terms of operating speed. As WDM technology is widely used in current high speed systems and necessary for future flexi-grid networks, optical regeneration of WDM channels is getting noticeable attention, while uniform channel performance and low crosstalk are its main challenges. The corresponding efforts are mostly focused on converting the initial WDM signal into time or space-multiplexed signals, perform the processing and then convert back to the WDM scheme. This approach works well for small number of channels (up to 4) but in practice as the channel count increases, the solution fails to be scalable [1].

Amongst all 3R techniques, optical parametric amplifier (OPA) is of particular interest as it preserves both amplitude and phase information [2,3]. One way to enable a uniform regeneration for WDM channels is to use dual-pump OPA (2P-OPA) where by setting the right dispersion parameters, a uniform flat gain is obtained over a large wavelength range [4]. Therefore, operating in saturation regime provides uniform 2R WDM regeneration (re-amplify, re-shape) over that range. If the pumps are intensity modulated, the gated gain creates a time window which has re-timing property and enables a full 3R scheme. In this paper we present a proof-of-principle 3R optical amplitude regeneration of five 10 Gb/s on-off keying (OOK) WDM channels in 2P-OPA with sinusoidal modulated pumps. The proposed system can be used in cascade with phase-sensitive (PS) OPA [5] to enable phase regeneration of quadrature modulation formats as well.

2. Principle, experiment and results

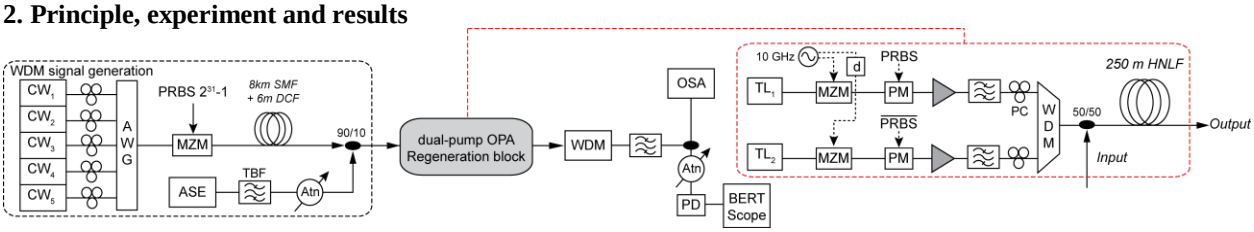

Fig. 1. Experimental setup. TL: tunable laser; MZM: Mach-Zehnder modulator; PM: phase modulator; d: electrical delay; PC: polarization controller, TBF: tunable bandpass filter; WDM: wavelength division multiplexer; OSA: optical spectrum analyzer; Atn: attenuator; PD: photo detector, BERT: bit error rate tester; CW: continuous wave laser; AWG: arbitrary waveform generator; ASE: amplified spontaneous emission.

The experimental setup for 3R WDM regeneration is shown in Fig. 1. The 3R block is a 2P-OPA with two pumps intensity modulated by 10 GHz sinusoidal waves. The pumps are synchronized by a delay, and phase modulated by a 2.5 GHz PRBS to increase the Brillouin threshold. Each pump is amplified by an EDFA, filtered by a 1 nm width filter and launched into a HNLF through a 50/50 coupler. The HNLF is L = 250 m long with ZDW at 1580.1 nm, nonlinear coefficient γ = 12 $W^{-1}m^{-1}$ and dispersion parameters $\beta_3 = 3\times10^{-41}$ $s^3m^{-1}$and $\beta_4 = 3\times10^{-55}$ s^4m^{-1}. The WDM input is five continuous wave (CW) lasers spaced by 300 GHz and coupled through an arrayed waveguide grating. The combined lasers are intensity modulated by a PRBS with 2^{31}-1 word length. The channels are decorrelated by passing through 8 km of SMF. To characterize the regeneration, signals are intentionally degraded by combining with ASE via a 90/10 coupler. The in-band OSNR of a channel is set by a tunable attenuator and bandpass filter. At regenerator output, the pumps are removed by a WDM filter while individual channels are selected by a 0.8 nm filter and detected on a 10 GHz detector. A bit error rate tester (BERT) is used to evaluate the performance of channels.

The OPA is optimized to yield an exponential gain (11 dB) which generates a Gaussian time window over 32 nm (1564 to 1596 nm) [4]. Figure 2(a) depicts the experimental and theoretical transfer function (TF) of the 3R block with five WDM channels. Clear saturation is observed for input power around 4 dBm. We choose the operating

region (shown by an arrow representing the 14 dB extinction ratio obtained from the modulator) such that zero level is in linear gain regime while mark level locates in saturated regime. This condition is preferred, as it leads to noise squeezing at mark level while avoiding severe inter-channel crosstalk due to high input power. Indeed, crosstalk arises from cross-gain modulation and spurious FWM and its power is proportional to the relative signal output power to the pump input power [6]. If this ratio is kept low enough, crosstalk effect is minimized as will be shown.

To verify the regeneration property of this scheme, we set the OSNR of the middle channel to 23 dB (non-degraded channels OSNR > 35 dB) and measured BER of the regenerated channel in presence of other channels, shown in Fig. 2(b). Three values of signal power, P_S, are considered to monitor the crosstalk. The back-to-back BER is also included for comparison. We verified that the regeneration block introduces negligible penalty (0.1 dB) to the back-to-back measurement by measuring BER after regeneration of an already pristine signal. For P_S = 2 mW, the BER of the degraded channel is improved and a sensitivity gain of 1.5 dB is measured. Similar improvements were obtained with OSNR degradation to 28 dB and 19 dB. In addition, we measured a jitter reduction from 4.6 to 1.4 ps, with the jitter after the OPA is governed by the electrical jitter used to modulate the pump and residual effect from the pump phase modulation. By increasing the input power to P_S = 8 and 20 mW, BER degradation is observed with BER floors appearing respectively at 10^{-6} and 10^{-4}, due to inter-channel crosstalk.

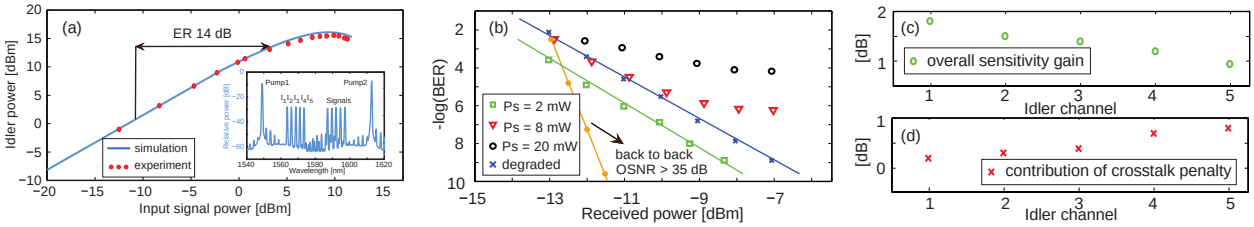

Fig. 2. (a) Experimental (red dot) and theoretical (blue line) static transfer function of regeneration block for five WDM channels (b) BER of degraded (23 dB OSNR) and regenerated middle channel at P_S = 2, 8 and 20 mW, (c) overall sensitivity gain and (d) contribution of crosstalk penalty for each channel at 10^{-9} BER level with 23 dB OSNR.

The performance of all five channels with P_S = 2 mW was measured. Figure 2(c) shows the overall sensitivity gain of each channel (in presence of other channels) at 10^{-9} BER level when the initial OSNR of the desired channel is set to 23 dB. The crosstalk penalty is also plotted in Fig. 2(d). This value is obtained by comparing the regenerated BER of single-wavelength and multi-wavelength input at OSNR > 35 dB. It is observed that while all channels are regenerated, the BER gain is slightly reduced (from 1.9 dB to 1 dB) due to the growing inter-channel crosstalk. In fact for regenerated channels closer to the ZDW, the efficiency of spurious FWM and thus the interference level increases as could be seen in Fig. 2(a) inset showing the output spectrum of regeneration block. However, by optimizing signal power and pump wavelengths, crosstalk effects can be controlled to some extent such that additional channels could be added. Finally, a crucial issue in 3R WDM regeneration is the inline synchronization. Simultaneous re-timing through a single time window requires that all bits are synchronous. In our experiment the bit synchronous operation is achieved by a 6 m long DCF which roughly aligns the bit slots within ±8 ps. The measured BER in all cases is constant over 60 ps detuning range corresponding to 60% of the bit slot. Therefore, within 44 ps detuning range of inline modulation time window, all WDM channels experience regeneration such that some error margin in the synchronization is possible. Clearly as the data rate increases, more precise synchronization is required.

3. Conclusion

We demonstrated simultaneous 3R optical WDM regeneration. We proposed 2P-OPA with sinusoidal modulated pumps as the regeneration block. Performance improvement was measured in terms of overall receiver sensitivity gain for five WDM channels modulated with 10 Gb/s NRZ-OOK data. We observed sensitivity gain better than 1.5 dB in simultaneous regeneration of five WDM channels. Our method improves the scalability of WDM regeneration by increasing the channel count without any need to change system complexity. This technique can easily operate at 40 Gb/s and also in cascade with phase regeneration techniques.

4. References

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