Wavelength Multicasting and Amplification of 5 Gb/s Data in the 2 Micron Band

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Abstract: We report wavelength multicasting to three 5Gb/s channels around 1950nm via broadband four-wave-mixing between RZ-OOK modulated pump and O-band signals. The thulium-assisted configuration enables high fidelity copying and output powers of 10's of mW.
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1. Introduction

Several works have recently presented advances in the field of fiber communications in the 2-µm window. Hollow-core photonic band gap fiber have proved able to transmit light in this band with very low loss, and thulium-doped fiber (TDF) amplifiers can be used to amplify channels distributed over more than 150 nm (approximately 1900-2050 nm) [1]. Moreover being able to generate and process light in this band can be advantageous for CO_2 detection and spectroscopy, or even to pump parametric sources in order to generate light further into mid-infrared. As far as communications are concerned, important network functionality is the ability to multicast information in an efficient manner. Indeed more and more applications, such as streaming, video calls or remote medicine, would benefit from a fast and simple way to send data from one to many network users.

Given the need for user scaling capabilities and efficiency, an interesting method is to leverage third-order wideband parametric conversion. While various architecture were proposed and demonstrated, one approach makes use of a Watt-level, intensity or modulated pump, launched in a nonlinear waveguide, such as fiber [2] or silicon nanowires [3,4], together with a set of continuous-wave (CW) signals, wavelength multiplexed and spectrally positioned close to the pump. Under proper dispersion conditions, the pump intensity modulation is imprinted on the idlers generated along the propagation and can also be copied on the signals given sufficient parametric gain.

While most of these experiments have only addressed the need for multicasting in the C- and L-band, fiber optical parametric amplifiers (FOPA) are able to generate powerful CW or intensity modulated light around 2 micron when they are used in conjunction with TDF amplifiers [5,6]. Moreover since the reported FOPAs are operating in the small signal regime, adding CW channels in O-band transparently results in the generation of multiple spaced channels in short-wave infrared (SWIR). Combining this method with the one previously described for C-band multicasting, we detail in this abstract the generation and characterization of 1-to-3 multicasting of 5 Gb/s RZ-OOK channels around 2 µm. The channels obtained are not only error free but are also significantly amplified resulting in an efficient multicasting operation.

2. Principle and experimental setup

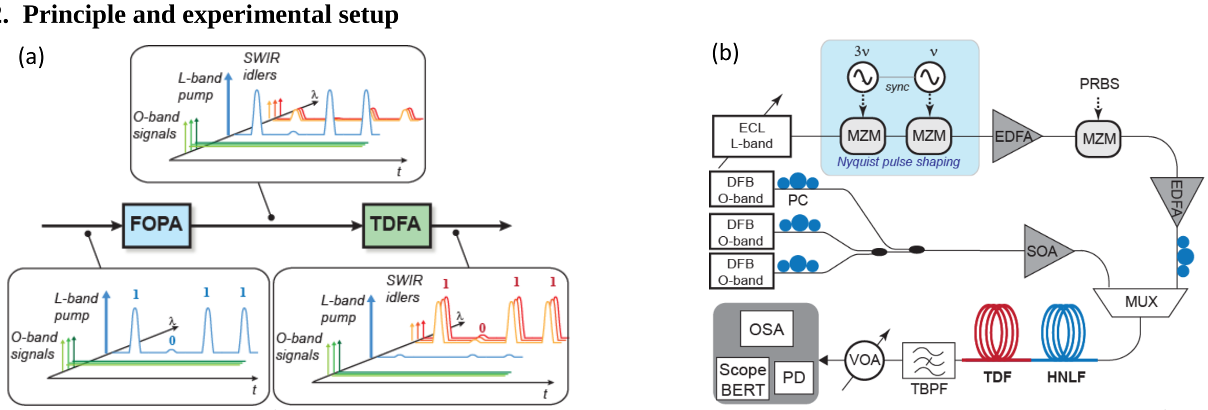

Fig. 1. (a) Schematic principle of the multicasting operation. (b) Experimental setup with ECL: external cavity laser, DFB: distributed feedback semiconductor laser, PC: polarization controller, MUX: 1310/1550 nm wavelength multiplexer, TBPF: tunable band pass filter, VOA: variable optical attenuator, OSA: optical spectrum analyzer, PD: 2 µm, 22 GHz photodetector.

The principle is depicted in Fig. 1(a). The intensity modulated pulsed pump is coupled with *N* signals in the O-band (*N* = 3 shown here). At the output of the FOPA, *N* idlers in the SWIR band carry the same data. The idlers are subsequently amplified in a TDFA directly pumped by the original L-band pump, for an efficient scheme resulting in multicasting and amplification. The TDFA also serves to filter the O-band signals. The experimental setup is shown in Fig. 1(b). A 1567.5 nm pump from an external cavity laser is launched through two Mach-Zehnder modulators (MZM) driven at frequency ν and 3ν, respectively (with ν = 5 GHz in our configuration). Under proper bias and clocks synchronization conditions, this arrangement results in a sinc-shape pulse train with a 1/9ν seconds peak-to-zero crossing width [7]. This versatile modulation scheme, which allows for an electrical control of the pulse width and repetition rate, represents a straightforward way to generate a high quality, fast pulsed source from a CW laser. The pulse train is then gated by a third modulator driven by a 2^{31}-1 pseudo-random bit sequence (PRBS) to emulate the data to be replicated on the multicast output. The pulse train is then amplified to 1.7 W average in an erbium-doped fiber amplifier (EDFA) and multiplexed with three CW O-band signals (set at 1302, 1308 and 1311 nm). Before the multiplexing, the signals are coupled together via 50/50 couplers and then amplified to a level comprise between 0.9 and 3 mW in a semiconductor optical amplifier (SOA). The signal powers after the SOA vary due to the initial unequal power of the three O-bands lasers and the different coupling ratios they undergo.

All waves are launched in a 30 m piece of highly nonlinear fiber (HNLF), giving rise through four-wave mixing to three idlers at 1947, 1955 and 1968 nm. The HNLF has an average zero-dispersion wavelength located at 1569 nm and a fourth order dispersion term negative in average. Previous studies have shown that pumping this fiber at 1567.5 nm enables the most efficient conversion from the O-band to around 1960 nm [6]. Moreover the dispersion fluctuations along the waveguide give some latitude in the spectral positioning of the waves and therefore allows for the simultaneous conversion of multiple channels, necessary for the multicast operation

At the HNLF output, an 11.5 m TDF piece is directly appended in order to recycle the pump power after the HNLF. The parametric mixer works in small signal regime, the undepleted pump thus represents a large amount of unused power at the output of the FOPA. The L-band pump can however excite the Tm^{3+} ions that subsequently transfer their energy to the idlers, improving the energy efficiency and output power of the device. The amplified idlers are then selected using a tunable bandpass filter with a 2 nm bandwidth and sent to the characterization section, consisting of an optical spectrum analyzer, and a 22.5 GHz 2 micron photodiode followed by an oscilloscope or the bit error rate tester (BERT).

3. Multicasting results

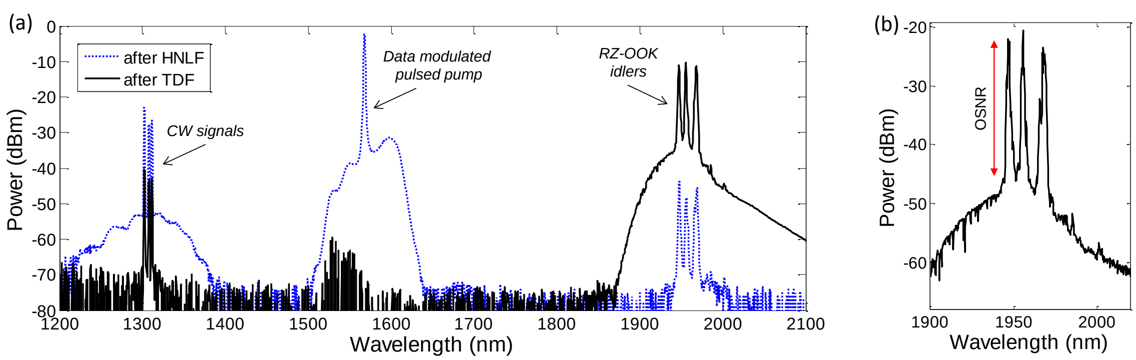

Fig. 2. (a) Spectrum at the output of the HNLF (dashed line) and at the output of the TDF (solid line), OSA resolution: 1 nm; (b) Zoom on the three idlers after TDF, OSA resolution: 0.05 nm.

The spectra of the multicast idlers at the HNLF output and after the TDF are shown on Fig. 2(a). While an optical attenuator was placed before the optical spectrum analyzer for all recorded spectra, the attenuation function is taken into account to retrieve conversion efficiencies (CE) and power levels. The CE, calculated from the signal to the idler at the output of the HNLF, is of -19.5, -21 and -21.2 dB at 1947, 1955 and 1968 nm, respectively. These CEs do not take into account the idlers duty cycle and we consider only their average power. The variation in CE comes from the uneven phase matching at various pump-signal detuning. This unequal power is partly compensated for by the TDFA as can be seen on Fig. 2(a); more than 30 dB of gain is obtained on all idlers while the L-band pump is completely depleted and the original O-band signals attenuated by 15 dB. The output power of each multicast channels integrated over their whole spectrum is 25, 33 and 63 mW at 1947, 1955 and 1968 nm, respectively. The optical signal-to-noise ratio (OSNR, peak to spontaneous emission spectral amplitude) is larger than 23 dB, as seen on Fig. 2(b), for all three channels. It can also be seen from Fig. 2(b) that the channels spectra deviate from the transform limited case for 1/9ν long pulses, which is ascribed to the compression of the idler pulses but also to the self-phase modulation (SPM) undergone by the pump in the HNLF. SPM broadens the pump spectrum and its spectral width is then transferred to the idler, with an efficiency that depends on the detuning, explaining the different spectra for each channel. Important parameters of the multicasting process, namely CE, gain and power for the three channels, are summarized in Fig. 3(a).

To characterize the multicasting performance, the channels were selected individually using the SWIR tunable grating filter, having a 2 nm bandwidth that encompasses most of their spectrum. The filtered output is sent to the photodiode connected to a BERT (synchronized with the PRBS generator). The waveforms are also observed on an oscilloscope and are shown in Fig. 3(b). The actual pulse width could not be retrieved from the observed waveforms due to the limited bandwidth of the receiver used; indeed the initial pump pulse already has a 45 GHz spectral width.

(a)

Idler	CE (HNFL)	Gain (TDF)	Output Average power
1947 nm	-19.5 dB	32.8 dB	25 mW
1955 nm	-21 dB	38 dB	33 mW
1968 nm	-21.2 dB	34.2 dB	63 mW

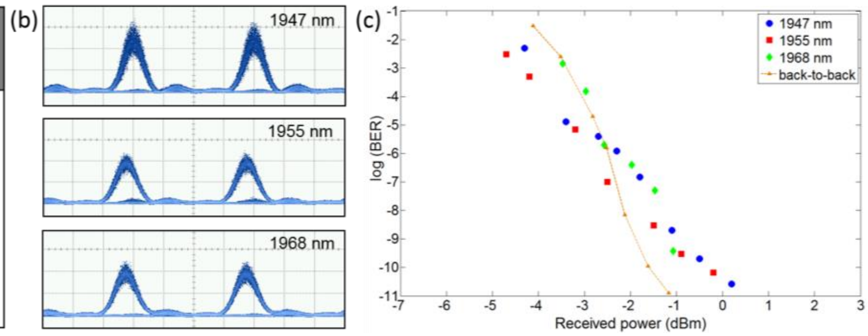

Fig. 3. (a) Idler conversion efficiencies (not taking into account the duty cycle), TDFA gain and output average power. (b) Eye diagrams (recorded on a 22.5 GHz detector) of the multicast channels at 1947 nm, 1955 nm and 1968 nm for an input power of -5 dBm. Time scale: 50 ps/div, voltage scale: 40 mV/div. (c) BER curves as a function of total integrated power of each channel at 5 Gb/s.

As expected from the retrieved OSNRs, the eyes are wide open for all three channels at an input power of -5 dBm and an error-free data replication from the pump to each idler is expected. The BER measurements, shown as a function of total integrated power, confirmed the good and uniform performance of the multicast operation as shown in Fig. 3(c). The BER increases quite rapidly when the received power is attenuated, although the observed eyes remained completely open as can be seen in Fig. 3(b). We believe our measurements are limited by the clock jitter in the BERT, to which NRZ signal detection is very sensitive. Thus the back-to-back measurement, performed on the pump before the second EDFA, exhibits a similar behavior. The BER measurements fully demonstrate that an error-free wavelength multicasting is possible with this scheme, with very little penalty.

In conclusion, we have demonstrated multicasting and amplification of a 5 Gb/s signal to the 2 micron band. Three error free channels with more than 25 mW of average power were obtained. Higher output powers and lower penalty could be easily obtained with a lossless O-band wavelength multiplexing system, enabling the independent amplification of each signal to over 10 mW before being combined to the FOPA. While maintaining the same conversion efficiency, a larger idler power would result in a better seeding of the TDF amplifier stage and therefore an OSNR improvement on each channel. Moreover more O-band lasers could theoretically be coupled into the HNLF to increase the number of multicast channels before triggering the strong signal regime of the parametric mixer. The maximum number of channels would then mostly be defined by their spectral width at the HNLF output and thus by the amount of SPM undergone by the pump. Finally, contrarily to schemes where the OOK data are encoded on the signal(s) [8], this method doesn't require any phase dithering of the pump to quench Brillouin scattering since sub-ns pulses are used.

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