Tunable Thulium-Assisted Parametric Generation of 10 Gb/s Intensity Modulated Signals Near 2 μm

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Abstract: *We report the demonstration of an all-fiber 10Gb/s modulation capable source near 2µm, tunable over more than 60nm with powers exceeding 2dBm, based on parametric conversion and appended Thulium amplification.*

Introduction

During past years, efforts have been focused on the design of fiber components and communications systems operating near 2 µm[1]. However, tunable laser sources and fast electro-optics modulators at these wavelengths are for the time being only emerging and lack the performance and versatility of their near infrared counterparts. To overcome these limitations, work has been recently conducted on wavelength conversion of modulated data from the conventional communication windows, such as O- or C-band, to the short wave infrared (SWIR) via four-wave mixing (FWM)[2,3]. However, sources of this kind relying only on distant parametric conversion in highly nonlinear fibers (HNLF) have a limited tunability, mainly dictated by the relatively small spectral region with sufficient conversion efficiency[4]. Recently we have proposed and demonstrated a widely tunable SWIR source reaching high continuous wave output powers by relying on Thulium assisted parametric conversion from the O-band[5]. Here we demonstrate that our proposed source can be used for transferring amplitude modulated data to the SWIR with an improved tunability due to the large gain spectrum of the Thulium doped fiber amplifier section. We performed measurements up to 10 Gb/s, limited by the bandwidth of our available photodiodes. We demonstrate that the source is tunable in wavelength from 1904 nm to 1968 nm with output powers up to 9 dBm. Wide open eyes are observed over the entire tuning bandwidth.

Experimental setup

The setup consists in two distinct stages. Firstly an intensity modulated SWIR idler is generated from FWM in a HNLF between a modulated O-band signal and a high power C-band pump (FOPA stage). Secondly, signal, pump and idler waves are directly injected into a Thulium doped fiber piece where the high remaining C-band pump power excites the Tm^{3+} ions for further amplification of the SWIR idler[5] (Thulium doped fiber amplifier -TDFA- stage).

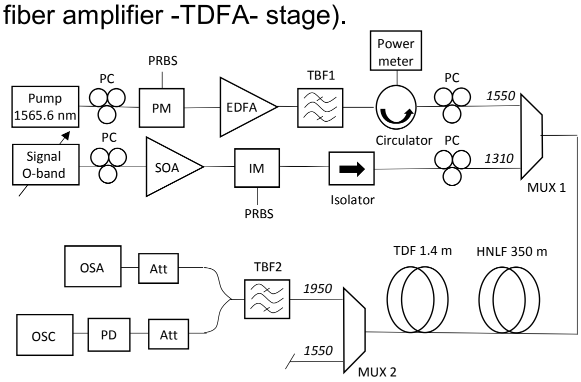

Fig. 1: Experimental setup. PC: polarization controller, PM: phase modulator, PRBS: pseudo-random bit sequence, SOA: semiconductor optical amplifier, EDFA: Erbium doped fiber amplifier, TBF: bandpass filter, IM: intensity modulator, HNLF: highly nonlinear fiber, TDF: Thulium doped fiber, MUX: wavelength multiplexer, Att: attenuator, OSA: optical spectrum analyzer, PD: photodetector, OSC: oscilloscope.

The setup is sketched on figure 1. The FOPA section consists in a CW pump from an external cavity laser (ECL) at 1565.6 nm, phase-modulated with a pseudo-random binary sequence (PRBS) to suppress stimulated Brillouin scattering (SBS), and amplified by a high power Erbium doped fiber amplifier (EDFA). A power of 31.7 dBm is obtained after filtering of the amplified stimulated emission (ASE) by a tunable band pass filter (TBF). A second ECL tunable over the O-band provides the signal wave. The signal is amplified by a semiconductor optical amplifier (SOA) before being intensity-modulated by a 2^{31}-1 PRBS. It is then coupled with the pump through a 1310/1550 nm wavelength multiplexer (MUX1) and both waves are injected in a 350 m long HNLF while the SBS return losses are monitored through a circulator. We characterized the HNLF and extracted the following parameters: an average zero dispersion wavelength (ZDW) of 1569.05 nm, 3^{rd} and 4^{th} order dispersion $\beta_3 = 4.6\cdot10^{-2}$ ps^3/km, $\beta_4 = -2.9\cdot10^{-5}$ ps^4/km and $\gamma = 14$ W^{-1}km^{-1}. After the HNLF, the TDFA simply consists in a 1.4 m long piece of a commercially available TDF appended to the HNLF. The Thulium is therefore directly pumped by the C-band parametric pump for an optimized power utilization. Subsequently to its generation in the HNLF and amplification in the TDF, the SWIR idler is separated from the pump by a 1550/1950 nm multiplexer (MUX2). A tunable 1 nm wide bandpass filter (TBF) specifically designed to operate around 2 μm is used to select the idler and reject the remaining pump and signal power as well as the SWIR amplified spontaneous emission. The filtered idler is finally attenuated and monitored on both an optical spectrum analyzer (OSA) and on the oscilloscope after detection by a 9 GHz InGaAs amplified photodiode. Note that a C-band 27 dB attenuator was used to limit the signal power sent into the OSA for every spectrum recording. Its attenuation over the entire spectrum from O-band to SWIR was characterized using a custom supercontinuum source. The attenuation of this component reached the stated 27 dB in O- and C-band but dropped to 20 dB around 1950 nm. This tilt in attenuation was taken into account for all conversion efficiencies and power calculations.

Results and discussion

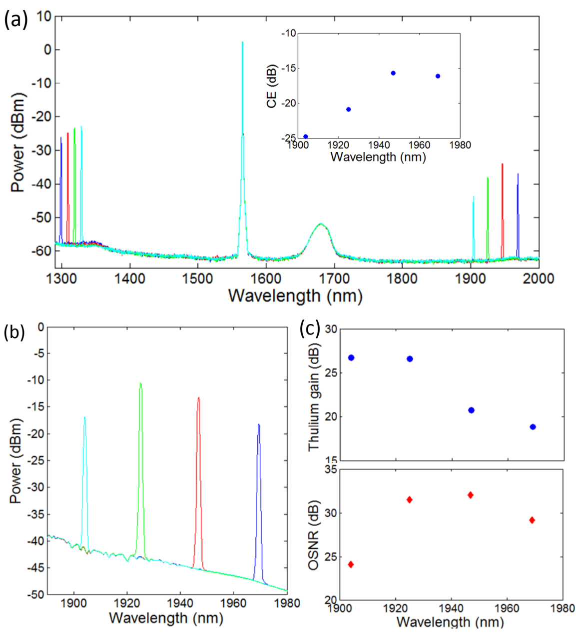

Fig. 2: (a) Superimposed spectra recorded after the HNLF for four signal wavelengths at 1300, 1310, 1320 and 1330 nm. Inset: conversion efficiency (b) Spectra of the amplified idlers after the TDF fiber. (c) Top: gain measured on the idler after TDF; bottom: measured OSNR at the output of the TDF. (OSA resolution: 1 nm).

First, we evaluated the performance of the parametric conversion by recording the spectra at the output of the HNLF. For demonstration purposes four O-band wavelengths were assessed. Parametric conversion of signals at 1300 nm, 1310 nm, 1320 nm and 1330 nm resulted in the generation of idlers at 1969 nm, 1947 nm, 1925 nm and 1904 nm, respectively. The superimposed spectra are shown in figure 2a. The measured conversion efficiency is shown in the inset of the figure. The combination of normal dispersion regime pumping and negative β_4 enables a targeted parametric conversion with little to no parametric noise amplification. The conversion efficiency reaches a maximum of -15 dB at 1947 nm. Clear narrow band amplification is not observed due to dispersion fluctuations in the HNLF leading to a large parametric gain broadening[4]. For our purposes, such broadening proves beneficial as idler generation with conversion efficiencies of at least -25 dB is observed over more than 60 nm. Finally we observe that the parametric pump is not depleted such that high power is available for pumping the Thulium stage.

We then recorded the spectra corresponding to the same input signals at the output of the TDF, which are displayed in figure 2b. In the Thulium the idlers undergo an amplification of up to 27 dB between 1900 and 1930 nm (figure 2c). A reduced ripple of 7 dB is observed between the 4 targeted wavelengths. We calculated that the obtained output SWIR modulated power varied between 2 dBm at 1969 nm and 9 dBm at 1925 nm. Taking into account the initial power of the O-band signal, we obtained very good overall conversion efficiency, ranging from 0 to 5.7 dB. An optical signal to noise ratio (OSNR), also plotted in figure 2c, in excess of 24 dB is obtained. The idler located at 1907 nm has the lowest OSNR due to the -25 dB conversion efficiency from the FOPA stage. Finally the quality of the generated SWIR data signal is assessed by recovering eye diagrams on the oscilloscope. The system was tested for data patterns of 7 Gb/s and 10 Gb/s due to the limitations imposed by the tunable filter and photodiode bandwidth. The input eyes recorded at 1320 nm with a C-band amplified 10 GHz photodiode are shown in figure 3. Distortions are already observed for a data rate of 10 Gb/s due to the limitations imposed by C-band equipment.

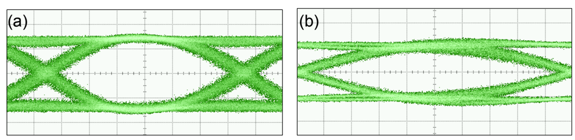

Fig. 3: (a) Eye pattern for a signal at 1320 nm modulated at 7 Gb/s (20 ps/division). (b) Same signal modulated at 10 Gb/s (10 ps/division).

Afterwards, the same measurements are performed for the amplified and filtered idler at the output of the setup, using the 2 μm amplified photodiode. It should be noted that the combination of WDM and 2 µm filter added 7 dB of losses before the photodiode. However due to the high power reached in the SWIR band, an additional tunable attenuator had to be positioned before the photodiode to limit the input power. Figure 4 presents the eye patterns recorded for the four different idler wavelengths when the modulation frequency of the signal is set at 7 Gb/s. Figure 5 shows the results for a 10 Gb/s modulation.

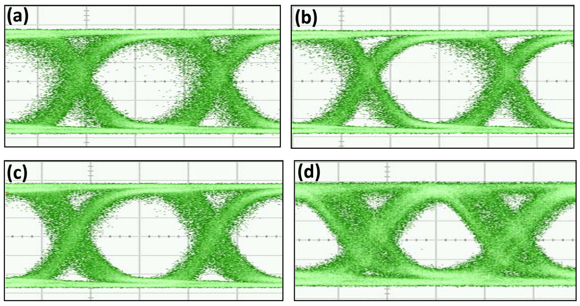

Fig. 4: Eye patterns for a 7 Gb/s modulation when the idler is located at (a) 1904 nm, (b) 1925 nm, (c) 1947 nm and (d) 1969 nm. Time scale: 50 ps/division.

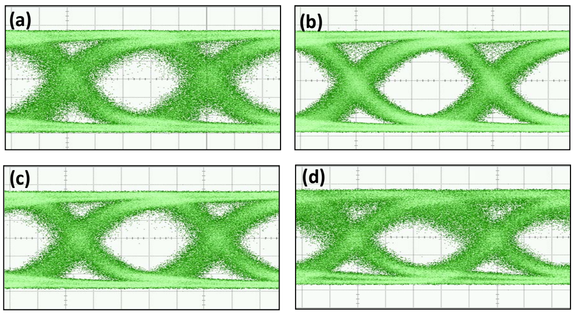

Fig. 5: Eye patterns for a 10 Gb/s modulation when the idler is located at (a) 1904 nm, (b) 1925 nm, (c) 1947 nm and (d) 1969 nm. Time scale: 20 ps/division.

Clear open eyes are recorded over the entire 60 nm bandwidth despite the addition of noise. We have tracked that the noise can be mainly attributed to the wavelength conversion in the FOPA stage. The noise can be reduced by optimizing the SBS suppression in the HNLF such that a more pristine pump is obtained, and by using shorter length of fiber HNLF to avoid group velocity dispersion between the distant signals. The Q factor of the recorded eyes was evaluated, taking into account noise on ones and zeroes. The results are shown in figure 6 and confirm the good data conversion between the O-band and the SWIR band. Average Q factors of 22 dB and 17.7 dB are obtained for 7 Gb/s and 10 Gb/s, respectively. The idlers located on the longer edge of the wavelength tunable range, showed a degraded Q factor despite a better OSNR at the output of the source. Optimization of the Thulium section for amplification in the longer wavelength range, such as utilizing a two stage design[5], could alleviate such degradation. Indeed the peak of the Thulium gain obtained from a 1.4 m long fiber is located at 1.85 µm.

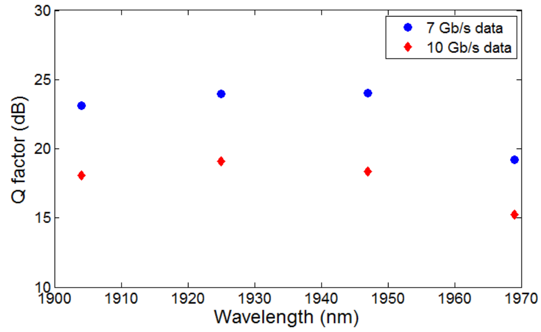

Fig. 6: Q-factor measurements on the three idler wavelengths at a bit rate of 7 Gb/s and 10 Gb/s.

Conclusions

We have demonstrated that our source relying on an integrated combination of a FOPA and a TDFA can efficiently transfer intensity modulated data to the SWIR band. The source shows error free eyes over more than 60 nm for 7 Gb/s data and over more than 40 nm for 10 Gb/s data. The wide tunability stems from the high SWIR output power (up to 9 dBm) obtained from our source and maintained throughout the tuning range. The setup also has the potential to project several O-band intensity modulated signals into SWIR, thus enabling the integrated generation of wavelength division multiplexed channel directly around 1.95 µm. Moreover with this architecture the pump power is used to pump both stages successively, yielding a wall-plug efficiency higher than for simple parametric converters of the same kind.

Acknowledgment

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