Widely Tunable Picosecond-Pulsed Source near 2 μm based on Cascaded Raman Wavelength Shifting

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Abstract *We demonstrate a cavity-less picosecond pulsed source near 2μm, tunable over more than 200nm based on third order cascaded Raman wavelength shifting. Up to 44% conversion is achieved for 100mW peak powers at 200MHz repetition rate.*

Introduction

The 2 μm spectral region has gathered significant interest during the past years as it is are well suited for sensing and communication applications[1]. Short wave infrared (SWIR) fiber sources based on classical fiber laser architectures have recently been demonstrated[2]. Alternative schemes based on parametric conversion in silica fibers, offering the advantages of a cavity-less design, have been reported these past years[3]. Relatively low power continuous wave (CW) generation as well as low repetition rate (of the order of the MHz) and high peak power pulsed regimes have been demonstrated[4,5,6,7]. In this paper we present the demonstration of an alternative design to the generation of a 200 MHz picosecond pulsed SWIR source based on the generation of second and third Raman Stokes peaks in a highly nonlinear fiber (HNLF). The source is tunable over more than 200 nm and features average powers near 1 mW as well as peak powers estimated at 100 mW.

Experimental setup

The generation of the SWIR Raman cascade relies on the injection of a C-band high peak power pulse into a 500 m long HNLF. The architecture of the setup is sketched in figure 1.

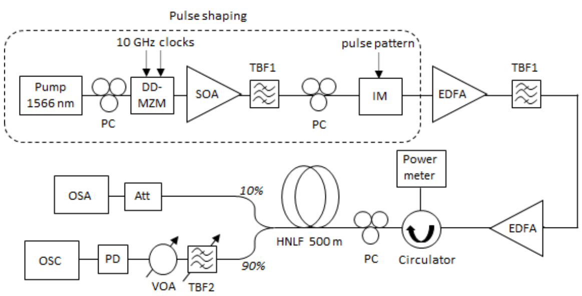

Fig 1: Experimental setup with PC: polarization controller, DD-MZM: dual-drive Mach-Zehnder modulator, SOA: semiconductor optical amplifier, TBF: tunable bandpass filter, IM: intensity modulator, EDFA: Erbium doped fiber amplifer, HNLF: highly nonlinear fiber, Att: fix attenuator, VOA: variable optical attenuator, OSA: optical spectrum analyzer, PD: photodetector, OSC: oscilloscope

The shaping of the pulse train is performed in two successive steps. The output of an external cavity laser (ECL) tuned at 1566 nm is first intensity-modulated through a dual-drive Mach-Zehnder modulator (DD-MZM) driven by two 10 GHz sine clocks whose relative phase and amplitude can be adjusted. A waveform made of nearly Gaussian pulses with a repetition frequency of 10 GHz and pulse duration (at half maximum) of about 43 ps is obtained after this first modulator[8]. In order to maintain the average power level required for subsequent amplification in a high power Erbium doped fiber amplifier (EDFA), this signal is amplified by a semiconductor optical amplifier (SOA) and filtered to remove the amplified spontaneous emission (ASE). The amplified waveform is then sent into a second intensity modulator driven by a pulse pattern having the following characteristics: 100 ps high-level duration and a duty cycle of 1/50. This pattern is synchronized with the clock driving the DD-MZM, and a high quality 200 MHz return-to-zero pulse train made of 43 ps pulses is thus obtained at the modulator output. In order to reach a pump power sufficient to stimulate the threefold Raman scattering in the HNLF, the pulse train is pre-amplified in a low-power EDFA whose ASE is filtered again and then boosted by a 5 W EDFA. A circulator is positioned right before the HNLF to monitor the back-scattered power due to stimulated Brillouin scattering (SBS) along with a polarization controller necessary to optimize the SWIR generation. Finally the pulse train is sent into the HNLF with an average power of 35 dBm.

The 500 m long segment of HNLF used has the following properties: a zero dispersion wavelength (ZDW) around 1610 nm, a third-order dispersion of $\beta_3 = 1.5 \cdot 10^{-2}$ ps^3/km, a fourth order dispersion assumed to be positive and a nonlinear coefficient of $\gamma = 10\ \mathrm{W}^{-1}.\mathrm{km}^{-1}$. By positioning the pump at 1566 nm, the fiber is pumped in the normal dispersion regime and power losses due to modulation instability generation are prevented. SBS being circumvented by the use of sub-ns pulses the dominant effect along the propagation is stimulated Raman scattering (SRS) with limited self-phase modulation[9], which leads to the generation of spectral components beyond 2 µm. The overall effect is monitored on the optical spectrum analyzer (OSA) by tapping some power directly at the output of the HNLF. A 1 nm wide tunable filter designed to operate around 2 microns (though tunable down to 1800 nm at the expense of increased losses) is positioned at the output of the HNLF to filter part of the spectrum and analyze only a narrow spectral fraction of the generated Raman cascade spectrum. This signal is characterized both spectrally on the OSA and temporally on the oscilloscope after detection by a 2 µm 9 GHz photodiode. It must be noted that 27 dB of attenuation was used for all spectra recording to limit the power sent into the OSA. The attenuation reached the stated 27 dB in C-band but dropped to 20 dB around 1950 nm. This tilt in attenuation was characterized with a custom supercontinuum source and taken into account for all power calculations. Before the photodiode, an additional variable optical attenuator was inserted to avoid photodiode saturation while visualizing the pulses.

Results and discussion

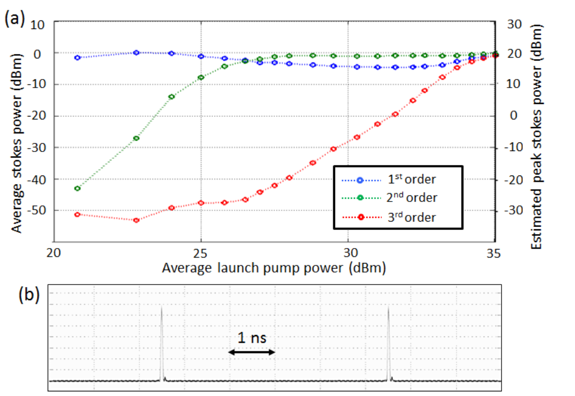

Fig. 2: (a) Average Stokes output power (left vertical axis) and estimated peak power (right vertical axis) as a function of the average pump power; (b) Input pulse pump train at 1566 nm observed on a 500 GHz optical sampling oscilloscope.

We first evaluated the evolution of the power conversion from the pump wavelength toward the Raman Stokes peaks as the average pump power was increased from 20 dBm to the maximum value of 35 dBm. As the pump power is set to 20 dBm, 1st order Raman peak near 1695 nm appears. For higher pumping power, power transfer is initiated toward the 2nd order peak around 1815 nm and finally toward the 3rd order peak around 1970 nm. Figure 2a shows the power measurements as a function of pump power. The powers are measured at the peak of the Raman within a 1 nm bandwidth. We were able to generate up to 3 successive Raman peaks that all converge toward a maximum average power of about 0 dBm. Taking into account the duty cycle applied to the pump we estimated that the maximum peak power obtained reaches 100 mW. This estimation however assumes that the duration of the pulses generated in SWIR is identical to that of the pump.

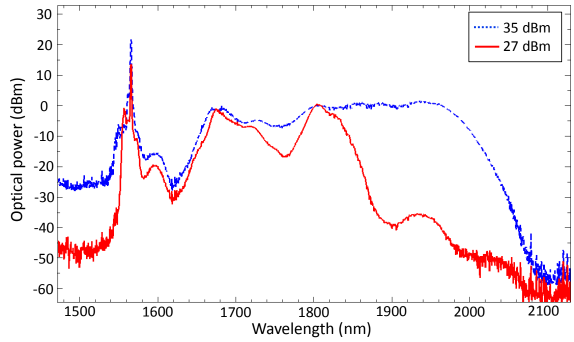

Fig. 3: Spectrum at the output of the HNLF for an average pumping power of 27 dBm (plain read line) and of 35 dBm (dotted blue line). The power was corrected to take into account the attenuation before the OSA.

Figure 3 shows spectra recorded at the output of the HNLF for an average pump power of 27 dBm and 35 dBm. The attenuation and its tilt were taken into account and true powers are displayed. The three Raman peaks are clearly visible for 27 dBm of pump, with the third one emerging. As pump power was increased, the 2nd and 3rd peaks started merging and such that a flat and wide supercontinuum is created in the HNLF for 35 dBm of average pump power. A ripple smaller than 3 dB is measured within the 1800 nm - 2000 nm range, with close to 44 % of the total power contained within the 7 dB bandwidth of the continuum.

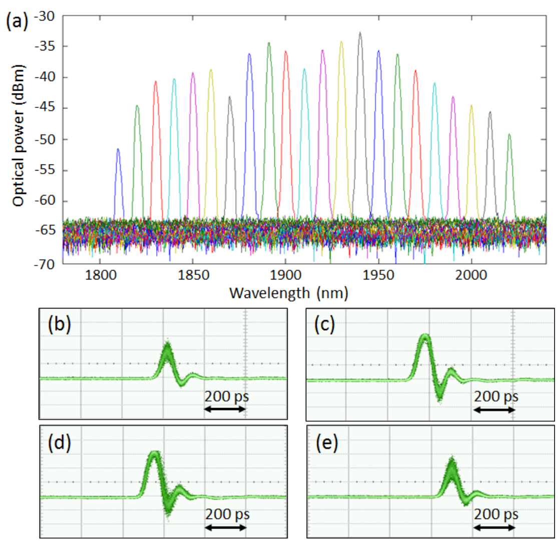

Fig. 4: (a) Superimposed spectra of filtered SWIR supercontinuum and the corresponding waveform detected on a 9 GHz photodiode for output source wavelength set at (b) 1820 nm, (c) 1850 nm and (d) 1970 nm and (e) 1990 nm (200 ps/div)

Afterward, the SWIR source obtained for a pump power of 35 dBm was temporally characterized by tuning the bandpass filter between 1800 nm and 2000 nm with 10 nm steps and observing the detected SWIR pulse train on the oscilloscope. Despite the limitation imposed by the 9 GHz bandwidth of our photodiode, the pulse train was clearly detected in all configurations and the results are displayed in figures 4 and 5. The superimposed spectra of the filtered SWIR supercontinuum are shown in figure 4a. The spectra reflect the wavelength dependent losses of the tunable band pass filter. Signals with wavelengths positioned on the edge of the filter tunable bandwidth experienced 15 dB more loss, which in turns limited the quality of the detection. Waveforms of four of the detected wavelengths, namely 1820 nm, 1850 nm, 1970 nm and 1990 nm are displayed in Figures 4b, c, d, and e, respectively. The resolution of the pulse width is limited by the impulse response of the photodiode, which clearly appears for all measurements. While the minimum measured pulse width was 50 ps, we can conclude that the detected pulses have a full width half maximum shorter than 50 ps. As expected edge pulses exhibit more noise due to excess losses through the filtering process. The overall normalized temporal characterization over the 1800 nm – 2000 nm wavelength range is plotted in figure 5. While the input power to the photodiode was controlled to maintain a constant level throughout the tuning process, some slight broadening of the pulses within the low loss region of the filter (between 1850 and 1950 nm) was still observed as can be seen in figure 5.

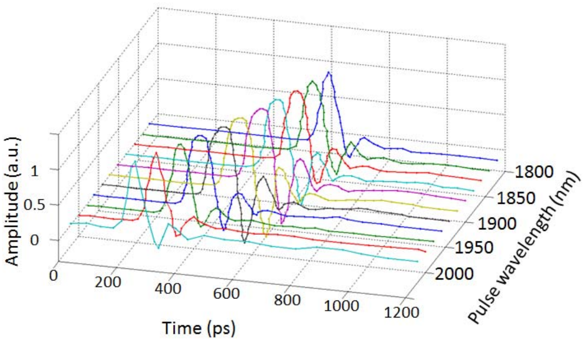

Fig. 5: Averaged detected SWIR pulses on the 9 GHz photodiode for various output wavelengths ranging from 1800 nm to 2000 nm.

Additionally, a quasi-linear temporal shift is observed as the wavelength was linearly swept, suggesting a linear chirp of the spectrum. It should be noted that an extended tuning range should be reachable as the 1st order and 2nd order Raman peaks merge within the supercontinuum (see figure 4a). However no filters were available at this wavelength range during the characterization of the source.

Conclusions

We have demonstrated a picosecond pulsed SWIR source with a 200 MHz repetition rate and relying on the filtering of a SWIR supercontinuum. The supercontinuum is obtained from efficient cascaded Raman wavelength shifting in a HNLF, leading to the merging of the second and third Raman Stokes order peaks. The obtained source exhibits a wide tuning capacity, expected to be larger than 200 nm. We could demonstrate the conversion toward SWIR of pulses shorter than 50 ps FWHM with an average power of 1 mW. We estimated that up to 44 % of the pump power is transferred to the wavelength region of interest. However the characterization of the source was limited by the tuning range of the 2 μm tunable bandpass filter and the relatively low bandwidth of the 2 μm detector. Additionally the delay experienced by the output pulses when the filtering wavelength is swept appears to be quasi-linear.

Acknowledgment

This work is supported by the European Research Council under grant agreement ERC-2012-StG 306630-MATISSE. The authors would like to thank the Institut Carnot Bourgogne and Institut Télécom, Télécom ParisTech for providing the HNLF.

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