Efficient broadband parametric conversion: reaching for the Mid IR

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ABSTRACT

In this paper, we report recent results on the efficient generation of SWIR sources exploiting broadband wavelength conversion in silica fibers. Optimized cavity-less designs of fiber parametric amplifiers (FOPA) associated with Thulium amplification capable of high CW powers, wide tunability and modulation will be presented. We also present how parametric conversion can be extended deeper in the Mid-IR by engineering of non-silica mixing platforms.

Keywords: Mid- infrared sources, nonlinear optics, wavelength conversion

1. Introduction

The short-wave infrared (SWIR) and middle-infrared (Mid-IR) are a core bands for molecular detection and identification. Hence, it hosts critical applications ranging from spectroscopy, health monitoring, sensing as well as free space communication [1]. To fully exploit the advantages of such spectral bands, versatile light generation and all optical processing capabilities are key elements. Recent developments in fiber lasers have shown the emergence of medium power tunable continuous-wave (CW) thulium-doped fiber lasers [2]. Pulsed operation can be achieved with optical parametric oscillators (OPO) or modelocked thulium-doped fiber lasers. They are widespread solutions despite possibly bulky setups, low repetition rates or limited tunability. Combining different mode of operations is also extremely difficult for a single architecture. An alternative approach to the generation of versatile sources is to rely on broadband wavelength conversion via degenerate four-wave mixing (FWM) [3]. The single pass and parametric nature of the process leads to replication of an initial signal to the targeted spectral band. However the low conversion efficiency of such broadband wavelength conversion limits achievable CW power or requires extremely high pump peak powers [4].

Here we will cover some of the recent advances made on versatile SWIR sources based on broadband wavelength conversion in silica fibers. We will first show how such cavity-less design associating telecom-driven parametric conversion and thulium amplification can lead to efficient light generation in the 2 micron spectral band. Various optimized designs capable of providing wide versatility in terms of operating modes will be described. The cavity-less nature, parametric origin and flexibility of the proposed source can offer new opportunities for Mid-IR applications.

2. Efficient wavelength conversion to the SWIR

In its simplest form, a parametric device uses a single pump wave that is coupled with a signal seed to a nonlinear waveguide. Efficient amplification and wavelength conversion is achieved by satisfying phase matching condition among pump, signal and idler waves. The advantages of parametric processes based on the $\chi(3)$ nonlinear tensor of the waveguide medium are numerous, in particular for the generation of light in distant spectral windows not easily accessible by conventional technology. The single pass, cavity-less, approach ensures replication of the signal properties to the idler wave as well as the promise for a mode-hop, widely wavelength tunable operation. Degenerate FWM based wavelength conversion to the SWIR (1.9 to 2.1 μm) can be achieved by coupling an O-band signal with a telecom band pump into a nonlinear transparent waveguide such as a silica highly nonlinear fiber (HNLF). However due to the stringent phase matching constraints and achievable nonlinearities, the parametric converter typically operates in an un-depleted pump regime such that most of the pump power remains unused. The consequential poor conversion efficiencies results in extremely low and usually inadequate, idler powers.

The operating principle of SWIR source is depicted in Fig. 1 and relies on the simple combination of a parametric converter stage together with a linear amplifying stage directly pumped by the parametric pump [5]. Degenerate FWM in the fiber optic parametric amplifier (FOPA) annihilates two pump photons located in the C-L band and generates one signal photon in the O-band as well as an idler photon in the SWIR. By tuning the signal, the idler can be widely tuned. The three waves are then directly coupled to a Thulium doped fiber where the remaining pump power exits the thulium ions into a metastable level such that light at longer wavelength can be amplified. The absorption and emission cross section of thulium are such that the parametric pump can be used for excitation while the idler wave falls in the amplified spectral region. Due to the very wide gain spectrum of thulium doped fiber amplifiers (TDFA), the entire range of idlers can be amplified. Such recycling of the parametric pump enables a much higher power transfer from the pump to the idler.

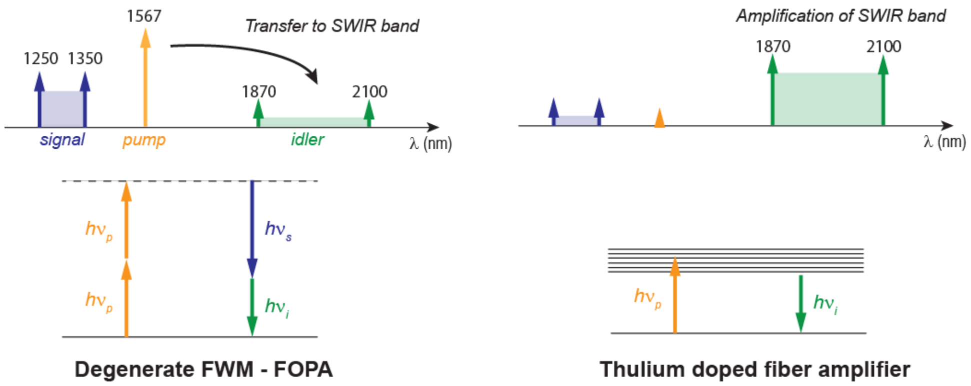

Fig. 1: Operating principle of high efficiency SWIR source. Degenerate FWM in the FOPA leads to the generation of an initial weak idler in the SWIR. A thulium doped fiber amplifier enables the re-use of the parametric pump and the amplification of the initial idlers. The signal is also attenuated The FOPA-TDFA architecture results in results in a versatile and energy-efficient source.

3. Source operation

The main advantage of the cavity-less, parametric origin of the source lies in its versatility. Depending on the format of the pump and/or signal, various modes of operation can be obtained, originating from the same simple principle. The basic architecture consists in a tunable continuous wave (CW) pump from an external cavity laser in the C-L band and a tunable CW signal in the O-band. The pump is amplified and coupled with the signal to a spliced cascade of highly nonlinear fiber (HNLF) and thulium doped fiber. Owing to the filtering effect of the TDF, no filter is required and the resulting SWIR light is directly monitored at the output of the TDF.

High power CW SWIR results from the combination of CW pump/CW signal. By pulsing the parametric pump, a high repetition rate pulsed SWIR source can be obtained [6]. Finally high quality data modulated SWIR light, with either non-return-to-zero (NRZ) [7] or return-to-zero (RZ) format, is generated from a data modulated signal/CW pump or CW signal/data modulated pulsed pump, respectively. Depending on the mode of operation, the lengths of fibers were adjusted to lead to the best performance. For CW operation, the length of HNLF was optimized at 350 m while a shorter segment of 30 m was used for pulsed operation to avoid unwanted nonlinear and linear effects. The TDF length can be adjusted to favour amplification is short or long wavelength regions, similarly to any amplifier design and depending on the desired outcome. Some of the experimental results are illustrated in Fig. 2.

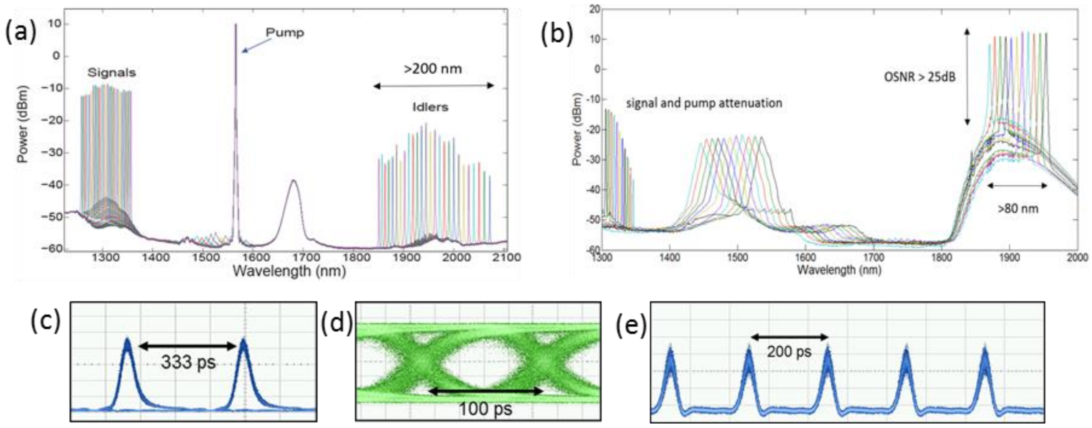

Fig. 2: (a) the output of a 350 m HNLF showing a broad conversion band originating from dispersion fluctuations, and (b) the output of the previous HNLF followed by a 4.5m TDF, featuring an equalized idler power over 700 mW; (c) 3 Gb/s data train embedded in pulse train at 1979 nm,(d) the eye pattern of a 10 Gb/s intensity modulated idler at 1947 nm generated by a CW pump and (e) pulse train at 1958 nm featuring a 5 GHz rep rate.

Aditional functionalities can also obtained by exploiting multiple simultaneous wave projections to the SWIR, to reach deaper into the SWIR or to perform multicasting. While the gain bandwidth of thulium doped fibers is wide, it extends only to approximately 2000 nm. Amplification to longer wavelengths (2000 – 2100 nm) can however be achieved with holmium doped fibers. The absorption cross section of holmium is relatively narrow with a peak at 1950 nm, which corresponds to the peak of emission for the fiber lengths and pumping powers used throughout these experiments The FOPA-TDFA assembly can therefore be modified in order to reach wavelengths up to 2.1 mm with the addition of an holmium doped fiber (HDF) amplification stage, of which the pump is generated directly from the initial FOPA-TDFA [8]. We take advantage of the broad conversion spectrum of the FOPA to simultaneously convert a fixed O-band signal toward 1950 nm and an additional tunable signal in the 2000-2100 nm band. After this parametric generation process, the idler at 1950 nm undergoes a large amplification in the TDFA while the idler beyond 2000 nm experiences only a slight gain. The amplified idler at 1950 nm then excites the $^5I_7$ upper state of the HDF with the de-excitation of this latter state then reinforces the longer-wave idler. A tunable source centered on 2050 nm is finally obtained at the HDF extremity since wavelength selection is achieved by simple tuning of the shorter-wavelength signal at the input of the HNLF. The output spectrum and evolution of the power ratio between idler and initial signal after each fiber (HNLF, TDF, and HDF) are shown in Fig 3. Clearly the shift of power from the short wavelength side of the SWIR towards the long wavelength side is obtained. Additionally, the transfer remains efficient with an overall transparency at the output of the source for wavelengths between 2010 till 2080 nm approximately

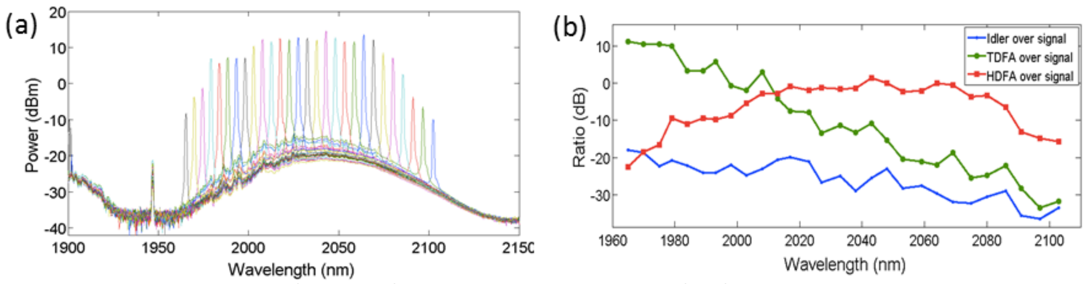

Fig 3: (a) Superimposed spectra of the amplified idlers when the signal is shifted from 1250 to 1300 nm. (resolution: 1 nm). Ratio of the idler power over its corresponding signal power after conversion in FOPA (blue), amplification in TDFA (green) and amplification in HDFA (red). This ratio was computed for a set of wavelength between 1970 and 2100 nm.

The above described FOPAs are able to generate powerful CW or intensity modulated light around 2 micron when they are used in conjunction with TDF amplifiers. Since the FOPA is operating in the small signal regime, adding CW channels in O-band transparently results in the generation of multiple spaced channels in the SWIR. As a proof of principle we recently showed 1-to-3 multicasting of 5 Gb/s RZ OOK data in the SWIR [9]. The multicast operation is obtained by combined a 1567.5 nm pulsed pump together with three CW O-band signals (set at 1302, 1308 and 1311 nm) to the cascade of 30 m HNLF and 11.5 m of TDF. Such architectures lead to the efficient generation of three RZ modulated idlers located at 1947, 1955 and 1968 nm. The output power of each multicast channels is measured to be 25, 33 and 63 mW at 1947, 1955 and 1968 nm, respectively while the optical signal-to-noise ratio remained larger than 23 dB for all three channels (Fig. 4). Wide open eye and error free BER were obtained in all cases. The number of channels can be easily increased by adding more O-band signals.

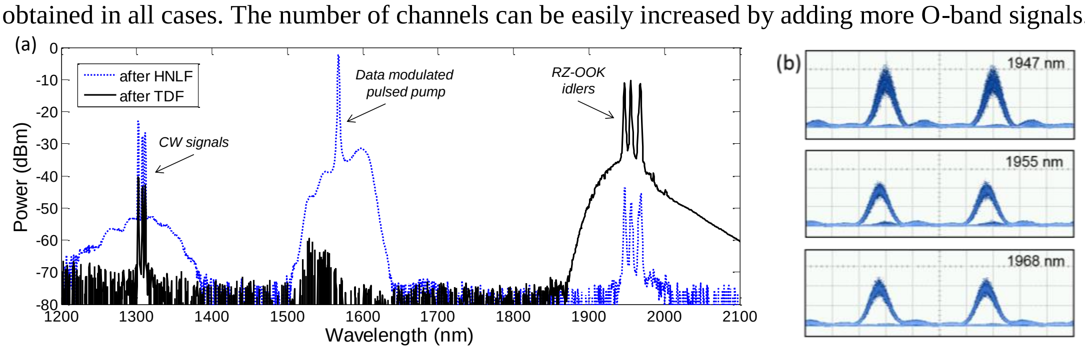

Fig 4: (a) Spectrum at the output of the HNLF (dashed line) and at the output of the TDF (solid line), OSA resolution: 1 nm; (b) eyes obtained in the SWIR.

4. Non silica platform

Photon mixing process is not inherently limited to any specific band, provided that the phase-matching condition can be met in a given nonlinear waveguide and sufficiently low loss waveguides can be fabricated. Given these constraints, moving deeper in the mid infrared, a nonlinear mixing stage specific to the mid-IR should be considered. Because of the excessive losses of silica beyond two micron, alternative materials exhibiting strong optical nonlinearity and large transparency windows in the MIR are under investigation. Beside silicon integrated platforms, promising all-fiber solutions are represented by microstructured chalcogenide optical fibers. Chalcogenide glasses have a wide transparency windows that can go up to 15 µm depending on the glass composition, and a third order nonlinearity a 1000 times that of silica [10]. To offset the strong material dispersion, control of their geometry is however essential to achieve phase matching for efficient FWM. Our recent research efforts have shown that small core GeAsSe microstructured fibers can be drawn with very good uniformity, leading to a zero dispersion wavelength close to 3 micron [11]. Continuous wave four wave mixing at 2 micron reaches conversion efficiencies of -25 dB with only mW of pump powers, without sign of saturation (Fig. 5). The fiber is a 27.5 cm long $Ge_{10}As_{22}Se_{68}$ photonic crystal fiber with 3 rings of holes, a core size of 4 µm and a diameter-to-pitch ratio r = 0.48 fabricated by PERFOS. For a pump at 1980 nm, propagation losses of 2 dB/m and dispersion of D = -183 ps/(nm km) were measured.

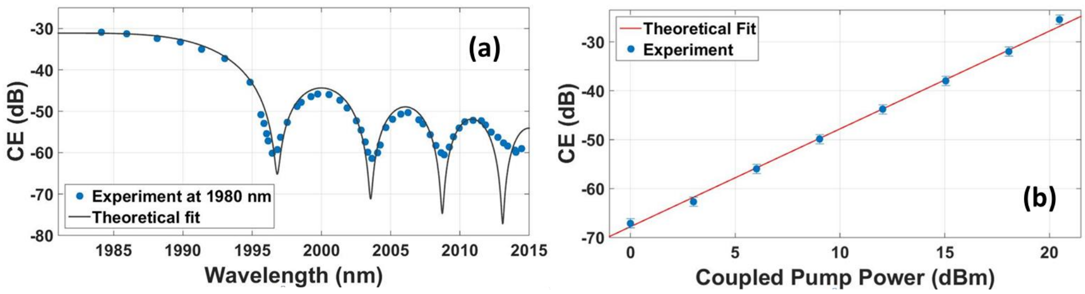

Fig. 5 (a) Experimental points and theoretical fits of the conversion efficiency (CE) as a function of the idler wavelength (pump at 1980 nm with 65 mW of CW power).; (b) CE as a function of the coupled pump power.

5. Conclusions

In conclusion, we have presented some of the recent results on versatile light sources based on broadband wavelength conversion. Highly reconfigurable SWIR sources with high power, tunability, modulation capability or high repetition rate pulsing are demonstrated by leveraging the parametric nature of the source in combination with efficient amplification. Moving deeper in the mid-IR requires the use of a different nonlinear mixing stage. Initial results indicate that, with state of the art fabrication techniques such as tapering, chalcogenide microstructured fibers providing large conversion efficiencies and bandwidth extending in the mid-IR are possible. The combination of the silica front end and the Mid-IR platform represent a versatile cavity-less architecture with unique properties.

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