High spectral power-density supercontinuum source at 1.3 μm suitable for optical coherence tomography applications

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ABSTRACT

The generation of a continuous-wave pumped supercontinuum source at 1.3 μm is described. The device makes use of a tunable Yb-doped fiber laser, a cascade of fiber Bragg-grating mirrors and a concatenation of standard silica fibers with stepwise decreasing dispersion. The generated supercontinuum spans from 1280 to 1513 nm, shows and average output power of 1.34 W and exhibits >0 dBm/nm spectral power density over 200 nm.

Keywords: supercontinuum, soliton self-frequency shift, optical coherence tomography

INTRODUCTION

Supercontinuum (SC) generation in optical fibers from continuous-wave (cw) laser has been studied intensively in the last years, both experimentally [1]-[7] and theoretically [8]-[13]. These broadband, high-power density and low-coherence light sources have been found to be extremely useful for optical coherence tomography (OCT) [11], [12]. The preferred wavelength range in this case lies in the region of 1300 nm, since in this spectral interval the live tissue exhibits low absorption and hence more penetration (see for instance [13]). Continuous-wave supercontinuum generation in fibers results from the fission of the partially coherent input cw beam into a sequence of Raman-shifted solitons through the combined effects of modulation instability (MI) and Stimulate Raman Scattering (SRS). Cw-induced spectral broadening is initiated by MI, which breaks-up the cw radiation into a train of ultrashort pulses when propagating in the wavelength region of small anomalous dispersion of the fiber. As the power is increased, the MI-generated pulses evolve into higher-order solitons (N-soliton), which in their turn, split into fundamental first order solitons (one-soliton) [9], [14] and undergo spectral shift towards longer wavelengths due to SRS. This process of Soliton Self Frequency Shift (SSFS) gives rise to a smooth and wide spectrum lying at wavelengths longer than the pump wavelength. Additionally, each of the fundamental soliton can, in the presence of higher-order dispersion, release excess energy in the form of blueshifted dispersive waves, enhancing the spectral broadening on the shorter wavelength part of the supercontinuum. The mechanism of Sc generation in this case is similar to SCs achieved using low-energy long pulses (~ps) in small anomalous dispersion regimes [14], [15]. The process of cw-pumped SC generation described above implies two restrictions from the point of view of the pump and the fiber used. First, the need of having an efficient MI implies that the pumping has to be done in the anomalous dispersion regime of the fiber. Second, since the cw-pumped SC spectra are typically composed of Raman-shifted solitons, the energy of the pump is mostly transferred to wavelengths that are longer than the pump wavelength. Thus, for the application of OCT, which requires having most of the SC energy around 1300 nm, most of the supercontinua developed up to now have been performed over photonic crystal fibers, which typically exhibit anomalous dispersion from below 1000 nm. However, for compatibility with existing components, the development of SC sources based on conventional (all silica) fibers results extremely interesting. With regards to this, most of the cw-pumped SC sources demonstrated up to now in conventional fibers have been developed using dispersion shifted fibers [3], [5], and their spectrum lies typically at wavelengths longer than 1500 nm. In this paper we present a new all-fiber design of cw-pumped SC sources in the spectral range between 1.2 and 1.5 μm. The SC presented here relies on standard single-mode fibers, which have their zero-dispersion wavelength around 1.3 μm. The generated SC features an output power pf 1.34 W and >0 dBm/nm spectral density over 200 nm. The spectral broadening is achieved by pumping in the small anomalous dispersion region of the fibers, which are arranged in stepwise decreasing dispersion order. In fact, according to recent theoretical results, dispersion decreasing fiber profiles can significantly improve the spectral broadening giving rise to shorter one-soliton pulse widths (hence broader spectra) [16].

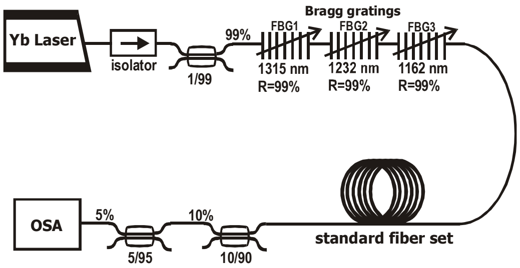


Fig. 1. Experimental Set-up. Yb laser: tunable Ytterbium-doped fiber laser emitting at 1104 nm; FBG: Fiber Bragg Gratings; OSA: Optical Spectrum Analyzer. The standard fiber set is made up of 4 fibers whose details can be seen in table.1.

EXPERIMENTAL SET-UP

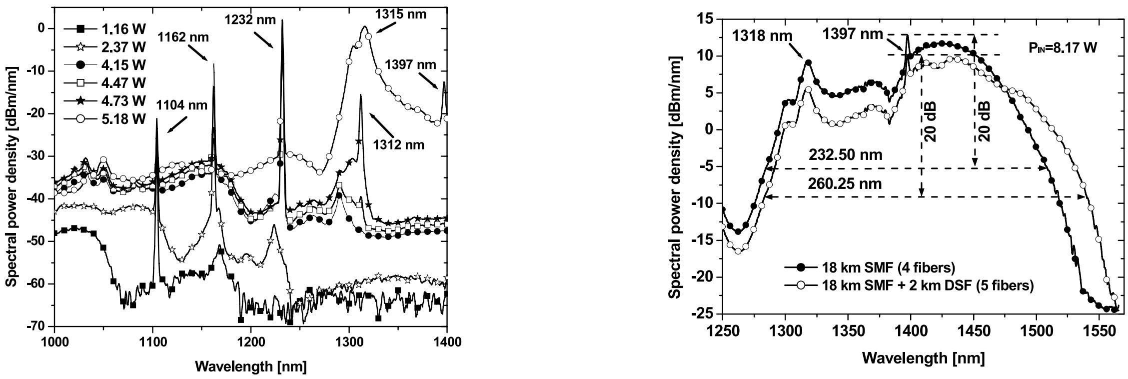
The experimental set-up is depicted in fig.1. As a pump, we use a cw Yb-doped fiber laser tuned at 1104 nm. The output of the laser is single-mode and the power can take values from 0.57 to 20 W. An isolator at 1100 nm is inserted at the laser output to prevent damage in the laser by back-reflected light. The isolator losses are approximately 2dB. A 1/99 optical coupler is then introduced to monitor the power inserted into the fiber arrangement and the back reflected power. To obtain efficient spectral broadening from cw laser in conventional fibers one needs to have the pump tuned at wavelengths in which the fiber exhibits small anomalous dispersion. Standard optical fibers have zero-dispersion wavelength (λ_0) around 1310 nm. Thus, to enable SC emission, we need to shift most of the laser power from 1100 nm to >1310 nm to efficiently induce modulation instability. In order to do this, we insert a cascade of Fiber Bragg Grating mirrors (FBGs) between the pump and the fiber set. As we will show in the next section, this arrangement allows to shift the laser emission at the desired wavelength without the need of a cavity. The FBGs have reflectivity >99% in all cases and total loss of 0.8 dB. Their bandwidths are centered at 1162 nm, 1232 nm and 1315 nm and have reflection bandwidths of 1.47 nm, 1.73 nm and 8.00 nm respectively. FBG at 1315 nm has its maximum and minimum reflection at 1312 nm and 1320 respectively. The non-linear medium is made of a set of four standard single-mode fibers (SMF) of different λ_0 and lengths. The fibers are arranged in increasing λ_0 order (hence decreasing dispersion order). The choice of fiber lengths is dictated by the material available at the laboratory. The main properties of the fibers are reported in Table 1. The total fiber length is 18 km, which is one order of magnitude longer than typical lengths of highly nonlinear fibers (HNLFs) used for cw-generated supercontinua. This agrees with the fact that conventional single-mode fibers exhibit a nonlinear coefficient, which is one order of magnitude smaller than HNLFs. The output spectrum of our source is analyzed by means of an optical spectrum analyzer (OSA) after passing through two couplers, which act uniquely as fixed attenuators. The input and output power is measured by means of an integrating sphere radiometer whose responsivity at 1100 nm is 6 x 10^{-4} A/W with 1% uncertainty [17].

	λ_0 [nm]	S_0 [ps/nm^2/km]	α (@ 1310 nm) [dB/km]	L [km]	D (@ 1315 nm) [ps/nm/km]
Fiber 1	1302	0.085	0.35	6.0	1.02
Fiber 2	1307	0.087	0.33	8.0	0.60
Fiber 3	1311	0.083	0.34	2.0	0.33
Fiber 4	1312	0.085	0.34	2.0	0.23

Table 1. Properties of the set or optical fibers used in the experiment

SUPERCONTINUUM GENERATION

The center wavelength of our laser is tuned at 1104 nm and hence lies well within the normal dispersion regime of standard fibers. Therefore our first aim is to shift the wavelength of the laser to the spectral region of anomalous dispersion of the fibers by using a frequency-selective reflecting structure made of FBG mirrors. The process of wavelength shifting can be qualitatively described as follows: when we increase the laser pump power and we pass the Raman threshold we observe strong stimulated Raman scattering (SRS). Backward SRS appearing at 1162 nm is reflected back into the fiber by FBG3, and is subsequently amplified as it propagates in the forward direction. The emission at 1162 nm acts as a laser and plays a similar role to the pump laser. The same principle with FBG2 and FBG1 gives rise to cascaded Raman frequency generation ending up with a peak at 1315 nm which falls in the spectral region of small anomalous dispersion of the standard fibers used in the experiment. In Fig.2 we can see the output spectrum for different pump powers (the values of pump power are measured at the input of the fiber set). When the input power takes the value of 1.16 W the first Raman at 1162 nm is clearly visible and the next Stokes order starts to appear (Fig. 2(a)). At 2.37 W the second Raman peak at 1232 nm is also present. At this stage, depletion of the spectral lines at 1104 nm and 1162 nm also begins to occur. At input power level of 4.15 W the spectral lines at 1104 nm and 1162 nm undergo almost full depletion and a peak at 1312 nm is clearly visible. When the input power amounts to 4.73 W the spectral broadening starts to take place around 1315 nm. Earlier results have been reported on similar methods for the generation of cw SC emission [1], [2], [5], which make use of a linear cavity configuration to shift the pump frequency into the anomalous dispersion region of the non-linear medium. It is worth to notice that, according to our results, a linear cavity is not strictly necessary to generate the spectral emission which will seed the SC broadening. As we can observe in Fig. 2(a), at power levels higher than 4.5 W the spectral broadening around 1315 nm starts to take place and an other Raman peak appears at 1397 nm. MI-induced soliton fission and Raman shift is also evident from the appearance of a smooth red-shifted tail in the pump spectrum.



(a) (b)

Fig. 2. Output spectra for different input powers. (a) Evolution of the pump broadening around 1315 nm. (b) Supercontinuum spectra for two different fiber configurations.

In Fig. 2(b) we show the SC spectra obtained for two different fiber configurations. The first one (black circles) makes use of the set of fibers shown in the in Table.1 arranged in dispersion-decreasing order. The input power is 8.17 W, while the SC output power is 1.36 W. The output spectrum spans over 232.5 nm as measured at 20 dB from the highest peak and exhibits >0 dBm/nm spectral density over 200 nm. The Raman-induced asymmetric broadening towards longer wavelengths is clearly visible. A significant feature is the appearance of a peak at 1397 nm and a strong power transfer to the region between 1400 nm and 1450 nm, which is caused by forward SRS. To our knowledge, this is the broadest cw-pumped SC spectrum obtained by the only use of standard optical fibers. In a further demonstration of the possibilities offered by dispersion management in such a set-up, a dispersion-shifted fiber (DSF) is added at the end of the fiber arrangement described above. The DSF is added at the end of the arrangement, in such a way as to keep a decreasing-dispersion configuration. This fiber is 2 km long and has its λ_0 at 1417 nm. Since a significant part of the SC power generated with the set-up described above lies at wavelengths slightly above the λ_0 of this fiber, we expected that the insertion of this fiber would stimulate soliton fission in this spectral region and provide further spectral broadening. As it can be seen, this arrangement improves the spectral width of our SC. In this case (achieved for 8.17 W of input pump power) the SC spectrum spans >260 nm as measured 20dB down from the highest peak, it has an output power of 0.840 W and exhibits >0 dBm/nm spectral density over 214 nm.

CONCLUSIONS

We have demonstrated pump spectral broadening and supercontinuum generation spanning more than 232.5 nm in the spectral range of 1.2-1.5 μm. This has been achieved by pumping a concatenation of conventional fibers with an Yb-doped fiber laser and a frequency-selective reflective structure that seeds supercontinuum emission at 1315 nm, in the regime of small anomalous dispersion of the fibers used in the experiment. We believe that such a SC profile is very promising for high power density, all-fiber SC applications. This source seems to be particularly interesting for ultrahigh resolution OCT. Further investigation will be necessary to obtain a flatter spectral profile.

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