Broadband, low intensity noise CW source for OCT at 1800 nm


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Abstract

We report on an all-fiber CW supercontinuum source, based on erbium amplified spontaneous emission (ASE) source pumping dispersion-shifted highly nonlinear step-index silica fiber. As low as $-120$ dBc/Hz intensity noise of the near-Gaussian >200 nm bandwidth radiation was recorded. The source can enable micron-scale optical coherence tomography around the low-scatter 1800 nm region.

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1. Introduction

The potential of OCT imaging of human tissue around 1.8 μm, where the higher water losses as compared to 600–800 nm range are offset by the dramatically reduced scattering, stimulates interest in broadband light sources operating in this region [1,2], but to-date has been limited to insufficient bandwidths and low-power format of the available fiber amplified spontaneous emission (ASE) and SLED sources.

Typically, the requirements for micron-scale axial resolution at these longer wavelengths include bandwidths (FWHM) of the light sources in excess of 150 nm (coherence length in tissue of <10 μm) and relative intensity noise below 100 dBc/Hz in the frequency ranges up to tens of MHz. Additionally, fiber format OCT scanners can naturally be employed at this wavelength and availability of an all-fiber format light source is essential in real-life applications.

Low noise, broadband continuum generation by CW pumping of highly nonlinear conventional fibers can be implemented at 1.8 μm providing that (i) the pump source wavelength is in the low anomalous dispersion region of the nonlinear fiber, (ii) its length is optimised to enable soliton-Raman dominated continuum generation [3], (iii) a complete effective Raman length of the fiber is utilized at this wavelength, and (iv) the intensity noise of the pump is minimised, especially in terms of longitudinal cavity modes intensity beat, to reduce its nonlinear amplification during the continuum generation process [4,5].

Here we demonstrate and characterise a compact all-fiber based light source that can enable 6–7 μm axial resolution OCT at 1.8 μm wavelength. Based on CW supercontinuum generation in high-nonlinearity fiber (HNLF) with a CW ASE all-fiber pump this source demonstrates down to $-120$ dBc/Hz relative intensity noise (RIN) level of the broadband radiation. Passive shaping of the continuum with a WDM coupler allowed us to pre-shape the spectrum in a 210 nm FWHM wide profile.

2. Experimental setup and results

To create a narrow-band ASE source required for efficient modulation–instability (MI)-induced supercontinuum generation a CW ASE emission of Erbium-doped amplifier (Fig. 1) was filtered through a tunable interference filter to a 1 nm band and amplified in the second gain stage to 10 dBm power.

The CW seed signal was further amplified in a commercial C-band Erbium fiber amplifier to 10 W of average power. As a preventive measure in case of back reflection from the measurement setup, a fiber-pigtailed optical isolator was included after the 10 W amplifier, though verified not to be required for supercontinuum generation itself.

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The output of the pump source was spliced to the anomalously dispersive Sumitomo high-nonlinearity step-index fiber with zero dispersion wavelength 1553 nm, nonlinearity coefficient $21 \, \text{W}^{-1} \, \text{km}^{-1}$ and mode field area $10 \mu\text{m}^2$. Despite a significant mismatch with the $10 \mu\text{m}$ core diameter of the pump output fiber, the lower melt temperature of the fluoride-doped silica cladding of HNLF enabled us to develop an efficient, $\sim 0.1 \, \text{dB}$ loss, splicing technique.

Critical to a smooth supercontinua generation, the wavelength of the tunable 1 nm bandwidth pump source was optimised with respect to initial MI broadening of the CW signal, the optimal value being $1562 \, \mu\text{m}$ at full pump power.

The optimal 200 m length of the HNLF, obtained through a cut-back technique, was chosen to enable supercontinuum extension just reaching $2 \mu\text{m}$ wavelength, marking rapid onset of the silica fiber loss, at the full pump power. Further increase in the fiber length, or pump power, would lead to Stokes transfer of the supercontinuum radiation towards the high loss region and subsequent integral loss and short wavelength depletion of continuum radiation [3]. As a result a 400 nm broad Raman-soliton CW continuum with output power of 6.2 W was generated at the HNLF output (Fig. 2).

To shift the median wavelength of the continuum from 1.76 $\mu\text{m}$ towards 1.8 $\mu\text{m}$ and suppress “ghost images” from the square-shaped spectrum, passive filtering of the output was implemented with a fused taper WDM fiber coupler, with a transmission maxima period of 400 nm around 1.55 $\mu\text{m}$.

Fig. 3 shows the dynamics of the evolution of the shaped continuum, demonstrating depletion of the residual pump radiation and a moderate centre wavelengths shift with the increase of the power. The maximum output power of 1.75 W was obtained at the coupler’s output with a resulting usable bandwidth of about 210 nm (FWHM), centred at 1.83 $\mu\text{m}$ (Fig. 3, red line). The corresponding 2.5 dB decrease in the shaped supercontinuum brightness was due to long-wavelength wave guiding loss in fusion coupler taper and can be further reduced by an appropriate choice of the coupler fiber.

The RIN of the continuum was measured in the 10–100 MHz frequency range by using a 1 GHz 50 Ohm-load PIN photodetector and 2 GHz bandwidth RF spectrum analyzer and was normalised to an integrated DC (zero frequency) signal from the detector. Fig. 4 shows the intensity noise trace of the source compared to a base line of the detection system.

The Raman-soliton nature of the CW pumped continuum and the absence of the unwanted Raman lasing in

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1 For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.
the HNLF cavity has resulted in a broadband homogeneous white-noise continuum in the given frequency range. This, along with the absence of the pump-laser cavity fundamental frequency imprint, and longitudinal mode-beats, compared to pumping with linear-cavity laser sources, resulted in an ultra-low noise level around $-118$–$122$ dBc/Hz in the $20$ kHz–$50$ MHz frequency range of interest for OCT.

3. Conclusions

A $1.75$ W, CW pumped Raman-soliton all-fiber light source with near-Gaussian bandwidth of up to $210$ nm around $1.8$ μm is demonstrated. ASE seeded Er-doped MOPFA pumping of a highly nonlinear anomalously dispersive fiber results in the intensity noise around $-120$ dBc/Hz in the range of $20$ kHz–$50$ MHz. The source can enable sub-$10$ μm resolution OCT of human tissue in this low-scatter wavelength region.

References