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Narrow core standard single mode fiber for supercontinuum generation from graphene-based mode-locked pulses

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ABSTRACT

In this work, a supercontinuum (SC) source is proposed and demonstrated using a highly-doped, 2 m long zirconia-erbium doped fiber (Zr-EDF) with a dopant concentration of 3800 ppm/wt and a narrow core 100 m long single-mode-fiber (SMF). A graphene based saturable absorber (SA) is used as a passive mode-locker, generating pulses with an average output power, pulse energy and peak power of ∼0.9 mW, ∼69.8 pJ and ∼83 W respectively and a repetition rate of 12.9 MHz. This is then amplified using a 140 mW amplifier, giving an output power, pulse energy and peak power of ∼75.0 mW, 5.8 nJ and ∼6.76 kW respectively and injected into a 100 m long SMF, to generate an SC output which spans from 1450 to more than 1700 nm, with a pulse width at its full-width-at-half-maximum (FWHM) of 120 fs, 7 times lower than the 840 fs FWHM width of the pulses from the fiber laser. The narrow core SMF performs comparably to longer lengths of standard SMF-28 fibers.

1. Introduction

It has been of interest to develop broadbandsources, which can find attractive applications in spectroscopy, as sensors for gas and liquid properties, as well as sources for optical component system testing. Broadband wavelength coverage spans from the visible region until the infrared regions that may comprise of many approaches of generation, such as xenon lamps, super luminescence emitting diodes (SLEDs) and others. Besides these, supercontinuum (SC) generation based on mode-locked lasers into various optical fiber types can be an interesting option. In this approach, the spectral broadening effect is accomplished by propagating optical pulses through a strongly nonlinear device based on the interplay of nonlinearity and chromatic dispersion. Apart from that, the power scaling of the seed signal is also an important factor for high conversion efficiency towards a broad supercontinuum generation. By launching intense seed pulses into a nonlinear fiber at or near its zero-dispersion wavelength, a very broadband supercontinuum source can be generated [1,2].

There have been reports of SC generation in fibers such as highly non-linear fibers (HLNFs) [3–5], giving a spectrum spanning from 1200 nm to 1700 nm. In microstructured optical fibers [2,6–8], SCs are generated within a range of 390 nm–1600 nm. These sources have been successfully been used for a variety of applications such as gas sensing [9], the characterization of optical

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components [10] and optical coherence tomography [11–13]. Of particular interest, besides having SC spectra that have very wide spans, there are also current interests to have SC spectra that are more focused towards the near infrared region (NIR), which can provide sources for applications such as in the area of molecular spectroscopy such as H_2O, C_2H_2 and C_2H_4 band stretching studies.

Although there have been many reports based on SC generation that can comply the above-mentioned wavelength regions, these require exotic and expensive fibers which are at times very difficult to handle, such as the difficulty of splicing PCFs to standard single-mode-fibers (SMFs) or the extreme cost of HNLFs. There is a need to have a low cost, SC source operating in a range of about 1400 nm–1700 nm, or longer, which at present can be met by using standard SMFs. An interesting feature of SMFs is that it has a higher optical damage threshold, and is also able to generate a high pulse energy output. There have been reports of SC generation from SMFs [14–18], with most covering the NIR region. However, most of these systems require very high-powered laser systems, which is necessary for the generation of the SC spectra.

In this work, we propose a low-cost approach for generating an SC output in the NIR region. The system comprises of a mode-locked laser system, which uses graphene as a saturable absorber (SA) and a highly doped zirconia-erbium doped fiber (Zr-EDF) as the gain media, giving an output power of ~0.9 mW, pulse energy of ~69.8 pJ and peak power of ~83 W. This is then amplified using an erbium doped fiber amplifier (EDFA) with an amplified spontaneous emission (ASE) output power of 140 mW, before being injected into a 100 m long SMF to generate the desired SC output. This is further extended to a standard SMF with a core size of 9/125 μm of lengths 200 m and 500 m respectively. This is the first time, to the knowledge of the authors, of the development of a relatively simple and low-cost SC generator for applications in NIR spectroscopy and also optical component characterization in the S−, C− and L−bands.

2. Experimental setup

The setup of the proposed SC source consists of a mode-locked fiber laser, which has an average output power of ~0.9 mW, pulse energy of ~69.8 pJ and peak power of ~83 W. The repetition rate of the mode-locked laser is about 12.9 MHz, corresponding to a pulse spacing of around 77.5 ns in the pulse train. The mode-locked laser that is used to generate the seed signal consist of a 2 m long Zr-EDF fiber with a dopant concentration of about 3800 ppm/wt and an absorption rate of about 18.3 dB/m at 980 nm. The Zr-EDF is a co-doped fiber, which incorporates glass modifiers and nucleating agents such as ZrO_2, Y_2O_3, Al_2O_3 and P_2O_5 and is co-doped with Er_2O_3 in a fused silica single mode fiber (SMF) and is pumped by a 980 nm laser diode (LD) through a 980/1550 nm wavelength division multiplexer (WDM). An optical isolator is placed after the Zr-EDF to ensure uni-directional operation and a polarization controller (PC) is placed immediately after it and is then connected to a 90:10. The 90% port is connected to a graphene based SA, which is sandwiched between two FC/PC connectors. The output of the SA is then connected to a 9 m long single-mode-fiber (SMF).

The graphene layer acts as a SA for mode locking purposes and the 9 m SMF is to make the cavity to have a negative dispersion in total. This will allow the mode-locked fiber laser to operate in a soliton mode. The dispersion parameter, D for the Zr-EDF is approximately +28.45 ps/nm·km [19], giving a group velocity dispersion (GVD) coefficient, β_2 of −36.86 ps^2/km. In the case of the SMF-28, the dispersion parameter, D is about +17 ps/nm·km, giving a GVD coefficient, β_2 of −22.02 ps^2/km. The total GVD for the entire cavity is −0.316 ps^2, which is estimated by taking into account the total length of each type of optical fiber, thereby putting the operation of the laser in the anomalous dispersion regime. One must note that the cavity is not optimized.

The output of the mode-locked fiber laser is then extracted through the 10% port of the coupler, and is then amplified using a 0.14 W erbium doped fiber amplifier (EDFA), which is then connected to a short length of 100 m SMF (Fibercore SM1500) with a mode-field diameter of about 4.2 μm with a cladding diameter of approximately 125 μm. The nonlinear coefficient of this SMF fiber is ~9 W^{-1} km^{-1}. On top of this, for comparison purposes, the experiment is repeated with two additional SMFs with lengths of 200 m and 500 m replacing the 100 m long SMF. These fibers have a mode-field diameter of about 9 μm and a similar cladding diameter as before. A Yokogawa AQ6317 optical spectrum analyzer (OSA) with a resolution of 0.02 nm is used to analyze the spectral properties of the generated mode-locked and SC spectrum respectively. The mode locked time characteristic is measured using an Alnair autocorrelator (HAC-200) whilst the pulse train is measured using a LeCroy 352 A oscilloscope together with an opto-electronic (OE) converter with a bandwidth of 6 GHz. The pulse width of the SC output is also measured using the autocorrelator (Fig. 1).

3. Results and discussion

From the experimentation, the ring laser starts to generate the soliton like mode-locking behavior at a threshold pump power of 60 mW, with careful adjustments of the PC. The threshold pump power is dependent on the cavity losses as well as the quality of the graphene layer. In this setup, all measurements are taken at a pump power of 100 mW. The optical spectrum of the mode-locked pulses taken from the OSA is shown in Fig. 2, giving a span from 1545 to 1580 nm at the output power reference level of about −67 dBm. The inset shows the ASE spectrum from the 2 m long Zr-EDF. The mode locked spectrum has a 3 dB spectral bandwidth of about 3.5 nm and a central wavelength at 1562.2 nm. The ASE spectrum spans from around ~1509 nm to ~1610 nm at the −60 dBm of output power reference level, with a high emission at ~1532 nm, which falls in the C−band region. Multiple Kelly's sidebands or sub-sidebands are also observed, indicating the system is operating in the soliton regime. The formation of the Kelly's sidebands as observed in the figure is due to the periodical perturbation of the intracavity [20], which confirms the attainment of the anomalous dispersion, soliton-like mode locking operation. The dispersion and nonlinearity of the intracavity medium are the two main laser cavity parameters interrelating with each other, which are responsible for the formation of the soliton-like pulse in the laser. The saturable absorber, graphene thin film, is the key enabler for triggering the formation of mode-locked pulses. Once the mode-locked pulses have been formed, the saturable absorber then plays the role to sustain the pulse stability. The measured average