Supercontinuum generation in dispersion shifted fiber kicked off by multi-cascade Brillouin process

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Brillouin mirrors based on a single-mode optical fiber are the simplest, completely passive and rather universal way to produce nanosecond pulses with extensive wavelength tunability. We consider an all-fiber solution, where a passively-Q-switched Er-doped fiber laser employing a multi-cascade stimulated Brillouin scattering effect (SBS) demonstrates a peak/average power contrast of 500W/25mW, and in association with a conventional dispersion shifted fiber (DSF) allows the generation of a nanosecond supercontinuum extending over the entire fundamental mode transmission range of the DSF, from 900 nm to over 1800 nm. Spectral selection allows the generation of tunable nanosecond pulses in this wavelength range.

Introduction

Being the lowest-threshold nonlinear phenomenon, stimulated Brillouin scattering (SBS) demonstrates unique spectral, temporal and spatial dynamic properties that are commonly employed in traditional solid-state laser systems. Nowadays, nonlinear SBS mirrors based on single- and multi-mode optical fibers are of particular interest for application in fiber lasers with a challenging possibility to keep all-fiber format. There are two principal tasks addressed through the use of a nonlinear SBS fiber mirror in fiber lasers: optical phase conjugation (OPC) [1] and passive Q-switching [2, 3]. The Q-switched fiber laser based on Brillouin mirror could be efficiently applied for supercontinuum generation in an optical fiber [2]. In our recent experiment a nanosecond supercontinuum extending over the entire fundamental mode transmission fiber range, from 900 nm to over 1800 nm has been observed with a conventional dispersion-shifted fiber (DSF) pumped by 25-mW average power from an Er/Brillouin-oscillator [4].

In this paper we describe expanding evolution of the experimental spectrum kicked off by multi-cascade Brillouin random process. In particular, we explain a specific attraction of multi-wavelength radiation for supercontinuum generation in an optical fiber. Since an optical spectrum generated by the Brillouin laser consist of several SBS components, a four-wave mixing between them causes an intensity modulation of the laser pulse within its time duration. This perturbation helpfully seeds the break-up of the pump radiation induced by modulation instability and in this way may support efficient generation of the Raman solitons. Being excited by nanosecond pulses the Raman solitons have to exhibit a wide distribution of their parameters. Importantly this distribution stochastically changes pulse-to-pulse because the Raman solitons originate from the mixing of the Brillouin components that the fiber laser randomly generates [3] from a spontaneous Brillouin noise. As a result the total soliton distribution covers the entire supercontinuum bandwidth and is averaged out by experimental measurements, which explains the remarkable continuity of experimental spectra.

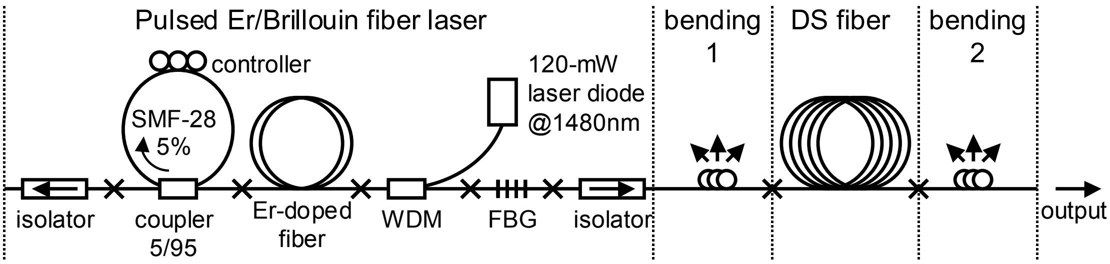

Fig.1. All-fiber spliced configuration used in the experiment

Experimental setup

The principal scheme of the experimental configuration is shown in Fig.1. The all-fiber format of the configuration is maintained by direct splicing of standard telecom components. Modulation instability and Raman scattering initiated by nanosecond pulses support supercontinuum generation that is realized by employing a DSF with a zero dispersion wavelength a slightly below the operating wavelength of the passively-Q-switched Brillouin fiber laser. The laser is pumped by a 120-mW laser diode at ~1480 nm. At such a low power level no fiber nonlinearity, except SBS, affects the laser performance [3]. For the reported operation pulse generation occurs with a repetition rate of ~5 kHz and an average power up to ~25 mW. A typical gigantic pulse has a FWHM duration of ~10 ns. The peak power is measured to be ~500 W and is subject to stochastic fluctuations around the maximum with a dispersion of ~15%. The use of ~35-GHz-reflection fiber Bragg grating (FBG) in the laser cavity localizes the laser wavelength centered at 1556.00 nm and limits the number of generated SBS components. For supercontinuum generation we used about ~200 m of a DSF (Corning) with a zero dispersion wavelength of 1547 nm and a slope of 0.074 ps·nm-2·km-1. By coiling the fiber on cylinders with different diameters (12mm, 10 mm. 8mm and 4 mm) we could introduce spectral-dependent losses in the fiber configuration to control the pump power in DSF (“bending 1”) and/or to tune the band of the emitted spectrum (“bending 2”). The spectrum has been measured with an optical spectrum analyzer Ando AQ-6317B.

Results and discussion

Optical spectra recorded for nine pump power levels are shown on different scales in Fig.2. The curves 8 correspond to the lowest pump power and essentially reproduce signatures of the Brillouin laser spectrum [3, 4]. A long-term limit of the laser linewidth is estimated to be ~0.4nm. The ratio between the peak of the laser spectrum and optical noise exceeds ~30dB all over the entire supercontinuum bandwidth. Fig.2(d) directly indicates to the Brillouin cascaded process as an origin of laser operation. The laser intensity is emitted through three SBS components localized near the Stokes side of the FBG reflectivity; the spacing between them corresponds to the SBS shift $\Delta_{SBS} \approx 11\, GHz$.

In the case of a maximal coupling between the laser and DSF, the spectrum described by curves 0 is spread from 900 nm to 1700 nm. A cut-off of the spectrum near 900 nm is observed below the cut-off wavelength of the DSF that is ~1000 nm. It means that multimode phase matching is responsible for generation of shorter wavelengths. Significant part of the emitted radiation obviously belongs to the range over 1700 nm.

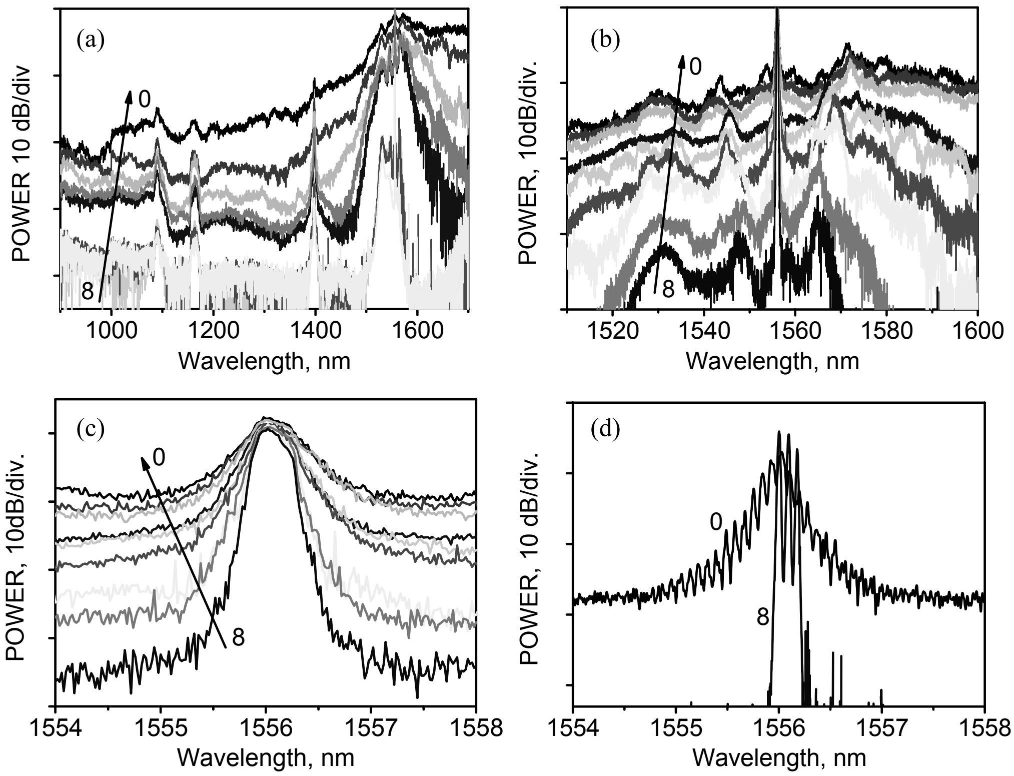

Fig.2. Optical spectra recorded at different pump power levels. Pump power is controlled by coiling the fiber on a diameter of ~12 mm ("bending 1"). Curve number corresponds to number of turns. Resolution is ~1 nm (a), ~0.1 nm (b, c), ~0.01 nm (d); spectra (a-c) are averaged on 20 realizations.

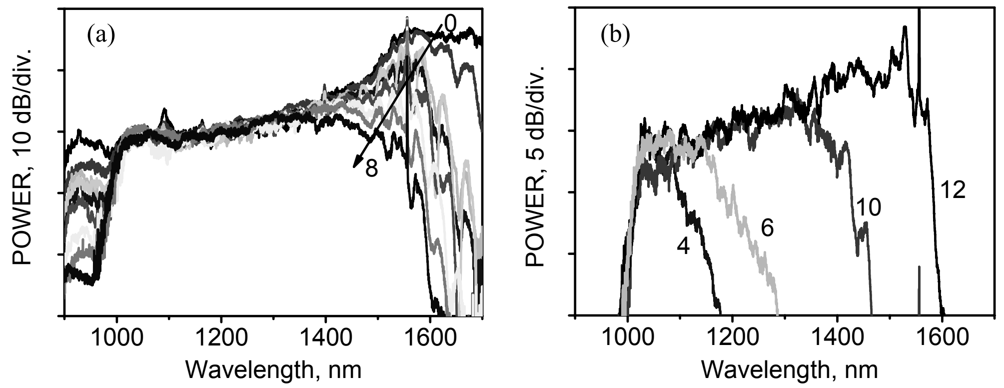

Fig.3. Optical spectra recorded with different filtering provided by coiling the fiber ("bending 2"). Curve number corresponds to number of turns (a), to coil diameter (b); coil diameter is 12 mm (a), number of turns is eight (b). Spectral resolution is ~1 nm; spectra are averaged on 20 realizations.

Fig.2(b) gives more details demonstrating that the modulation instability is the origin of supercontinuum generation. For low pump power levels, the output spectrum exhibits a clear signature of the influence of four-wave mixing through the generation of two nearly symmetric modulation instability sidebands around the pump wavelength. The asymmetry in the intensity of those sidebands is caused by SRS amplification of the longer wavelengths and attenuation of the shorter ones. For higher pump powers, the effective FWM and the Raman gain increase, which leads to a continuous broadening of

the generated spectrum. This broadening mainly occurs on the long wavelength side of the pump wave, but the short wavelength components are also significantly generated.
Although this scenario is rather typical for the supercontinuum generated by nanosecond pulses, features specifically associated with the employing of multi-cascade Brillouin radiation as a pump are also present. One can see from the Fig.2(c) that an increase of modulation instability is accompanied by significant broadening of the laser line. The broadening mechanism is clearly seen from Fig.2(d): as far as an optical spectrum generated by the Brillouin laser consists of several SBS components, a four-wave mixing between them results in cascade generation of new spectral peaks with the same equidistant spacing. New spectral peaks cause a perturbation of the laser pulse within its time duration and could efficiently seed the break-up of the pump radiation induced by modulation instability into the train of Raman solitons.
Spectral filtering provided by coiling the fiber in the point "bending 2" (see Fig.1) leads to the generation of the nanosecond pulses with a tunable spectrum width as it is shown in Fig.3. Despite a low spectral power density (~0.3 μW/nm), the peak power of the pulses has been observed to remain within the Watt power scale. As the bandwidth of the pulse source is reduced from 300 nm to 50 nm the pulse peak power decreases from 10 W to 1 W and the pulse duration from 10 ns to 2 ns, correspondingly.

Conclusion and acknowledgements

Nanosecond pulse laser sources with extensive wavelength tunability are of great interest for numerous applications. The use of Q-switched lasers for supercontinuum generation allows combining broadband wavelength coverage with the possibility to keep a low average power level. Until recently such supercontinuum sources have been available based only on the use of conventional solid-state or microchip Q-switched lasers operating in the sub-nanosecond regime and in combination with photonic crystal fibers (PCF) with an obvious disadvantage of integrating bulk laser and fiber components. The demonstrated approach opens the potential to produce nanosecond, wavelength tunable pulses through the complete visible and infrared spectrum. An increase of operable power levels may be achieved by utilizing the total available power budget for the fiber laser in conjugation with the use of special fibers, like highly nonlinear fibers and photonic crystal fibers. An additional attraction of these sources is their compact, robust, low-cost, all-fiber integrated format.
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