Broadband Optical Supercontinuum Generation in a Long Cavity Fibre Laser

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Abstract Summary

We describe optical supercontinuum generation in an actively mode-locked fibre ring laser using a pulsed mode-locking technique. Recirculation of a section of the continuum facilitated spectral broadening.

Keywords-ring laser; supercontinuum; active mode-locking

I. INTRODUCTION

Supercontinuum (SC) light sources based on optical fibres have drawn much attention in recent years due to their multiple applications, such as telecommunications [1], metrology [2] and optical coherence tomography [3]. This fascinating phenomenon is usually generated by injecting high power laser, either pulsed [4, 5] or continuous wave (CW) [6, 7], into a nonlinear medium. New spectral components are generated over a wide range of wavelengths due to the complex interaction of dispersion with several nonlinear phenomena, such as self phase modulation (SPM), cross phase modulation (XPM), four-wave mixing (FWM) and stimulated Raman scattering [8].

SC generation in a fibre laser was first reported by Chernikov et. al. [9], in which the laser was Q-switched. Kang et. al. subsequently reported SC in a passively mode-locked fibre laser [10]. El-Taher et al. reported SC generation in ultra-long Raman fibre cavities, using fibre Bragg gratings to provide optical feedback [11]. CW SC generation in a fibre ring laser has been reported by Lee et. al. [12, 13]. The latter works all required a relatively high power fibre amplifier and the latter two results required a long length of nonlinear passive fibre (e.g. up to two kilometers of dispersion-shifted fibre) to assist spectral broadening and reduce the pulse repetition rate.

In this paper we demonstrate SC generation in an actively mode-locked erbium-doped fibre ring laser using a relatively low power erbium-doped fibre amplifier. An optical SC spanning approximately 600nm bandwidth around 1530nm was produced in a 1.1 km length of dispersion-shifted fibre. A pulsed mode-locking technique [14] was used to mode-lock pulses at a low repetition rate with relatively high peak power [15]. In this way, the SC could be generated using a relatively low-power erbium doped fibre amplifier.

The paper is organized as follows: In Section II we describe the experimental setup, in Section III we report and discuss the experimental results. We summarize the content of the paper in Section IV.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1, and is similar to that used by Baldo et. al. to generate high power and highly chirped pulses [15].

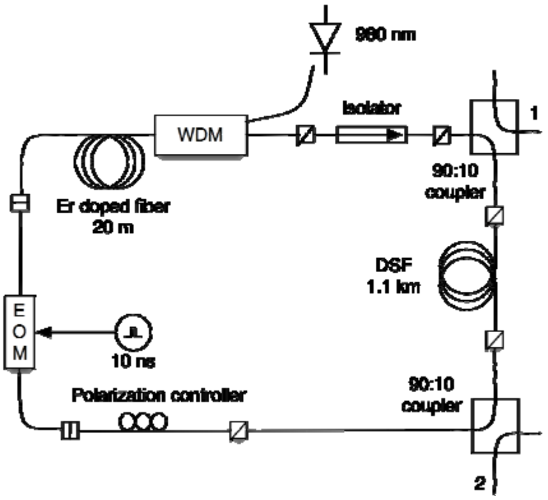

Figure 1. Schematic of the experimental setup of the fibre laser.

The cavity was composed by 20m Er-doped fibre amplifier (Lucent HP 980) counter-directionally pumped by up to 150 mW at 980 nm, followed by an isolator to force unidirectional lasing. The cavity contained 1.1 km of dispersion shifted fibre (DSF) with zero dispersion wavelength at 1545nm. A polarization controller was used to compensate for birefringence and optimize the polarization of the light entering an electro-optic modulator (EOM), used to actively mode-lock the cavity. The EOM was driven by a 10 ns pulse generator triggered by a frequency synthesizer with 1 Hz resolution tuned to the cavity round trip time, to produce pulsed optical transmission. The output of the laser was monitored with an optical spectrum analyzer and 2GHz photodetector circuit at two points via a 10% output coupler; (1) after the amplifier and

(2) after the DSF. The photodiode was connected to an oscilloscope and to a RF spectrum analyzer to monitor mode-locking. All the components were made of SMF28 fibre, and the total fibre length of such components was approximately 20 m. The fibre connecting the components in the setup was SMF28, and its length was approximately 20 m. The zero dispersion wavelength (ZDW) was estimated from the dispersion map of the cavity, and was found equal to 1537 nm, with a dispersion slope of 0.078 ps/nm^2/km.

III. EXPERIMENTAL RESULTS

The mode-locking frequency of the fibre laser was measured by applying a sine wave to the modulator and maximizing the spectral width of the pulse spectrum. Whenever the frequency of the sine wave approached the fundamental frequency of the cavity, the pulses on the oscilloscope became stable and narrow, and the RF spectrum was a comb of modes with Gaussian envelope curve centered on the mode-locking frequency. The fundamental frequency of the cavity was 178 kHz.

After having measured the fundamental frequency of the cavity, the modulator was driven by the pulse generator, to enforce pulsed mode operation to the laser. With the amplifier driven with the maximum power available from the 980 nm pump, and the EOM driven with the 10 ns pulse generator tuned to the cavity fundamental frequency, we observed a broadband continuum at the output of the DSF, as shown in Fig. 2. The gray trace was obtained with the cavity slightly detuned (1 kHz) so the laser was not mode-locked, but instead operated continuous wave (CW), with the lasing wavelengths centered at 1530 nm. When the frequency of the pulse generator was tuned to the fundamental frequency, the average power circulating in the forward direction, as calculated from the output power measured at (2), was 1.64 mW. Due to the slow response of the photodiode, it was impossible to resolve the short pulses generated in the cavity. By using the FWHM of the measured impulse response of the photodiode (T_P = 2.5 ns) and the round trip time (T_{RTT} = 5.61μs), it is possible to give a lower bound estimation of the peak power, with the following formula:

$$P_{peak} = Pav\ T_{RTT}/T_P = 3.6\ \text{W}. \qquad (1)$$

The mode-locked pulse wavelength was in the normal dispersion regime of both the cavity and the DSF fibre, resulting in a highly chirped and high energy pulse not subject to breakup due to modulation instability [15, 16]. The mode-locked pulse in turn generated a broadband supercontinuum, extending from 1200 nm to 1830 nm. The part of the supercontinuum that fell within the gain bandwidth of the EDFA recirculated around the cavity with the mode-locked pulse; the combined spectrum exiting the EDFA, as measured at (1), is shown in Fig 3. The main part of the optical continuum observed after the DSF (Fig. 2) was therefore produced by a single pass of the mode-locked pump pulse (and residual continuum) through the DSF.

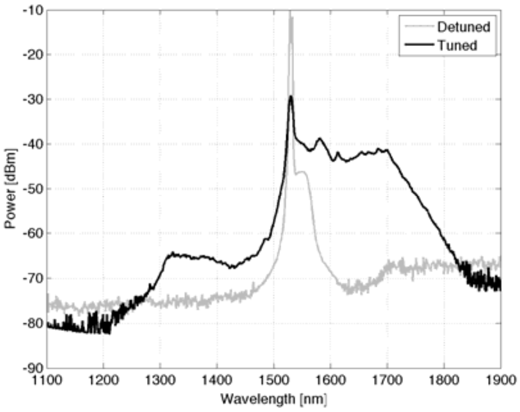

Figure 2. Output spectra taken from the cavity from coupler 2: with a frequency slightly detuned from the fundamental (gray) and with a frequency equal to the fundamental (black).

According to the standard model of optical continuum generation when pumped in the normal dispersion regime [8], the initial spectral broadening of the mode-locked pulse was caused by self phase modulation, but in this case was also assisted by the noisy SC signal around 1530 nm [17]. The component of the pump pulse which broadened across the ZDW of the DSF (1545nm) then underwent fission, again assisted by the remnant noisy SC signal, spawning solitons which were immediately translated towards longer wavelengths by stimulated Raman scattering. Due to the vicinity of the lasing wavelength to the ZDW and the small dispersion slope of the DSF, cross phase modulation (XPM) between spectral components travelling at the same group velocity was most likely the main cause of spectral broadening towards shorter wavelengths seen in Fig. 2.

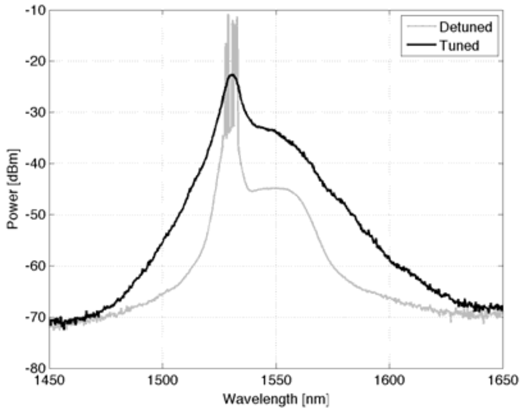

Figure 3. Output spectra from coupler 1. In grey, the spectrum obtained with the detuned cavity; in black the spectrum obtained when the cavity is tuned and SC is generated.

As mentioned above, the component of the optical continuum within the gain-bandwidth of the EDFA recirculated with the mode-locked pump pulse and was amplified with the pump pulse. As shown in Fig. 3, the power spectral density of the optical continuum after the EDFA was observed to be approximately 13dB higher than the amplified spontaneous emission noise emitted by the EDFA when the cavity was not mode-locked. Outside the gain-bandwidth of the EDFA the optical continuum was absorbed, which prevented recirculation of the whole extent of the optical continuum generated in the DSF. Nevertheless, the recirculation of part of the continuum within the EDFA gain bandwidth was sufficient to seed the broader optical continuum each pass through the DSF, thereby generating a wider continuum than would have been possible without recirculation (e.g. by placing the DSF outside the laser cavity).

IV. CONCLUSIONS

We have demonstrated SC generation in a pulse-mode-locked optical fibre ring laser with low average pump power. Placing a long DSF (i.e. in which the continuum was generated) inside the laser cavity had three main advantages. Firstly, the long cavity together with pulsed mode-locking enabled the generation of mode-locked pulses with low average power but high peak power, and sufficient to generate an optical continuum. Secondly, the cavity dispersion was normal at the mode-locked pulse wavelength, which prevented breakup of the mode-locked pulse due to modulation instability. Thirdly, it enabled recirculation of that part of the optical continuum which fell within the gain-bandwidth of the EDFA, which in turn, thanks to SPM, seeded rapid breakup of the high peak power mode-locked pump pulse, and resulting in a broader continuum than would otherwise have been possible.

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