64-fs L-band Pulse Generation by an All-Fibre Er-Doped Laser

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Abstract *We demonstrate a L-band all-fibre erbium-doped laser mode-locked by nonlinear polarisation rotation. The use of a single gain segment with appropriate length and dispersion and a L-band optimised Brewster fibre grating as an in-fibre polariser enables the generation of 64-fs pulses at 1.59 µm.*

Introduction

Femtosecond fibre oscillators offer significant advantages over solid-state systems because of their simplicity, cost, and reliability. Ultrashort erbium-doped fibre lasers (EDFLs) working in the 1.6 µm band have attracted much attention in recent years, owing to their capability to expand the band of telecommunications and sensing[1],[2], and their wide applications in spectroscopy, biomedical diagnostics and surgery. Operation of EDFLs at 1.6 µm can be realised through control of the linear cavity loss[3] and based on this principle, a number of studies on *L*-band EDFLs mode-locked through nonlinear polarisation rotation (NPR) or saturable absorbers have been reported[4],[5]. However, these lasers operate in the soliton regime and, thus, the pulse duration and energy are constrained. Whilst lengthening the EDF can force the laser emit in the *L*-band[1],[6],[7], the extra losses introduced by an overlong EDF make it difficult for the laser to achieve stable mode locking. Moreover, in lasers operating at net normal dispersion, large bandwidths and high pulse energies are favoured by short fibre cavities. Sub-100-fs *L*-band pulses can be obtained from fibre lasers exploiting the similariton[8] or dissipative-soliton[9] pulse formation mechanisms[10,11]. However, such laser designs require two segments of different types of EDFs to force the laser operate at 1.6 µm, hence two pump diodes.

In this paper, we demonstrate the generation of 64-fs stretched pulses[12] from an all-fibre erbium-doped laser emitting in the 1.6-µm band, which uses a Brewster fibre grating optimised for the *L*-band as an in-fbre polariser[13] and only one section of EDF with appropriate length and dispersion. The design is simple and suitable for all-fibre integration.

Laser configuration and principle

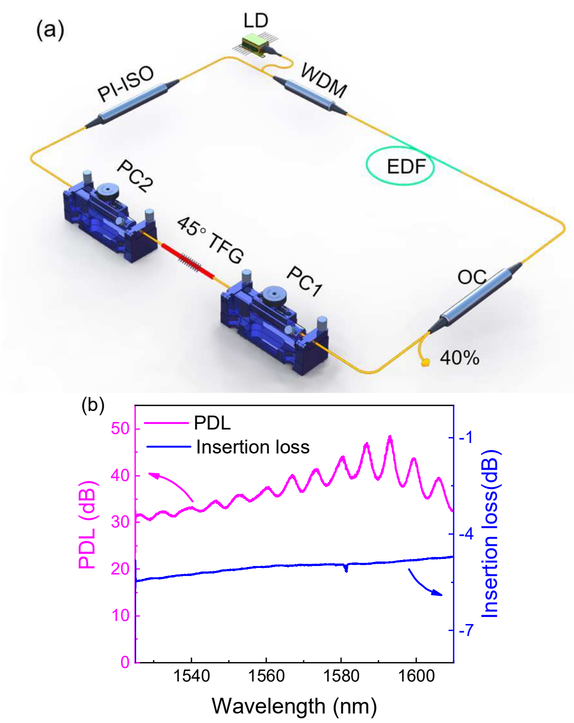

Fig. 1: (a) Experimental setup of the *L*-band stretched-pulse mode-locked fibre laser. (b) PDL response and insertion loss of the Brewster fibre grating.

The experimental setup is sketched in Fig. 1(a). A 1.575-m-long highly doped EDF with a nominal absorption coefficient of ~80 dB/m at 1530 nm and a group velocity dispersion (GVD) of –45.1 ps/(nm·km) at 1590 nm constitutes the gain medium. The EDF is pumped by a laser diode operating at 980 nm through a wavelength-division multiplexer and providing up to 704-mW pump power. Other fibres in the cavity are standard single-mode fibre (SMF) with a GVD of +19.4 ps/(nm·km) at 1590 nm, yielding a small normal cavity dispersion, which triggers operation of the laser in the stretched-pulse regime[12]. A Brewster fibre grating with strong polarisation-dependent loss (PDL) sandwiched with two polarisation controllers, converts NPR to amplitude modulation, initiating and stabilising mode-locked operation[14,15]. A polarisation-independent isolator ensures single direction oscillation. A fibre coupler after the EDF taps 40% of laser power out of the cavity for measurement. In our laser setup, the relatively long EDF length permits to acquire 1.6 μm emission, while the strong PDL of the Brewster fibre grating favours the generation of ultrashort pulses[16]. The Brewster fibre grating is UV inscribed into a length of hydrogenated SMF using the standard phase mask scanning technique. A description of its operation principle and fabrication procedure can be found in Ref.[17]. Figure 1(b) shows the transmission properties of the grating over the spectral range 1525 nm to 1610 nm, acquired by a commercial optical vector analyser incorporating a tunable laser. It is seen that the grating features a PDL (measured as the peak-to-peak difference in transmission with respect to all possible states of polarisation) of ~48 dB at 1593 nm, while the PDL remains well above 35 dB over a wide range of the *L*-band.

Results

Through management of the cavity dispersion realised by finely tuning the SMF length, we found that the optimal cavity length is 5.02 m, yielding a net dispersion of ~0.006 ps^2 at 1590 nm. Under this cavity length, mode-locked operation of the laser can be easily obtained when the pump power is above 150 mW by properly adjusting the PCs. The performance of the laser at 200-mW pump power is summarised in Fig. 2. The output pulse train as observed on the oscilloscope (Fig. 2(a)) shows a pulse spacing of ~24.6 ns, yielding a repetition rate of ~40.63 MHz. The signal-to-noise ratio in the radio-frequency spectrum of the laser output (Fig. 2(b)), measured by a RF spectrometer with a resolution bandwidth of 1 kHz over a 1-MHz range, is 58.4 dB. The low noise background in the RF spectrum over a 3.2-GHz range (10-kHz resolution bandwidth) also provides evidence of stable single-pulse mode-locking operation. The corresponding Kelly sideband-free, wide optical spectrum profile shown in Fig. 2(c) is a signature of the stretched-pulse operation regime. The spectrum, measured with a 0.05-nm resolution, is centred on 1591 nm and has a bandwidth at full width at half-maximum (FWHM) of 65.1 nm. The autocorrelation trace of the pulse (Fig. 2(d)) indicates a FWHM pulse duration of 240 fs when a Gaussian fit is assumed. By optimising the SMF pigtail of the laser output port, the pulses can be de-chirped to 64 fs. The time-bandwidth product of the compressed pulses is 0.49, which is very close to the Fourier transform limit for Gaussian pulses (0.441). These pulses are the shortest pulses generated so far in the *L*-band from a fibre laser using a single segment of EDF. The average output power is 16.5 mW, corresponding to a pulse energy of 0.41 nJ. Increasing the pump power beyond 200 mW resulted in multiple pulse formation in the laser as a result of a peak-power-limiting effect of the laser cavity[18].

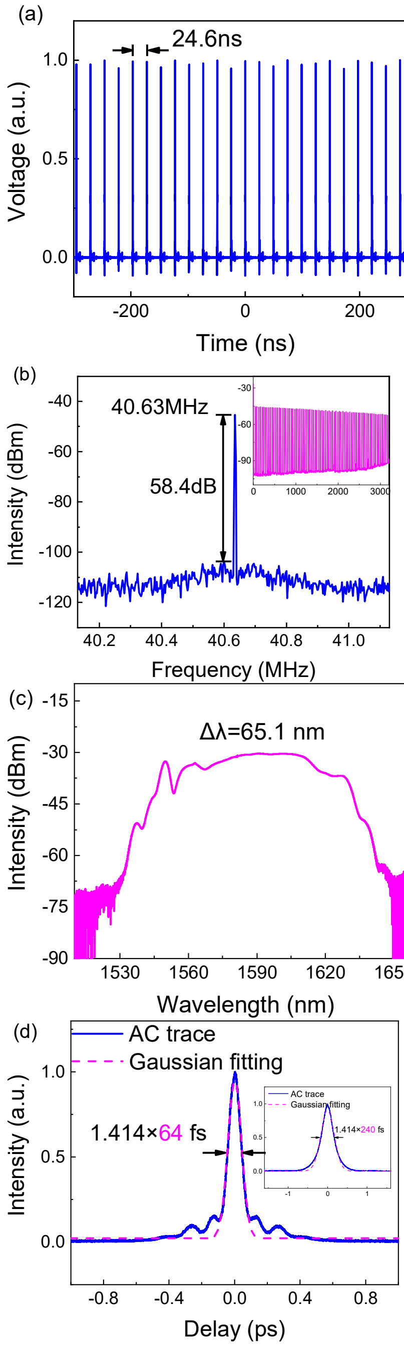

Fig. 2: Mode-locking operation at 200-mW pump power. (a) Pulse train. (b) RF spectrum. (c) Optical spectrum. (d) Autocorrelation traces of the chirped and dechirped (inset) pulses.

To confirm the pulse generation regime in the laser, we performed numerical simulations of the laser based on a non-distributed model that includes the dominant physical effects of the system, namely GVD, self-phase modulation, gain saturation and bandwidth-limited gain for the EDF, as well as the discrete effects of the saturable absorber element. The simulation parameters were the same as the experimental values. The spectral width at FWHM of the simulated output pulses and the FWHM pulse duration after de-chirping were 63.1 nm and 60 fs, respectively, in a good agreement with the measured values. The in-cavity pulse evolution displayed in Fig. 3 clearly shows that the laser operates in the stretched-pulse regime[12]: the pulse temporally stretches and compresses twice per round-trip, reaches a minimum duration in the middle of the EDF and SMF segments, and acquires both signs of chirp.

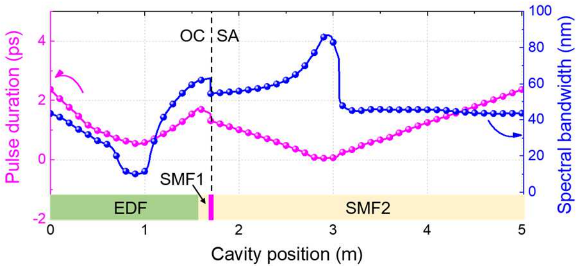

Fig. 3: Simulated evolution of the FWHM temporal (red) and spectral (blue) widths of the pulse along the cavity.

Conclusions

We demonstrated a sub-70-fs all-fibre erbium-doped laser that operates in the *L*-band and requires only one gain segment. This laser delivers pulses at 40.63-MHz repetition rate and 1.59-μm central wavelength that can be compressed externally to 64 fs. To our knowledge, this is the shortest duration obtained in *L*-band EDFLs using a single gain segment. Our laser design lends itself well to fibre integration, and thus will be highly desirable for a variety of applications requiring *L*-band ultrashort pulses.

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