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Effect of the doped fibre length on soliton pulses of a bidirectional mode-locked fibre laser

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Abstract. **A passively bidirectional mode-locked fibre laser is demonstrated using a highly concentrated erbium-doped fibre (EDF) as a gain medium. To accomplish mode-locked operation in a short cavity, use is made of carbon nanotubes (CNTs) as a saturable absorber. Soliton pulses are obtained at a wavelength of 1560 nm with a repetition rate ranging from 43.92 MHz to 46.97 MHz and pulse width stretching from 0.56 ps to 0.41 ps as the EDF length is reduced from 60 cm to 30 cm.**

Keywords: *passive mode-locked fibre laser, highly concentrated erbium-doped fibre, carbon nanotubes, soliton pulse.*

1. Introduction

Mode-locking is a technique which is traditionally applied to generate ultrashort pulses in fibre lasers [1, 2]. Passively mode-locked fibre lasers offer many applications ranging from basic research to optical communications, material processing and medicine due to their simplicity, low cost as compared to actively mode-locked lasers and high quality pulse generation [3, 4]. Various techniques of passive mode-locking have been demonstrated using nonlinear polarisation rotation (NPR), semiconductor saturable absorber mirrors (SESAMs), nonlinear polarisation evolution (NPE) and graphene and carbon nanotubes (CNTs) [5 – 10]. Note that NPR based on the Kerr effect can have a very fast response and generate high energy pulses [11]. SESAMs are often used for passive mode-locking despite their complex, costly and time consuming fabrication process. However, a SESAM as a saturable absorber is more preferable compared to NPE due to the fact that NPE can lead to long-term instabilities [12]. In recent years, graphene and carbon nanotubes are used as saturable absorbers in fibre mode-locked lasers. They have benefits of a faster response time than SESAMs and can be directly deposited on the fibre ends.

Recently, saturable absorbers (SAs) have attracted researcher's attention in achieving passive mode-locking by using new technologies based on CNTs [13]. CNTs are unique tube-shaped materials that have been intensively investigated in scientific research and industrial applications which enable them to be used for various high-performance electronic and photonic devices [13, 14]. Since the CNT discovery, many investigators have studied this new form of carbon with regard to the optical limiting properties of carbon nanotube suspension [15]. CNTs are of particular interest in the field of photonics due to their unique properties such as low loss, polarisation insensitivity, ease of integration into optical systems and fast recovery time especially in mode-locked erbium doped fibre lasers (EDFLs) [16]. Various configurations and techniques have been investigated for a CNT mode locker in an EDFL [17].

Nowadays, numerous schemes based on bidirectional mode-locked fibre lasers have been well presented [18 – 20]. Passively mode-locked fibre lasers without an optical isolator inside their cavities can concurrently generate two pulse trains (bidirectional mode-locking). Over the past several decades, bidirectional mode-locked lasers have been extensively investigated and known as attractive devices for numerous sensing applications [21].

In this paper, a passively bidirectional mode-locked fibre laser is demonstrated using a highly concentrated erbium-doped fibre (Liekki EDF) as a gain medium in conjunction with a CNT saturable absorber. A short cavity is used to generate high repetition rate pulses in mode-locked fibre lasers. The effect of the EDF length on the performance of the mode-locked fibre laser is also investigated.

2. Experimental setup

Figure 1 shows the configuration of a mode-locked erbium-doped fibre laser. The resonator consisted of a highly concentrated EDF, a 980/1550 nm single-mode wavelength division multiplexer (WDM), a 1% output coupler and a

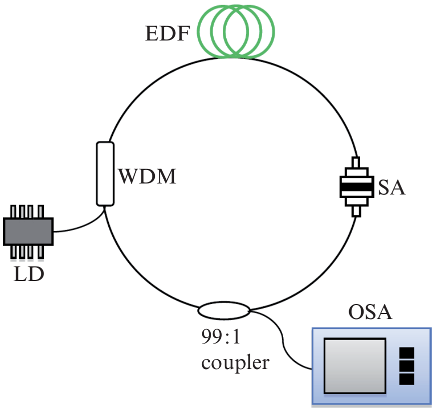

Figure 1. Experimental setup of the mode-locked fibre laser.

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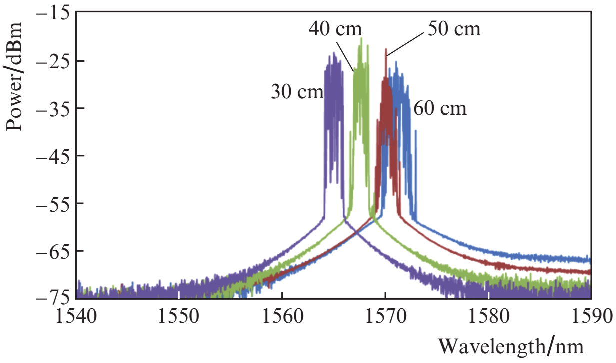

Figure 2. Output power spectra at different EDF lengths.

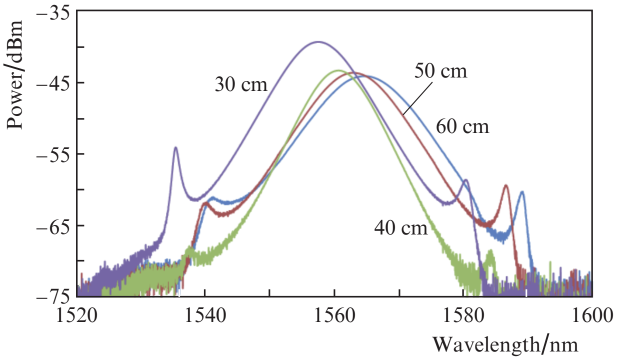

Figure 3. Optical spectra of the output of a soliton mode-locked EDFL at different EDF lengths.

CNT-based SA. As a gain medium use was made of the EDF (Liekki Er-110-4/125) with a peak core absorption of 110 dB m^{-1} at 1530 nm. In the experiment, the EDF length was varied from 30 cm to 60 cm. The cavity was pumped via the 980/1550 nm WDM by a 980-nm laser diode (LD) with a maximum current 180 mA which provides 59 mW of optical power. The common port of the WDM was coupled to a 60-cm EDF. The other end of the WDM coupler (1550 nm port) was connected to 99 : 1 fused coupler. Between the 99 % port of the coupler and the EDF we placed a CNT-based SA in the form of a film sandwiched between two fibre ferrules. Unlike other fibre ring lasers, in this cavity we used no isolators and polarisation controllers. The total length of the laser cavity was ~5 m. The output of the mode-locked laser was retrieved via the 1 % port of the 99 : 1 coupler which was connected to an optical spectrum analyser (OSA, Yokogawa) with a resolution of 0.02 nm. A LeCroy 352A oscilloscope together with an Agilent 83440C lightwave detector was used to measure the properties of the

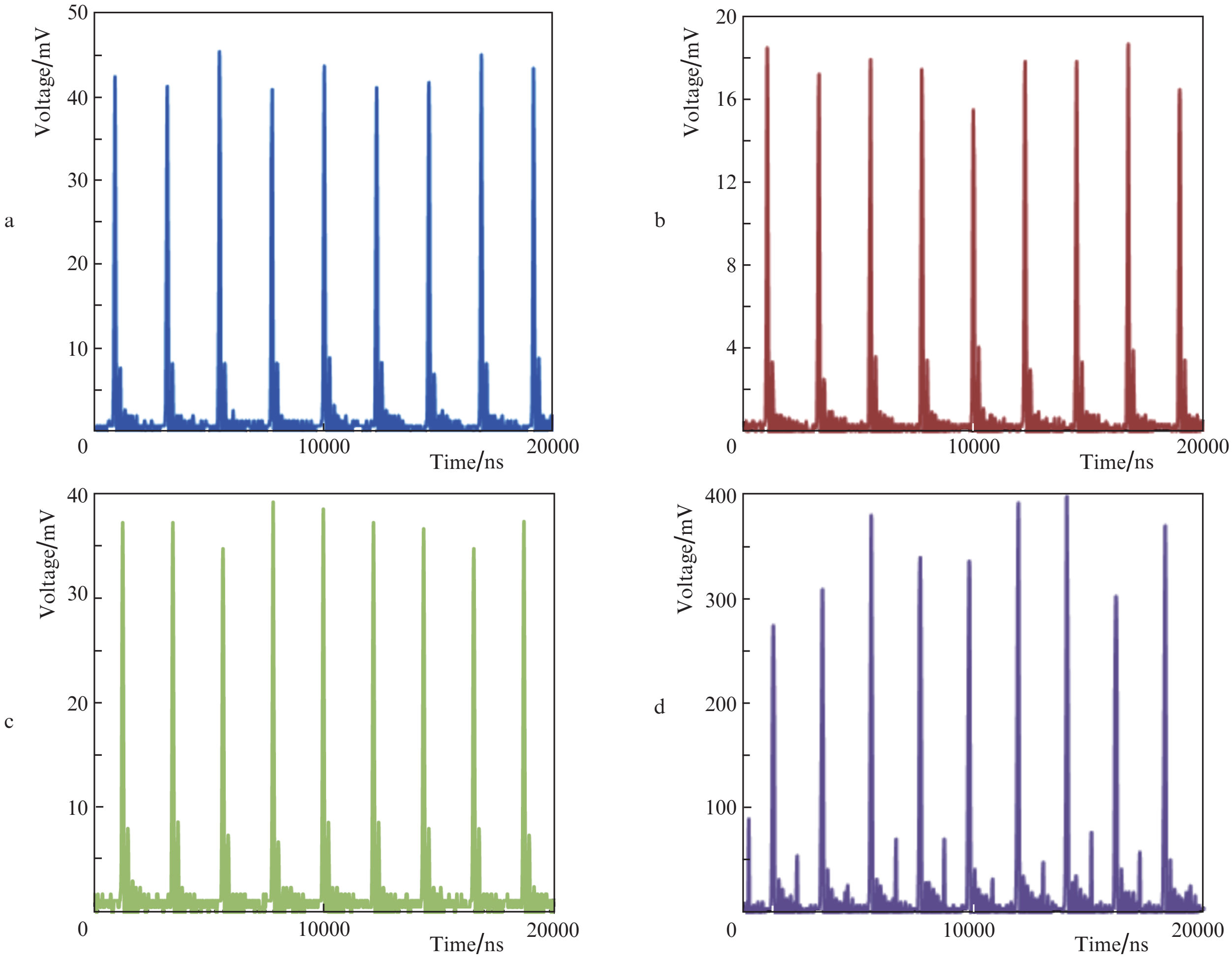

Figure 4. Output pulse trains obtained at EDF lengths of (a) 60, (b) 50, (c) 40 and (d) 30 cm.

mode-locked pulse train. The radio frequency spectrum of the mode-locked pulse was observed using an Anritsu MS2683A radio frequency spectrum analyser (RFSA). The lengths of the EDF in the experiment were equal to 50, 40 and 30 cm.

3. Results and discussion

Figure 2 shows the output power spectra of the laser at different EDF lengths. One can see that the wavelength shift to the left with decreasing EDF length.

Figure 3 shows the optical spectra of the output of the mode-locked fibre laser at various EDF lengths. The pump power threshold (at 980 nm, which was fixed in the experiments) for cw laser operation is around 59 mW. For the EDF lengths of 30, 40, 50 and 60 cm, the bandwidths at a 3-dB level were 8.1, 8.8, 10.1 and 11.4 nm, respectively, for the centre wavelengths of 1557, 1560, 1563 and 1565 nm. One can observe a significant difference between the spectra of mode-locked lasers with the EDF length of 30 and 40 cm due to interplay of the group-velocity dispersion (GVD) and nonlinearity. When the GVD together with Kerr nonlinearity is anomalous, the pulses are formed by a balance between positive nonlinear and negative dispersion phase changes. The net cavity dispersion was approximately -0.13 ps^2, which enables soliton shaping in the laser at an average intracavity dispersion of -14 ps^2 km^{-1}.

Figure 4 shows the output pulse trains of the proposed system as observed from the oscilloscope. One can see that the pulse trains have a constant spacing of 22.8, 22.4, 21.8 and 21.3 ns which correspond to the equivalent repetition rates of 43.92, 44.62, 45.87 and 46.97 MHz for EDF lengths of 60, 50, 40 and 30 cm, respectively. This indicates that the shorter the cavity length, the smaller the mode spacing. It is in agreement with the formula $\tau = 2L/c$, where τ is the mode spacing and L is cavity length. Under an incident pump power of 59 mW, the average output power for EDF lengths of 60, 50, 40 and 30 cm was 23.44, 24.04, 30.20 and 36.64 μW, respectively. The calculated pulse energy was 0.52, 0.54, 0.66 and 0.78 pJ, respectively.

Figure 5 shows the RF spectra of the mode-locked laser output at different EDF lengths. One can see that the main peak for the EDF length of 60 cm corresponds to the cavity repetition rate of 43.92 MHz with a signal-to-noise ratio of 63 dB (Fig. 5a). When the EDF lengths were 50, 40 and 30 cm, the observed signal-to-noise ratios were 59, 58 and 26 dB at the equivalent repetition rates of 44.62, 45.87 and 46.97 MHz, respectively (Figs 5b–5d). Therefore, as the cavity length decreases, the signal-to-noise ratio also decreases.

The temporal output of the soliton-pulse fibre laser at various EDF lengths is shown in Fig. 6. The autocorrelation trace of the pulse shows that the pulse profile is described by the sech^2 function with a full width at half maximum (FWHM) of 0.41, 0.48, 0.52 and 0.56 ps at EDF lengths of 30, 40, 50 and

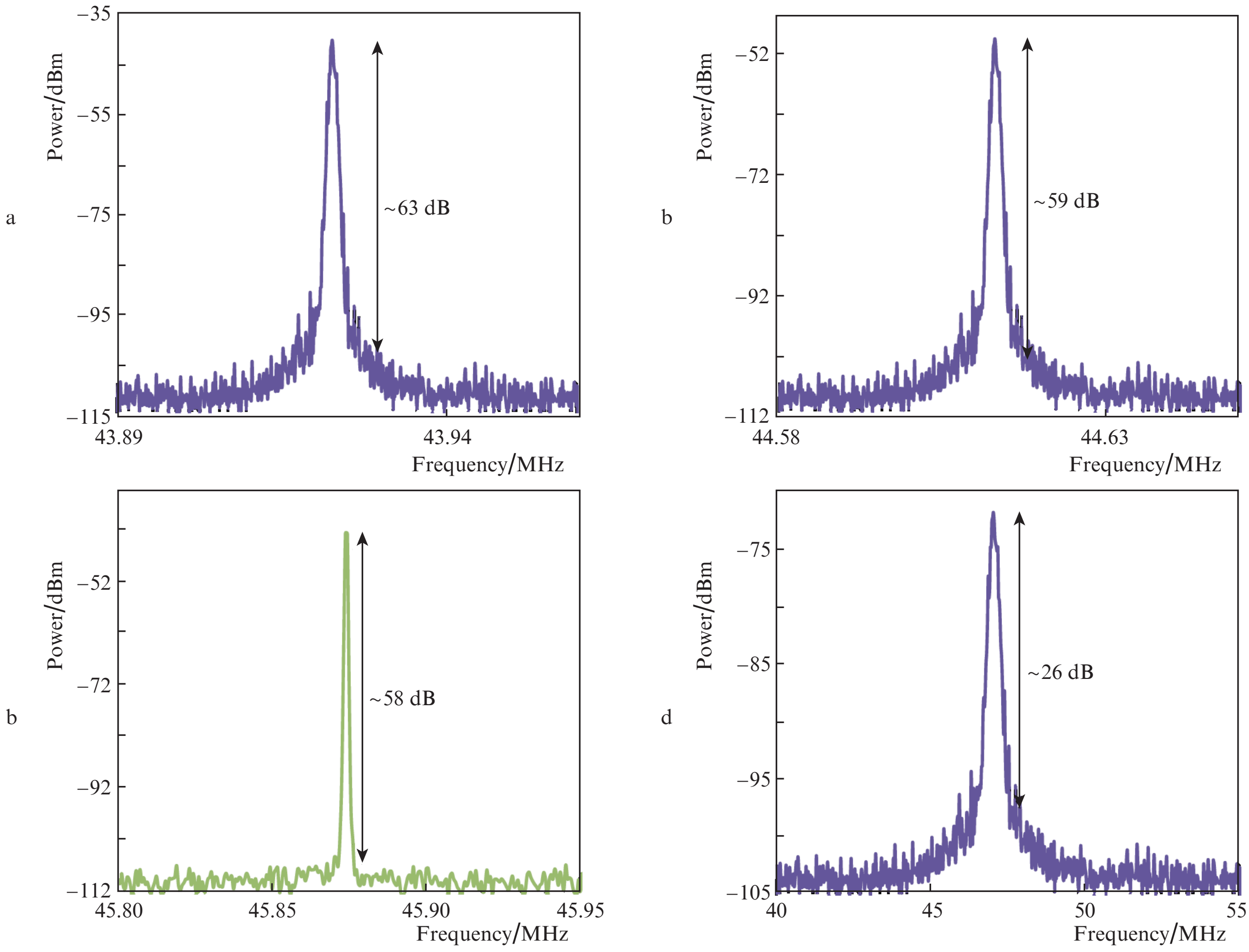

Figure 5. RF spectra of the laser at EDF lengths of (a) 60, (b) 50, (c) 40 and (d) 30 cm.

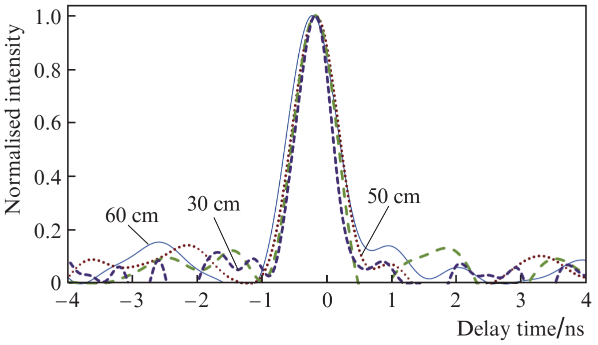

Figure 6. Auto-correlation trace of the output pulse from the EDFL at different EDF lengths.

60 cm, respectively. A decreasing trend of the pulse duration is observed as the length of the gain medium decreases.

The comparison between repetition rates and pulse durations at different EDF lengths is shown in Fig. 7. One can see that as the EDF length increases, the repetition rates decrease. Moreover, the shorter the cavity length the narrow the pulse width.

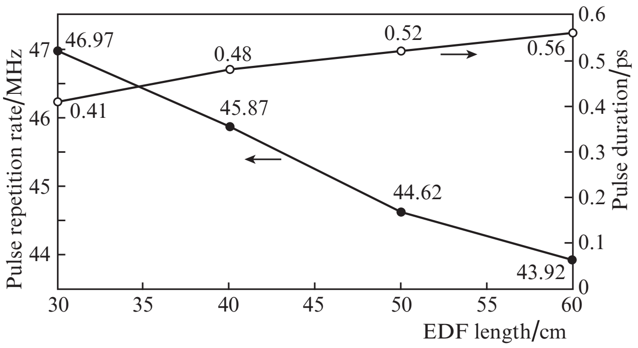

Figure 7. Changes in the repetition rate and pulse duration at different EDF lengths.

The experiment shows that this bidirectional ring laser is actually independent of the polarisation direction. Since we did not use an isolator and a polarisation controller in this configuration of the laser, its cost is lower than that of a unidirectional laser. Furthermore, the absence of an isolator and polarisation controller allows one to reduce the loss inside the cavity.

4. Conclusions

Thus, using CNTs as a saturable absorber we have demonstrated a bidirectional passively mode-locked fibre laser based on a highly concentrated EDF. The proposed laser generates soliton pulses of spectral width and repetition rate ranging from 0.41 ps to 0.56 ps and 43.92 MHz to 46.97 MHz, respectively, as the EDF length is varied from 30 to 60 cm. It is found that the repetition rate increases with decreasing EDF length.

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