Quantum Electronics **46** (11) 979 – 981 (2016)

CONTROL OF LASER RADIATION PARAMETERS

DOI: 10.1070/QEL16142

Generation of ultrashort pulses with minimum duration of 90 fs in a hybrid mode-locked erbium-doped all-fibre ring laser

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Abstract. **Regimes of ultrashort pulse generation in an erbium-doped all-fibre ring laser with hybrid mode locking based on single-wall carbon – boron nitride nanotubes and the nonlinear Kerr effect in fibre waveguides are studied. Stable dechirped ultrashort pulses are obtained with a duration of ~90 fs, a repetition rate of ~42.2 MHz, and an average output power of ~16.7 mW, which corresponds to a pulse energy of ~0.4 nJ and a peak laser power of ~4.4 kW.**

Keywords: *mode locking, single-wall nanotubes, soliton, ultrashort pulses, fibre laser.*

1. Introduction

For the last two decades mode-locked fibre lasers emitting ultrashort pulses (USPs) have been widely used in various fields of science and engineering [1]. Note that some applications require stable pulse duration and repetition rate, as well as low intensity noise and phase noise of USP sources. In particular, the stabilisation of these parameters is especially important in frequency metrology, comb spectroscopy, terahertz pulsed spectroscopy, telecommunications, and other fields [2 – 5]. Recently, interest has been attracted to hybrid mode locking, which allows one, on the one hand, to achieve reliable mode locking start-up and, on the other hand, to improve USP parameters [4, 6, 7].

Stable USP generation in the hybrid mode-locking regime in fibre lasers occurs due to the combined action of two saturable absorbers: a slow absorber (with a response time up to about 0.2 ps), for example, semiconductor saturable-absorber mirror (SESAM) [8], graphene films [9], or carbon nanotubes [10]; and a fast absorber based on nonlinear polarisation evolution (NPE) in fibre waveguides (with a response time of ~10 fs) [11, 12]. Carbon – boron nitride nanotubes (C : BNNT) have been recently used as an efficient saturable absorber with saturation parameters and modulation depth sufficient for reliable mode locking start-up in ultrashort-pulse erbium fibre lasers [13].

In the present work, we obtained for the first time stable dechirped ultrashort pulses with a minimum duration of ~90 fs in an erbium-doped all-fibre ring laser with a negative intracavity group-velocity dispersion and hybrid mode locking based on single-wall carbon – boron nitride nanotubes and NPE in fibre waveguides.

2. Experimental setup

The scheme of the all-fibre ring laser cavity is shown in Fig. 1. As a slow passive absorber, we used single-wall carbon – boron nitride nanotubes (C : BNNT) [13, 14]. Fast mode locking based on NPE was achieved using a commercial isolator – polariser (ISO-PM), which also served as an isolator for obtaining unidirectional generation. Two polarisation controllers (PCs) placed in the ring cavity from two sides of the isolator – polariser were used to adjust the fibre laser regimes. As an active erbium-doped fibre, we used a 1.34-m long fibre with an Er^{3+} absorption of ~43 dB m^{-1} at the pump wavelength and a dispersion coefficient of -30.7 ps nm^{-1} km^{-1} at the wavelength $\lambda = 1550$ nm. For precise adjustment of dispersion inside the cavity, we used SMF-28 (Corning Corp., USA) fibre with negative group velocity dispersion (GVD) in the region of 1550 nm. The total intracavity dispersion parameter β_2 in the scheme was -0.021 ps^2 at $\lambda = 1550$ nm.

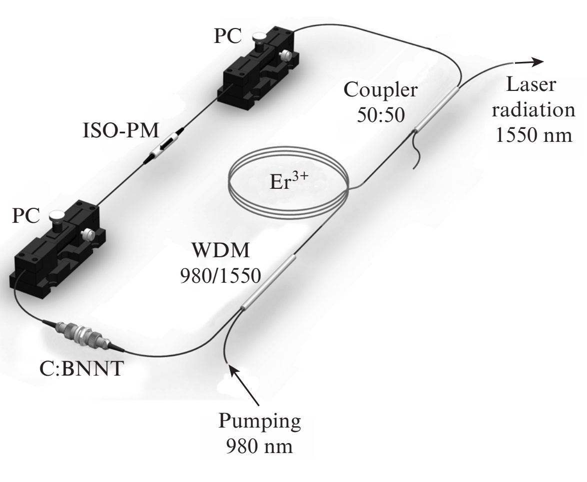

Figure 1. Scheme of the hybrid mode-locked erbium-doped fibre ring laser.

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Received 23 May 2016; revision received 30 September 2016
Kvantovaya Elektronika **46** (11) 979 – 981 (2016)
Translated by M.N. Basieva

The active erbium-doped fibre was pumped by a single-mode laser diode at wavelength $\lambda_p = 980$ nm with a maximum output power up to 330 mW via a 980/1550 (WDM 980/1550) spectrally selective fibre coupler. The laser radiation was coupled out of the cavity through a fibre-optic coupler with a branching ratio of 50/50.

3. Experimental results and discussion

By adjusting PCs, we obtain two self-starting single-pulse regimes of the studied laser with different spectral widths (the spectra of laser pulses are presented below). The inset in Fig. 2a shows a typical oscillogram of laser pulses recorded with an Infinium MSO9254A oscilloscope (Keysight Technologies, Santa Rosa, USA). The mode-locking threshold was observed at an average pump power of 100 mW ($\lambda_p = 980$ nm) for both generation types. An increase in the pump power to the maximum value (330 mW) caused no oscillation suppression in both regimes. It should be noted that such a low threshold pump power (compared, for example, with the threshold in the case of mode locking based solely on NPE [2]) is explained by the combination of two mode-locking mechanisms, when a slow saturable absorber reliably switches the mode-locking regime and a fast mechanism completes the pulse formation [4].

Figure 2b shows a spectrum of electric signals at the fundamental repetition rate of the oscillator (recorded using an FSL 3 model.03 electric spectrum analyser (Rohde&Schwarz GmbH & Co. KG, Munich, Germany), which completely corresponds to the 4.93-m cavity length and lies in the region of 42 MHz (resolution 300 Hz). The spectrum for both generation regimes has a clearly pronounced peak at a frequency of 42.22 MHZ with a signal-to-noise ratio of 63 dB, which indicates a pulse-to-pulse lasing stability. The inset in Fig. 2b shows the frequency spectrum in the range from 10 kHz to 2 GHZ with a resolution of 30 kHz. Note that the high signal-to-noise ratio in the high-frequency region points to mode-locking stability [15].

Figure 3a presents the spectra of pulses for two types of mode-locked generation at an average output power of 16.7 mW. The narrower emission spectrum (*1*) is best described by the function $\mathrm{sech}^2(\lambda)$ with FWHM $\Delta\lambda_{\mathrm{FHWM}} \approx 4$ nm, while the broader emission spectrum (*2*) is approximated by a Gaussian function with $\Delta\lambda_{\mathrm{FHWM}} \approx 56$ nm. Figure 3b shows the corresponding measurements of pulse intensity autocorrelation functions for two oscillation types and their approximation by a Gaussian function for a ~2-m length of the fibre from the coupler to the autocorrelator (model FR-103WS, Femtochrome Research Inc., Berkeley, USA). Note that the Gaussian shape of the spectrum and pulse is typical for generation of stretched pulses [16] or dispersion-managed (DM) solitons [5,17]. The pulse spectrum in the form $\mathrm{sech}^2(\lambda)$ is typical for classical soliton [18]. However, the absence of side

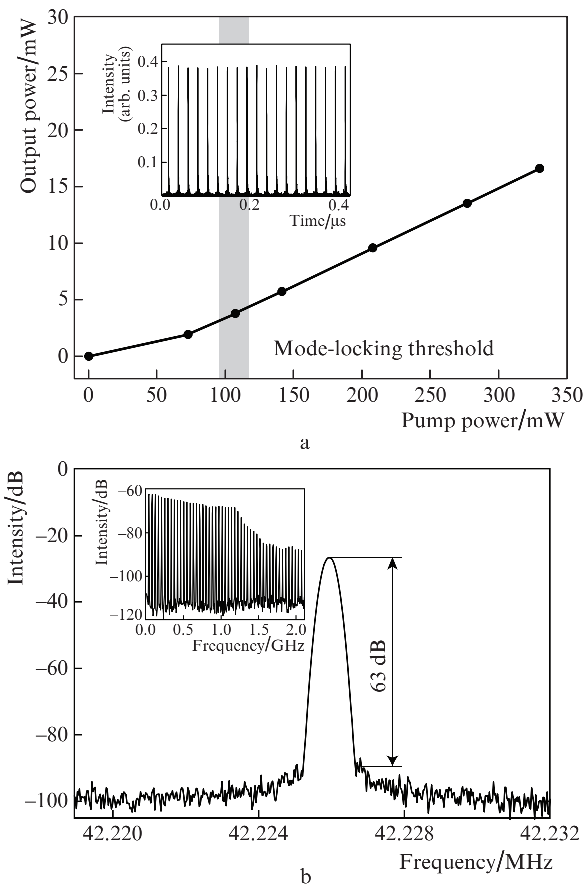

Figure 2. (a) Dependence of the average output optical power on the pump power (the inset shows an oscillogram of ultrashort pulses) and (b) frequency spectra of the laser.

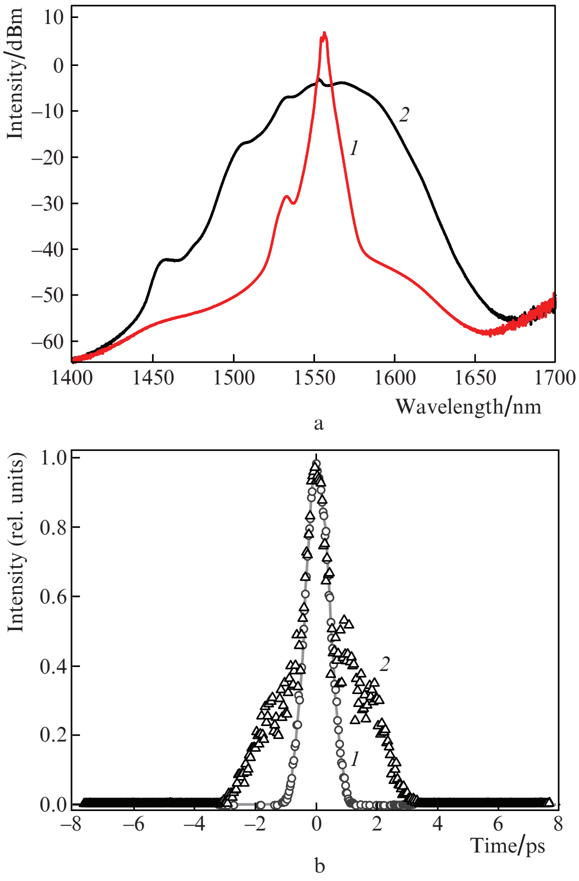

Figure 3. (a) Spectra and (b) intensity autocorrelation functions of pulses described by (*1*) sech^2 and (*2*) Gaussian functions, as well as Gaussian approximation (solid curve) of USPs in the ring erbium-doped fibre laser. The average output pulse power is 16.7 mW, the pulse repetition rate is 42.2 MHz, and the pulse duration (FWHM) is 650 fs.

peaks caused by the modulation instability of classical solitons indicates generation of DM solitons similar to classical solitons (such transformations were studied, for example, in [19]). Taking into account the aforesaid and the negative value of intracavity GVD, we can suggest that ultrashort pulses generated in the steady state regimes are DM solitons.

The pulse FWHM was estimated to be ~650 fs for both generation types. Note that the time–bandwidth product for the sech^2 pulse is TBP = $\Delta\nu\tau_{\min} \approx 0.322$, while this product for the Gaussian pulse is TBP $\approx$ 4.45 (typical TBP for a pulse with a Gaussian spectrum is approximately 0.441). Thus, the frequency bandwidth of the obtained sech^2 pulse is close to its limit (for classical soliton, TBP $\approx$ 0.315).

Figure 4 shows the intensity autocorrelation function and the phase of a dechirped pulse with a Gaussian spectrum for a ~1.7-m length of the fibre from the coupler to the system analysing the ultrashort laser pulses (Swamp Optics LLC, GRENOUILLE Model 15-40-USB, USA); the inset shows the laser spectrum at the maximum output power. Note that the minimum duration of pulses with a Gaussian spectrum obtained by changing the length of the output SMF-28 fibre was ~90 fs (FWHM); in this case, the TBP was equal to 0.47, i.e., the temporal pulse width was close to its limit. The absence of any shoulder on the obtained autocorrelation function (Fig. 4), which is usually observed in the case of compression of high-energy pulses in fibres (see, for example, [20]), indicates that the pulse compression occurs only due to dispersion in the fibre and points to the absence of nonlinear effects upon propagation of relatively low-energy pulses.

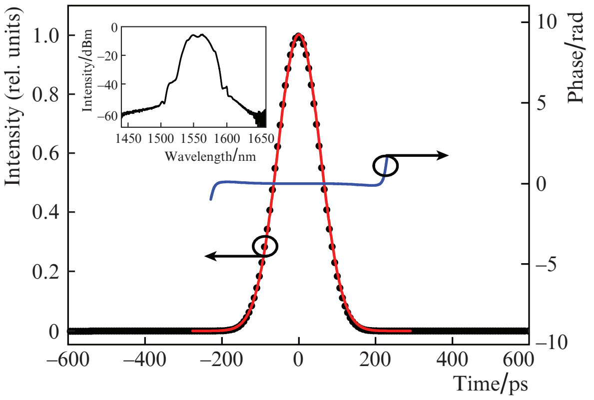

Figure 4. Intensity autocorrelation function and phase of an USP with a Gaussian spectrum (the laser spectrum is shown in the inset). The average output pulse power is 16.7 mW, the pulse repetition rate is 42.2 MHz, and the pulse duration (FWHM) is 90 fs.

Thus, in this work we obtained stable dechirped USPs with a repetition rate of 42.22 MHz, an average output power of 16.7 mW, and a minimum pulse duration of 90 fs, which corresponds a pulse energy of ~0.4 nJ and a peak output power of 4.4 kW in an all-fibre erbium ring laser with hybrid mode locking based on single-wall carbon–boron nitride nanotubes and nonlinear polarisation evolution in fibre waveguides.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 16-38-60102 mol_a_dk) and by the Grants Council of the President of the Russian Federation for the State Support of Young Scientists (Grant No. MK-7724.2016.8).

The authors thank A.K. Senatorov, M.M. Bubnov, and M.E Likhachev (Fiber Optics Research Center, Russian Academy of Sciences) for supplying active fibre waveguides and measuring their main characteristics.

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