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Passive harmonic mode-locking in an erbium-doped fibre laser

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Abstract. **We report an all-fibre erbium laser operating in the regime of passive harmonic mode-locking based on the effect of nonlinear polarisation rotation. The generation of the 67th harmonic with a pulse repetition rate of 5.62 GHz and a duration of 1.8 ps is demonstrated. It is shown that as the harmonic number increases, both the frequency modulation parameters and the pulse duration change.**

Keywords: *mode-locking, ultrashort pulses, harmonic mode-locking, fibre laser, frequency modulation.*

1. Introduction

High-repetition-rate (HRR, with a pulse repetition rate of more than 1 GHz) fibre lasers that generate ultrashort pulses (USPs) are in demand in many areas of science and technology. In optical metrology and molecular spectroscopy, highly stable USP laser systems make it possible to obtain output data with an improved signal-to-noise ratio with decreasing measurement time. Such systems are also suitable for navigation systems where high-precision frequency standards and high-speed data transmission systems are required. HRR laser sources occupy a special place in radiophotonics, being a powerful stimulus for the development of various sectors of photonics: highly stable continuous wave and pulsed lasers (including USP lasers), broadband photodetectors, fibre filters, and photonic analogue-to-digital converters for frequencies above 10 GHz.

There are several ways to produce HRR laser systems: the use of solid-state or semiconductor lasers with a short resonator [1], of microresonators [2], and of laser systems operating in the regime of harmonic mode-locking [3], i. e. the regime during which several pulses are simultaneously present in the resonator at specified time intervals. Mode-locking can be obtained using saturable absorbers (SESAM or carbon nanotubes) [4, 5] and nonlinear fibre mirrors [6]. One of the most common mechanisms to provide mode-locking in fibre lasers is based on nonlinear polarisation rotation (NPR) [7]. For example, the authors of Refs [8 – 11] obtained harmonic mode-locking at the 3rd, 322nd, 928th, and 27655th harmonics. However, such laser systems often contain bulky elements, and active elements are used to stabilise the generation process and reduce noise.

2. Experimental setup

This paper demonstrates a pulsed ring fibre laser passively harmonic mode-locked by nonlinear polarisation rotation. The scheme of the experimental setup is shown in Fig. 1.

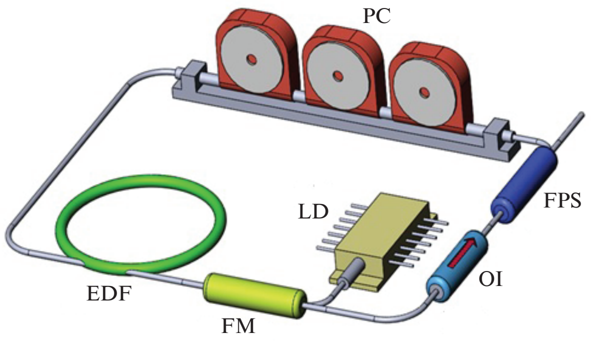

Figure 1. Schematic of the experimental setup:
(PC) polarisation controller; (EDF) active erbium-doped fibre; (FM) fibre multiplexer; (LD) pump laser diode; (OI) optical isolator; (FPS) fibre polarisation splitter.

A 1 m length of erbium-doped fibre was used as an active medium. The absorption coefficient at the pump wavelength was 6.4 dB m^{-1}. The total length of the resonator, taking into account the used delay line on a single-mode fibre, was 2.4 m, which ensured a pulse repetition rate of 84 MHz (corresponding to the fundamental harmonic of the resonator). The pumping was carried out by radiation of a single-mode semiconductor laser diode with a wavelength of 1461 nm. The pump power varied from 30 to 180 mW. Harmonic mode-locking was obtained by carefully adjusting the polarisation controllers and optimising the pump power.

3. Results and discussion

As a result of the experiments, we have found several working points, in which a stable laser operation regime was observed, and these regimes could be combined in a series by generation

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wavelengths. Thus, at a wavelength of 1555 nm, it was possible to obtain harmonic mode-locking at frequencies of 480 MHz and 1.85 GHz, at a wavelength of 1558 nm – at frequencies of 84, 168 and 840 MHz and at a wavelength of 1560 nm – at 3.11, 3.95 and 5.62 GHz. Oscillograms obtained using a Tektronix MDO3052 oscilloscope with a 500 MHz band are shown in Fig. 2. The corresponding autocorrelation functions obtained with an AVESTA AA-20DD autocorrelator are also shown. The maximum pulse repetition rate of 5.62 GHz corresponds to the 67th harmonic of the resonator. The spectra of the output radiation are shown in Fig. 3.

The duration of the generated pulses varied from 0.8 to 1.8 ps. The dependence of the pulse duration on the frequency in the regime of harmonic mode-locking is shown in Fig. 4. It can be assumed that for the generation regime to be stable at high harmonics, it is needed to increase the spectral power density (due to the narrowing of the spectrum) in order to compensate for the drop in peak power, as well as to maintain a sufficient nonlinear rotation of the polarisation plane.

The relative level of phase noise in various regimes of laser operation is shown in Fig. 5. It can be seen that with an increase in the harmonic number, the noise level increases sharply, which is due to the absence of strong mechanisms for stabilising the pulse repetition rate in a passively harmonic mode-locked resonator.

In measuring the frequency modulation of pulses, the length of the resonator was shortened, as a result of which the main pulse repetition rate increased to 97 MHz. The frequency modulation, duration and width of the pulse spectrum were measured using an HR150 FROG analyser (Coherent

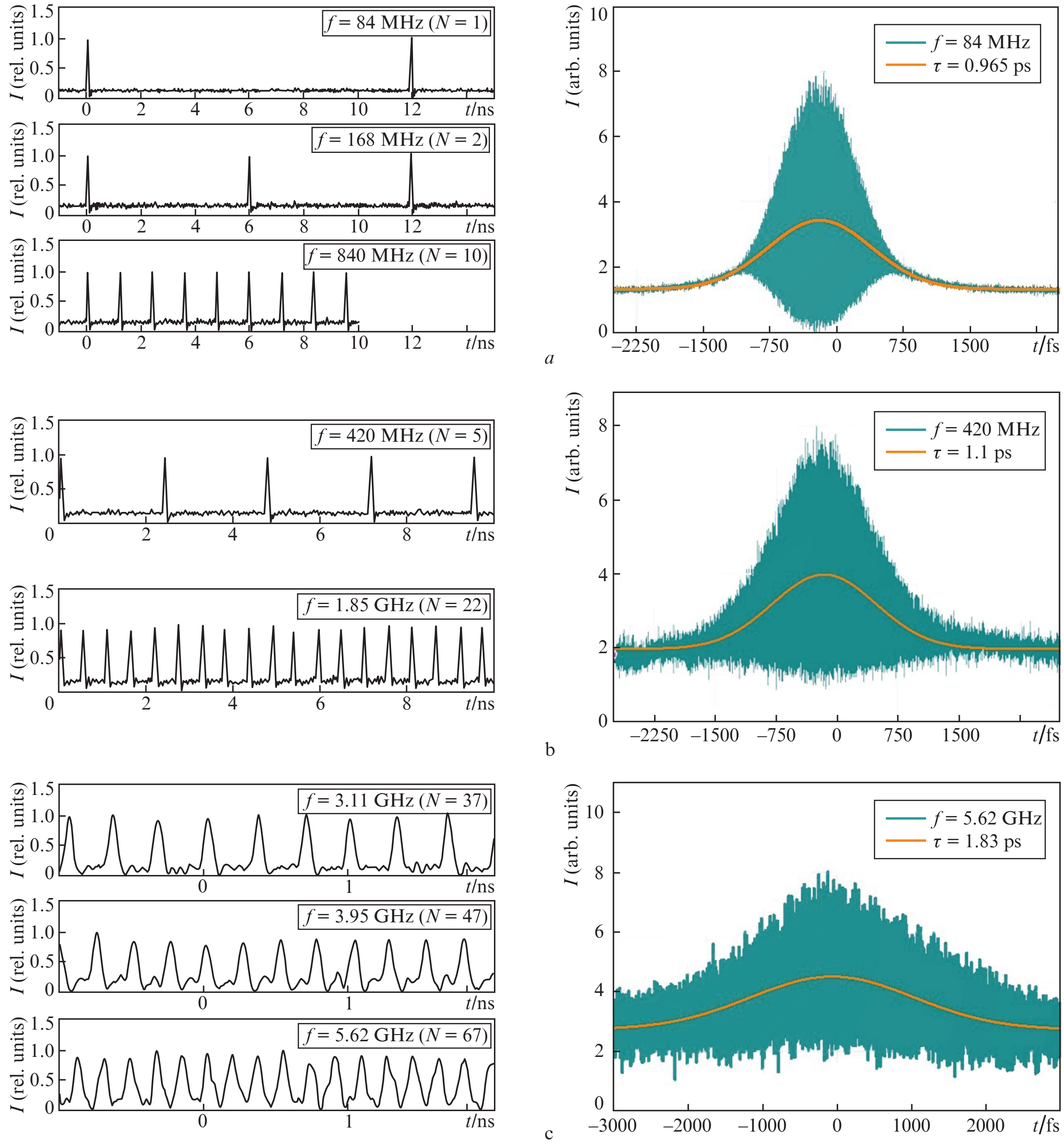

Figure 2. (left) Oscillograms and (right) corresponding autocorrelation functions of output pulses for generation wavelengths of (a) 1558, (b) 1555 and (c) 1560 nm: f is the pulse repetition rate; N is the harmonic number; and τ is the pulse duration.

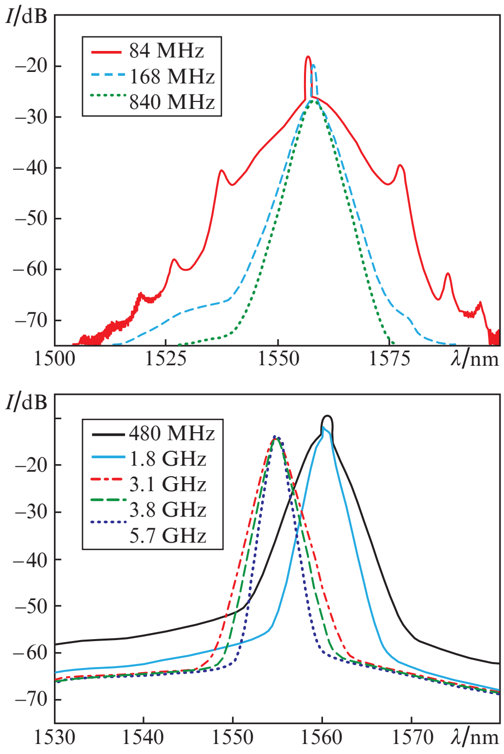

Figure 3. Output spectra for different harmonics.

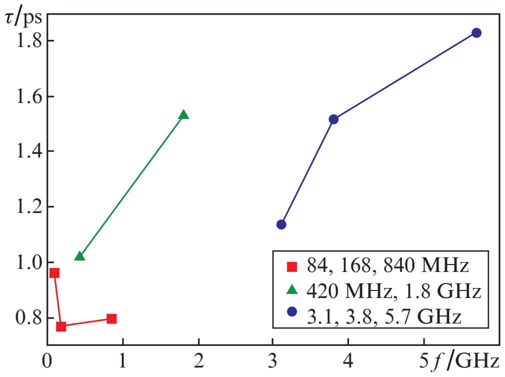

Figure 4. Dependence of the pulse duration τ on the pulse repetition rate f.

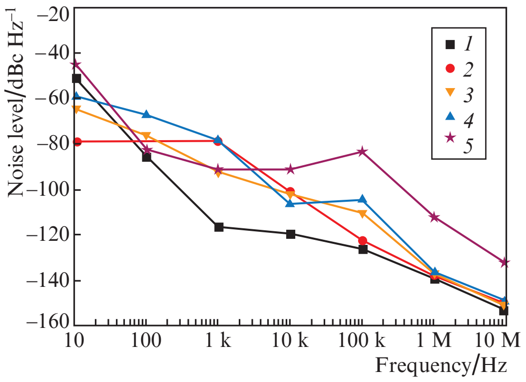

Figure 5. Relative level of the laser phase noise (*1*) at the fundamental frequency, (*2*) at the fundamental frequency in the cw regime, and (*3*–*5*) at the frequency of (*3*) the 4th, (*4*) 6th, and (*5*) 11th harmonics.

Table 1.

f/MHz	τ/ps	C/GHz ps^{-1}	$\Delta\lambda$/nm
97*	0.74	−1300	5.9
97	1.63	−143	2.67
200	1.5	−94	1.98
400	2.5	−94	1.85
580	2	−100	1.62
900	1.5	−87	2.1
1200	1.5	90	1.47

*When the laser operates in the strong frequency modulation regime ($C = -1300$ GHz ps^{-1}), we failed to obtain a series of harmonic mode-locking regimes.

Solutions). The measurement results are shown in Table 1. The frequency-modulated pulse shapes at the fundamental, 6th and 13th harmonics are shown in Fig. 6, from which it follows that with increasing harmonic number, the frequency modulation of the pulse is greatly distorted.

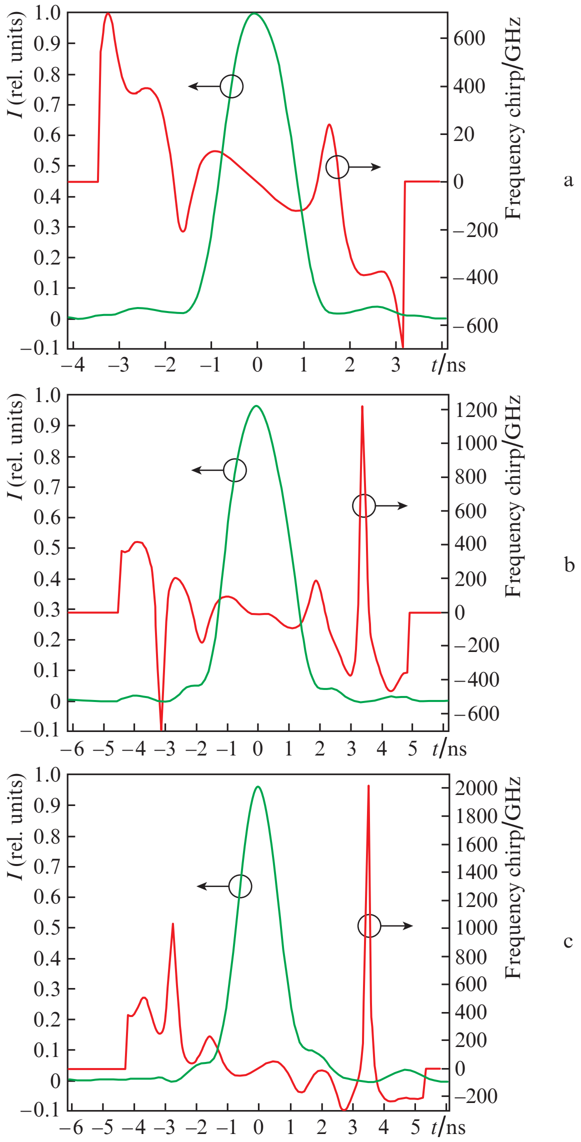

Figure 6. Output-pulse carrier shape and frequency chirp (a) at the fundamental frequency and (b, c) at the frequency of (b) the 6th and (c) 12th harmonics.

4. Conclusions

Thus, we have fabricated an USP laser system on the basis of a harmonic mode-locked ring fibre laser. The generation of the 67th harmonic (5.62 GHz) has been obtained at the fundamental laser frequency of 84 MHz. It has been found that there are operating points at which the laser can be tuned by harmonic frequencies at given wavelengths. In this case, the pulse duration is varied in the range from 0.8 to 1.8 ps. It has been established that at high harmonics the phase noise deteriorates on average by 25–30 dB. As the harmonic number increases, frequency modulation becomes more distorted.

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References

1. Bandelow U., Radziunas M., Vladimirov A., Hüttl B., Kaiser R. *Opt. Quantum Electron.*, **38**, 495 (2006).
2. Kippenberg T.J., Holzwarth R., Diddams S.A. *Science*, **332**, 6029 (2011).
3. Li X., Zou W., Chen J. *Opt. Express*, **23** (16), 21424 (2015).
4. Sotor J., Sobon G., Macherzynski W., Abramski K.M. *Laser Phys. Lett.*, **11**, 055102 (2014).
5. Komarov A., Leblond H., Sanchez F. *Opt. Commun.*, **267**, 162 (2006).
6. Chen H.R., Lin K.H., et al. *Opt. Lett.*, **38**, 845 (2013).
7. Peng J., Zhan L., Luo S., Shen Q. *J. Lightwave Technol.*, **31**, 3009 (2013).
8. Yan M., Li W., Yang K., Bai D., Zhao J., Shen X., Ru Q., Zeng H. *Opt. Lett.*, **37**, 3021 (2012).
9. Amrani F., Haboucha A., Salhi M., Leblond H., Komarov A., Grelu P., Sanchez F. *Opt. Lett.*, **34**, 2120 (2009).
10. Lecaplain C., Grelu P. *Opt. Express*, **21**, 10897 (2013).
11. Chen H., Chen S.-P., Jiang Z.-F., Hou J. *Opt. Express*, **23**, 1308 (2015).