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Quasi-regenerative mode locking in a compact all-polarisation-maintaining-fibre laser

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Abstract. **A novel technique of mode locking in erbium-doped all-polarisation-maintaining-fibre laser has been developed and preliminary investigated. The proposed quasi-regenerative technique combines the advantages of conventional active mode locking (when an intracavity modulator is driven by an independent RF oscillator) and regenerative mode locking (when a modulator is driven by an intermode beat signal from the laser itself). This scheme is based on intracavity intensity modulation driven by an RF oscillator being phase-locked to the actual intermode frequency of the laser. It features also possibilities of operation at multiple frequencies and harmonic mode-locking operation.**

Keywords: *fibre laser, mode locking, intensity modulator.*

1. Introduction

Mode-locked fibre lasers, generating regular trains of ultrashort pulses, can successfully be used to solve many fundamental and applied problems. Lasers with all-polarisation-maintaining-fibre cavity design, free of precisely adjustable optomechanical elements, are especially promising for practical applications. Depending on the implementation, mode locking in all-fibre lasers is classified as passive and active.

Passive mode locking can be implemented by placing saturable absorbers of different types (e. g., based on semiconductors [1], carbon nanoparticles [2], or other materials [3]) in the cavity. A drawback of this approach is that the low radiation resistance of absorbers and their dynamic characteristics limit significantly the attainable temporal and energy parameters of pulsed lasing.

Another approach to the implementation of passive mode locking is to use the nonlinear effects arising in cavity fibres. A typical way is to apply nonlinear birefringence in a cavity equipped with a polarisation discriminator [4, 5] or nonlinear phase shift of pulses in a cavity with a nonlinear loop mirror [6]. This technique is free of some drawbacks inherent in the application of saturable absorbers; however, it calls for cavities of somewhat more complicated design with elements that should be precisely aligned. Cavity misalignment or a small drift of pump parameters may lead to deterioration or even breaking of mode locking in these lasers. Triggering mode locking in them (from switching on to switching on) may require to adjust the cavity alignment elements and (or) pump power.

Note that not all the aforementioned mode locking techniques make it possible to use all-fibre cavities, which completely exclude evolution of the laser beam polarisation state. In addition, passive mode locking limits the possibilities of implementing stable harmonic (multipulse) lasing regimes.

In view of the aforesaid, different ways of active mode locking (AML) in fibre lasers are actively investigated and applied. In most cases, an intracavity modulator is used for this purpose; generally, it is a fibre electro-optic intensity modulator, designed according to the Mach–Zehnder interferometer scheme. A periodic signal is applied to the modulator from an external driving RF generator, which should generally provide amplitude modulation with a frequency $f_{\rm mod}$ multiple of the fundamental intermode cavity frequency $f_{\rm im}$:

$$f_{\rm mod} = nf_{\rm im} = nc/L,$$

Here, c is the speed of light; L is the optical cavity-round-trip length (at the lasing wavelength); and $n = 1, 2, 3, \ldots$

Thus, one can obtain either the mode locking regime with a fundamental pulse repetition frequency ($f_{\rm rep} = f_{\rm im}$) or harmonic mode locking with a pulse repetition frequency multiply exceeding the fundamental frequency ($f_{\rm rep} = nf_{\rm im}$). These active mode-locking techniques were investigated both in fibre lasers with a small cavity length and high pulse repetition frequency [7, 8] and in fibre lasers with ultralong cavities and a low (submegahertz) fundamental pulse repetition frequency [9].

The main factor limiting the long-term stability of the active mode-locking regime is the random mismatch between the modulation frequency $f_{\rm mod}$ (driving generator frequency) and the cavity intermode frequency $f_{\rm im}$. The frequency mismatch can be accumulated with time because of the frequency drift of the insufficiently stable driving RF generator and the

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drift of the optical fibre laser cavity length, which is due to a change in the environmental conditions (temperature, pressure) and mechanical relaxation processes occurring in the cavity elements.

However, this mismatch between the modulation and intermode frequencies in a cavity with nonzero chromatic dispersion is known to be compensated to a certain extent due to the so-called frequency pulling. The essence of this effect is that a small smooth detuning of the modulation RF frequency from the initial value (corresponding to stable mode locking) leads to a smooth shift of the centre lasing wavelength without mode locking interruption. A change in the lasing wavelength at nonzero intracavity chromatic dispersion causes a change in the group delay in the cavity and, therefore, a variation in the pulse repetition period/frequency corresponding to the change in the modulation frequency $f_{\rm mod}$.

The self-tuning effect for the wavelength and pulse repetition frequency following the change in the modulation frequency was previously investigated both in fibre lasers with a high-frequency (including harmonic) AML [7, 8] and in ultralong fibre lasers with a low-frequency AML [9].

It was found experimentally that the frequency pulling and the related dispersion self-tuning of the lasing wavelength and pulse repetition frequency make it possible to maintain high-quality mode locking without significant deterioration of lasing parameters only at a small mismatch between the modulation (driving generator) frequency and the cavity intermode frequency (or a frequency multiple of it). Generally, the ultimate relative mismatch between the modulation frequency and the repetition frequency, which is determined by the optical cavity length, does not exceed $\sim 10^{-5}$.

Long-term maintenance of the highly stable AML regime can be implemented using the following active stabilisation method: simultaneous automatic control of the laser cavity intermode frequency (via control of the optical cavity length by means of a piezoceramic actuator) and the modulation frequency with respect to an external highly stable reference RF oscillator (frequency standard), using phase-locked-loop frequency control (PLLFC) electronic systems. This approach makes it possible to obtain high long-term stability of frequency–time lasing parameters [10]; however, the technical realisation of this system is fairly complicated and not always justified (it is redundant for most applications that are not related to precise frequency–time metrological systems [11, 12]).

Another approach to the long-term maintenance of the stable AML regime in a fibre laser, using no schemes of optical cavity length control and highly stable reference RF oscillators, is simple regenerative mode locking. Under these locking conditions, the driving RF signal (modulation frequency) for the intracavity intensity modulator is formed directly from the intermode beat signal detected by a photodiode placed at the laser output [13]. In the case of regenerative locking in fibre lasers, the circuit for detecting and forming the driving RF signal includes generally, along with a photodetector, a high-Q dielectric (ceramic) filter, a low-noise high-gain amplifier, and an adjustable phase shifter. The circuit, tuned to operate at a certain higher harmonic of intermode frequency $f_{\rm im}$, provides stable harmonic mode locking with a corresponding pulse repetition frequency (generally, very high: up to $\sim$10 GHz) [14]. This approach provides good correspondence between the modulation frequency and the corresponding intermode frequency harmonic, without any stabilisation of the optical cavity length. In addition, one does not need an external highly stable reference driving RF generator. A drawback of this regenerative mode locking regime is the potential possibility of transferring the amplitude noise (amplitude fluctuations) of intermode beatings to the modulation signal, which may lead to deterioration of laser noise characteristics. This problem is generally solved by introducing a limiting (saturated) amplifier into the circuit for forming a driving RF signal [15]. This measure somewhat complicates the circuit and imposes additional requirements, related to taking into account and correcting the phase delay in the regenerative mode locking scheme. In addition, since this regenerative circuit is generally tuned to a certain (fairly high) harmonic of the intermode (pulse repetition) frequency, it cannot be rapidly tuned to other harmonics or to the fundamental frequency without changing the element base.

The purpose of this work was to experimentally investigate the possibility of designing a compact all-fibre erbium-doped polarisation-maintaining laser, in which stable mode locking would be maintained automatically by means of a simple circuit solution, combining methods of conventional AML and regenerative mode locking. The proposed solution should also provide mode locking both at the fundamental intermode frequency and at its harmonics (harmonic mode locking). The scheme is intended to cover the range of pulse repetition frequencies from 10 to 100 MHz. This laser source, providing extremely stable mode locking, with polarisation maintenance and high beam quality, can be applied to solve various experimental problems of photonics and metrology [16] and to develop novel telecommunication, medical, and commercial technologies.

2. Experimental

The proposed design is based on the use of an all-fibre ring cavity, all optical fibres and elements of which maintain polarisation. The schematic of erbium-doped fibre laser and unit for generating a driving RF signal (to maintain automatically active mode locking) is shown in Fig. 1.

The ring cavity is formed by a polarisation-maintaining erbium-doped fibre amplifier based on a commercial polarisation-maintaining erbium-doped fibre (Nufern PM-ESF-7/125), which was pumped by a laser diode at a wavelength of 980 nm. The unidirectional lasing regime is maintained in the cavity using a polarisation-maintaining fibre-optic isolator. A polarisation-maintaining 20% fibre-optic coupler (OC1) is used to extract laser radiation from the cavity; some part of the radiation at the output of this coupler is directed (by another coupler, OC2) to an optoelectronic unit to form a driving RF signal for the intracavity modulator (denoted as the mode locking driver). A reference RF signal is selected in this unit using a high-speed photodetector (based on an InGaAs photodiode) and electronic filtering and amplification circuits; the frequency of the reference signal is determined by the laser radiation intermode beat frequency. The driving RF signal for the intracavity modulator is formed using an integrated voltage-controlled oscillator (VCO) (Minicircuits, JTOS series). The driving RF signal frequency is compared with the intermode beat frequency detected by the photodiode (reference frequency) in a digital phase–frequency detector (PFD) based on an AD9901KQ integrated circuit. At a nonzero error signal, the phase-locked-loop control of VCO frequency with respect to actual intermode frequency is performed using a closed feedback loop. The driver circuit includes several additional elements used to tune and optimise the PLLFC of

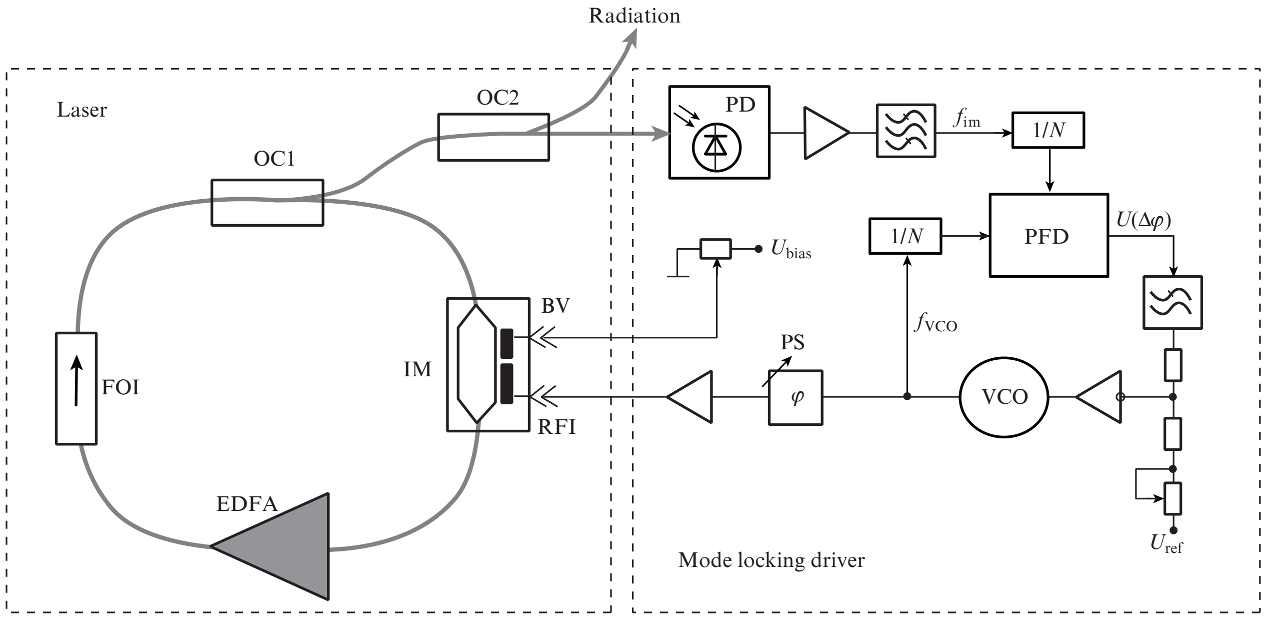

Figure 1. Schematic of the fibre laser cavity and electronic mode locking driver: (IM) radiation intensity modulator (BV is the input for a bias voltage and RFI is the modulator RF input); (EDFA) erbium-doped fibre amplifier; (FOI) fibre-optic isolator; (OC1, OC2) fibre-optic couplers; (PD) photodiode for detecting intermode beats; (1/*N*) adjustable RF dividers; (PFD) phase–frequency detector; (VCO) voltage-controlled oscillator; (U_{ref}) adjustable reference voltage for VCO; (PS) adjustable phase shifter; (U_{bias}) adjustable bias voltage for intensity modulator; and (f_{VCO}) VCO output signal frequency.

VCO and implement harmonic mode locking (at different higher intermode frequency harmonics). These elements are as follows: adjustable frequency dividers (1/*N*) at the PFD input; an adjustable integrating unit in the feedback circuit; an adjustable phase shifter (PS); and a voltage adder at the VCO input, which makes it possible to set the initial oscillator frequency (to this end, a reference voltage U_{ref}, controlled by a potentiometer, is applied to the adder).

A telecommunication electro-optic intensity modulator designed according to the Mach–Zehnder scheme (Photline MX-LN-40) was used in the cavity. This modulator is of polarisation-maintaining type, with a fibre input and output. The half-wave voltage on the RF modulator input is about 5 V, and the half-wave voltage on the bias input is about 6 V. The bias voltage U_{bias} applied to the modulator is controlled using a potentiometer. The bias voltage in preliminary experiments was set such as to locate the working point near the half maximum of the modulator transfer function. The RF signal amplitude at the modulator input was also controlled. It was chosen experimentally to obtain the best mode locking, with allowance for the inevitable compromise between the increase in the modulation depth and the rise in the modulation nonlinearity.

The total optical length of the entire cavity corresponded to the fundamental intermode frequency ~13.8 MHz (for wavelengths close to 1.56 μm).

3. Results and discussion

To trigger mode locking, it was sufficient to set (by the corresponding potentiometer) a reference voltage U_{ref} for VCO such as to make the modulation frequency be approximately equal to the fundamental intermode laser frequency or multiple of it (case of harmonic locking). Then it was necessary to close (using a toggle switch) the feedback loop in order to trigger automatic VCO frequency control. The wide capture range of the PLLFC applied to VCO allows for a rather rough setting of the initial VCO frequency, with a deviation from the actual value of intermode laser frequency as large as 10%.

Mode locking triggering led to a significant broadening of the optical lasing spectrum (Fig. 2). The latter was measured by a Yokogawa AQ6370 optical spectrum analyser with a resolution of 0.02 nm.

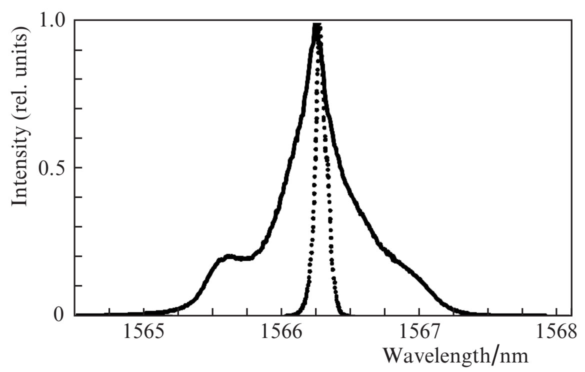

Figure 2. Optical lasing spectra in the (dotted line) free-running and (solid line) mode-locking regimes.

In addition, a high-speed InGaAs photodiode and a broadband RF spectrum analyser Tektronix RSA3308B were used to record the RF intermode beat laser spectrum. Figure 3 shows an RF spectrum of a comb of intermode beat frequencies in the mode locking regime, obtained by modulating with a frequency equal to the fundamental intermode frequency. In this case, even the high-frequency components of the intermode beat spectrum had a high signal-to-noise ratio (~60 dB), which indicated a proper mode locking quality. An oscillogram of a regular train of pulses with the fundamental repetition frequency, generated under these conditions, is shown in

Fig. 4. The measurement was performed using a Tektronix DPO7254 oscilloscope with a temporal resolution of ~0.4 ns. The average output lasing power in this regime reached ~25 mW, a value corresponding to a pulse energy of ~1.8 nJ. A rough estimate of the pulse width based on the spectral width (in the spectrally limited sech^2-pulse approximation) yields a value of about 6 ps.

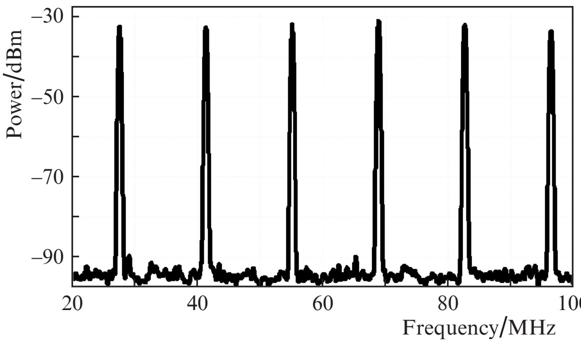

Figure 3. RF intermode beat spectrum of the laser in the mode-locking regime with modulation at the fundamental intermode frequency ($f_{mod} = f_{im}$); the analyser resolution is 300 kHz.

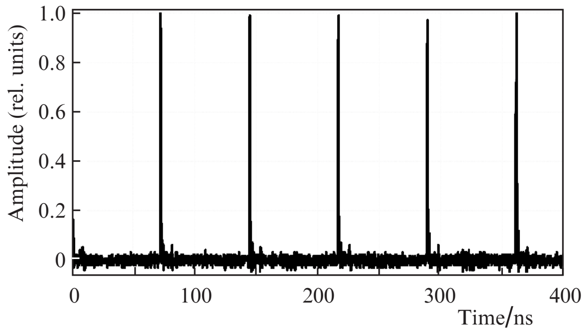

Figure 4. Oscillogram of a generated train of pulses with the fundamental repetition frequency ($f_{rep} = f_{im}$).

It was established that, due to the phase-locked-loop VCO frequency control (with optimal tuning of the phase shifter and signal amplitude at the RF modulator input), the mode locking regime can be maintained in the laser for a practically unlimited time. Testing was performed for 24 h, without any measures for additional passive or active laser cavity stabilisation under laboratory conditions with a significant (by several kelvins) diurnal change in the ambient temperature. Additional mechanical impacts on the laser cavity (vibrations and fibre bendings) also did not lead to mode locking interruption.

We performed a preliminary test of the harmonic mode -locking triggering. To this end, the reference VCO voltage was set (using the adjusting potentiometer) such as to make the VCO frequency in the open feedback loop regime be approximately equal to the doubled fundamental intermode frequency (i.e., ~27.6 MHz). To select this frequency, an appropriate filter was introduced into the intermode beat detection circuit. After that the feedback loop was closed to implement VCO automatic frequency control. The mode locking was optimised by adjusting the phase shifter and the RF signal amplitude at the modulator input. As a result, we obtained a mode locking regime with two pulses per cavity round-trip period. As well as the mode locking with the fundamental pulse repetition frequency, the regime of harmonic mode locking demonstrated a long-term stability of its characteristics without applying any additional measures for laser stabilisation. The results of measuring some characteristics in this regime, specifically, the RF intermode beat spectrum (the beat suppression at the fundamental frequency amounts to –35 dB) and the oscillogram of a generated regular sequence of pulses (the pulse repetition frequency is twice as large as the fundamental frequency), are presented in Figs 5 and 6.

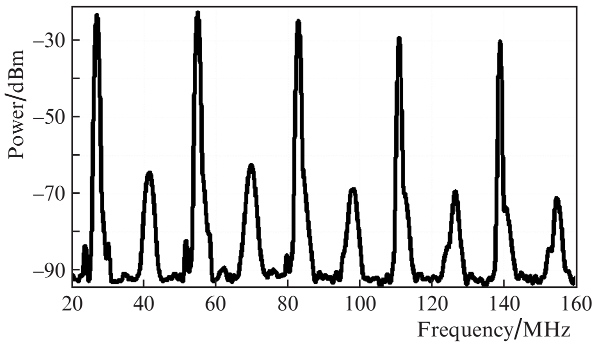

Figure 5. RF intermode beat spectrum in the harmonic mode-locking regime ($f_{mod} = 2f_{im}$); the analyser resolution is 500 kHz.

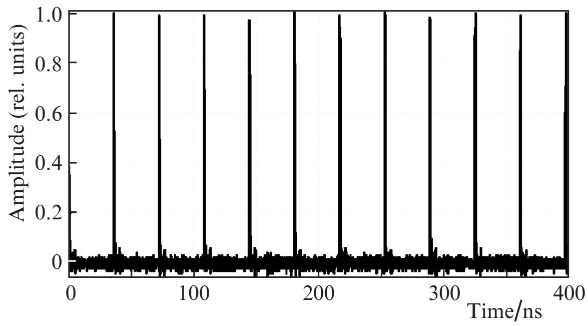

Figure 6. Oscillogram of a regular train of pulses generated in the harmonic mode-locking regime ($f_{rep} = 2f_{im}$).

In further work, we are planning to study in more detail the harmonic mode-locking regimes using the proposed scheme at frequencies multiply exceeding the fundamental intermode frequency. In addition, it is planned to search for optimal driver tunings in different mode-locking regimes. This research will call for adjusting the parameters of the entire PLLFC circuit and setting the optimal modulation regime, which is determined by the position of the working point on the modulator transfer function and by the modulation signal amplitude.

4. Conclusions

We implemented and preliminary investigated a compact all-polarisation-maintaining-fibre erbium-doped laser, where an original optoelectronic scheme, automatically maintaining mode locking by intracavity amplitude modulation, is applied. The developed scheme combines the principle of direct regenerative mode locking with the use of a simple driving generator based on a VCO being phase-locked to the actual laser intermode frequency. This 'quasi-regenerative' scheme, being simple in implementation, can maintain stable mode locking for practically unlimited time without any additional tools for stabilising the optical cavity length and protecting it from significant changes in the environmental conditions.

In contrast to the conventional regenerative mode locking, the implemented scheme excludes the amplitude noise transfer into the driving RF signal and, on the whole, provides a higher quality modulation and, therefore, lower noise level in the output laser radiation. In addition, the implemented scheme has configuration flexibility, which allows one to switch easily from the fundamental intermode frequency to harmonic mode-locking regimes. This short-pulse laser source can be used to solve many applied problems due to its extremely high mode locking stability.

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