Quantum Electronics **42** (3) 216–219 (2012)

CONTROL OF LASER RADIATION PARAMETERS

PACS numbers: 42.55.Wd; 42.60.Da; 42.60.Fc; 42.65.Sf
DOI: 10.1070/QE2012v042n03ABEH014707

Additive mode locking based on a nonlinear loop mirror ring laser

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Abstract. **We present an experimental demonstration of additive pulse mode locking based on a nonlinear loop mirror ring laser. The proposed design uses nonlinear phase shifts induced by a loop mirror. The results show that interference between two overlapping pulses from two coupled fibres, containing a nonlinear medium for power-dependent phase modulation, leads to pulse compression, and can provide mode locking with different repetition rates depending on the interplay or combination between the modulated frequency (active mode locking) and the nonlinearity (passive mode locking) generated in the loop mirror.**

Keywords: *mode locking, ring laser, optical loop mirror, and nonlinear fibre.*

1. Introduction

Fibre ring lasers are rich and active research fields in optical communications [1, 2], spectroscopy [3], temperature sensor [4], and biomedical diagnostics [5]. Fibre ring laser can be designed for cw or pulsed operation and linear or nonlinear operation; they can ensure fast or slow repetition rates, narrow or broad pulse widths, etc. for various photonic applications [6]. There are two general types of nonlinear ring lasers: a nonlinear optical loop mirror (NOLM) [7], and a nonlinear amplifying loop mirror (NALM) [8, 9]. Both these devices operate using the same general principle. The nonlinear fibre loop mirror has recently received great attention as a fast switch for signal processing and communications. In addition, it has been used as a fast saturable absorber to mode lock laser oscillators and reshape optical pulses [10].

Mode-locked lasers can be categorised as passive, active, and additive. Passively mode-locked fibre lasers are practical alternatives to bulk laser systems due to their simplicity, compactness, efficient heat dissipation, and the ability to generate high-quality pulses [11]. A passively mode-locked laser has its longitudinal modes locked in phase without any RF source through an internal nonlinear process that couples the longitudinal modes.

Active mode-locking is one of the key techniques for the generation of ultra-short, transform-limited optical pulses and is achieved by the direct modulation of the optical field during each laser cavity round-trip. This method is particularly important especially when synchronisation between optical and electrical signals is required [12]. The advantages of active mode locking include the ability to propagate at variable frequencies rather than maintaining the same frequency throughout the cavity.

Additive-pulse mode locking (APM) is a combination of the advantages of the both passive and active mode locking. The APM technique sometimes also called coupled-cavity mode locking [12, 13] was one of the key techniques for starting the era of ultrafast optics. It has been widely used for generating ultrashort pulses with durations of picoseconds or femtoseconds from various laser systems, including Nd:YAG, colour-centre, Ti:sapphire, and Er-doped fibre lasers [14]. The general principle of additive-pulse mode locking is to obtain an artificial saturable absorber by exploiting nonlinear phase shifts in a single mode fibre. The fibre is contained in a resonator, which has the same round-trip time as the laser resonator and is coupled to it with a semi-transparent dielectric mirror. The pulses returning from the fibre loop into the main laser resonator (cavity) interfere with those pulses which are already in the main resonator.

An APM-based nonlinear optical loop mirror (NOLM) ring laser is a device consisting of a fibre loop and a coupler. Rather than using mirrors to reflect the beam through the gain medium many times, fibre forms a closed loop around the gain medium with output coupled directly out of the loop through a fibre coupler from the cavity [15].

A normally reflecting loop mirror becomes totally transmissive. This nonlinear transmission can be used to realise pulse shaping and switching.

If dispersion is ignored, the transmission of a NOLM is given by:

$$|E_2|^2 = |E_{\rm in}|^2\Big(1 - 2\alpha(1-\alpha) \times \Big\{1 + \cos\Big[(1-2\alpha)|E_{\rm in}|^2\, 2\frac{\pi n_2 L}{\lambda}\Big]\Big\}\Big), \qquad (1)$$

where α is the splitting ratio of the NOLM, n_2 is the nonlinear index, L is the length of the loop, λ is the operating wavelength, $E_{\rm in}$ is the input field, and E_2 is the transmitted field.

In this work, we present an APM-based NOLM ring cavity laser in which dispersion is ignored by using a laser source operating at 1300 nm. The APM is generated by combination of the Ge-doped fibre in the loop mirror as the passive mode locking element and direct modulation of optical field during each round-trip as the active mode locking.

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Received 16 August 2011; revision received 6 December 2011
Kvantovaya Elektronika **42** (3) 216–219 (2012)
Submitted in English

2. Experimental

The experimental setup of the additive harmonically mode-locked fibre loop mirror is shown in Fig. 1. The principal elements of the system are frequency generator, laser source operating at 1300 nm (zero dispersion at typical fibre communication wavelengths), 2×2 optical coupler, optical closed loop with the Ge-doped nonlinear optical fibre, optical detector, and fast oscilloscope. The frequency generator provides periodic timing slots to produce a regular pulse train, while nonlinear fibre shortens the pulse compared to that expected from generator.

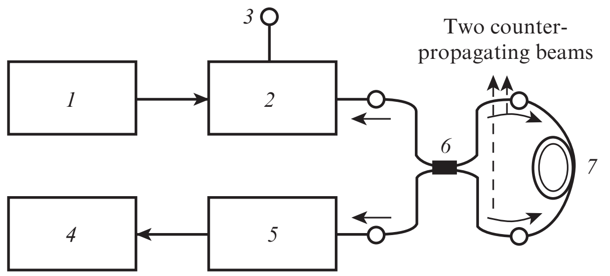

Figure 1. Experimental setup of a NOLM ring laser for additive mode locking: (*1*) frequency generator; (*2*) 1300-nm laser source; (*3*) dc bias; (*4*) fast oscilloscope; (*5*) optical detector; (*6*) 2×2 coupler; (*7*) 1-m-long Ge-doped optical fibre.

The NOLM is a fibre component of simple construction that we use to mode lock the laser. In this work a NOLM is designed by connecting a 20% Ge-doped optical fibre between the two end pigtails of a 2×2 optical fibre coupler. The Ge-doped fibre is used to generate a differential phase shift, due to the nonlinear index of the Ge fibre, causing light that at low power is reflected into the laser cavity to generate a mode-locked pulses. Due to the frequency dependence of the coupler, the coupler acts as a reflector when its coupling coefficient is 50% and as a partial reflector for other values of the coupling coefficient.

3. Results and discussion

The laser output was characterised using an autocorrelator and a fast sampling oscilloscope. The optimum output characteristics in terms of both shortest pulse duration and highest repetition rate were observed when the modulated frequency is higher. Fast sampling oscilloscope traces presented in Fig. 2 show that the pulse repetition rates correspond to the modulated frequency and fundamental cavity round-trip time, thereby confirming that the laser was operating in a fundamental mode-locked regime with only a single pulse circulating intracavity. Figure 2 demonstrates the 3-, 1-, 0.3, and 0.1-μs round-trip repetition times of the fibre laser. These variations in the repetition rate are due to the change in the modulated frequency and modulation current and their interplay with the nonlinear phase shift generated in the Ge fibre. The intensity

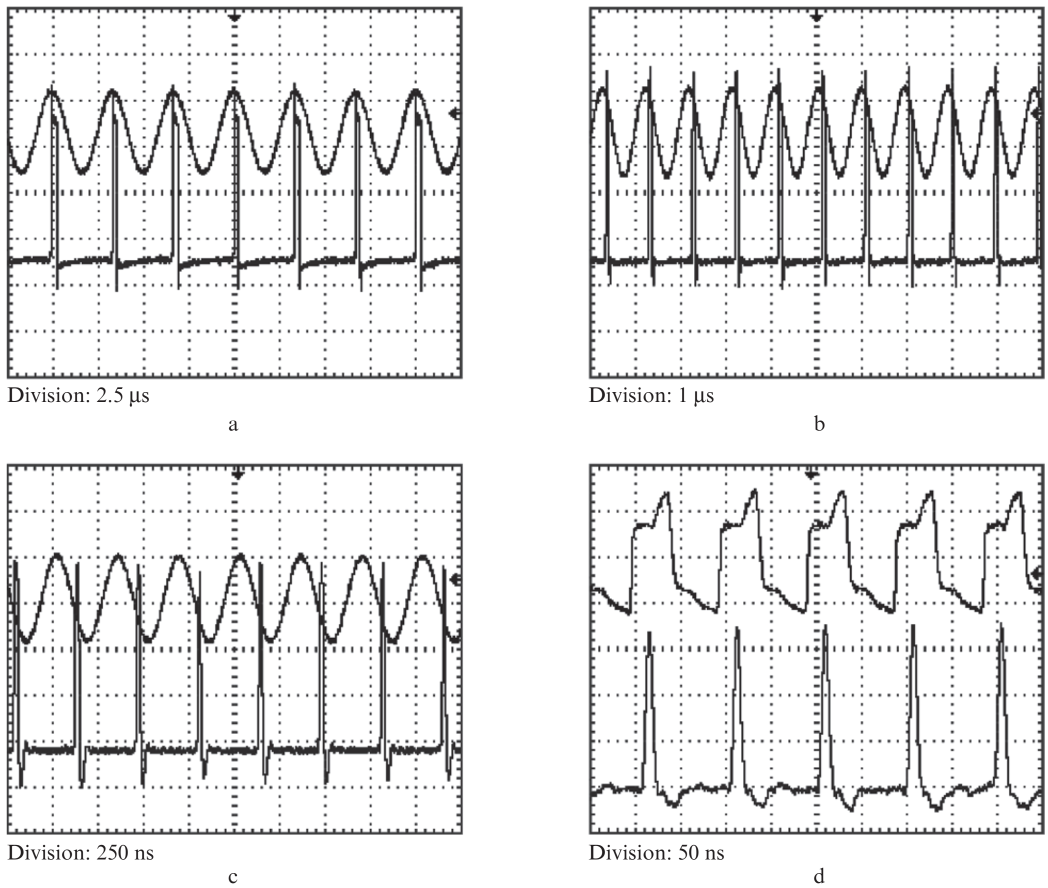

Figure 2. Oscilloscope traces of pulses at round-trip transit times in the cavity of 3 (a), 1 (b), 0.3 (c) 0.3 and 0.1 μs (d). Top panels correspond to signals at the input to the loop and bottom panels – to signals at the output from the loop.

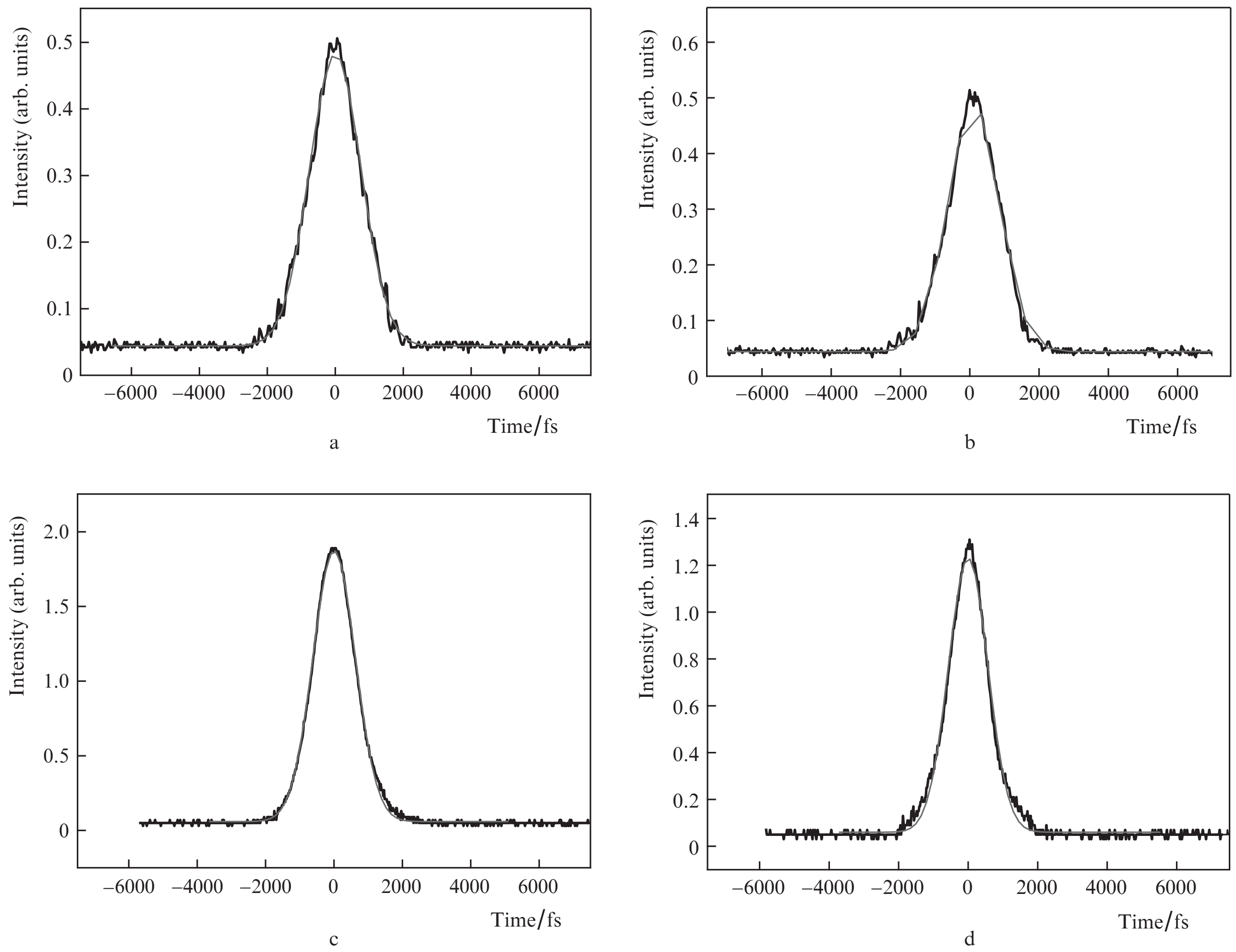

Figure 3. Experimentally recorded autocorrelations of a number of laser pulses. The thin line shows a fit to the expected hyperbolic secant squared. The full-width of the autocorrelations, obtained from the fit curves are 1.54 (a), 1.47 (b), 1.2 (c) and 1 ps (d), respectively.

spikes correspond to ringing in the electronic system excited by the photodiode's impulse response to a very short optical pulse. These spikes are much longer (on the order of 10 ns) than measured autocorrelation widths (between 1.0 ps and 1.5 ps for mode-locked pulses). As a result of the increased modulated frequency, both the pulse duration and the pulse-to-pulse spacing decrease and, as a consequence, the repetition rate increases.

The transmission of a light beam through the loop mirror from the input pigtail to the output depends on the splitting ratio of the coupler as in Eqn (1). We used $\alpha = 0.5$ to generate $|E_2|^2 = |E_{\text{in}}|^2$. In this case, light will be evenly split; with one beam acquiring a $\pi/2$ phase shift when the light that is sufficiently intense passes through the nonlinear fibre. After the beams have circulated around the loop, they interfere at the output pigtail. The beam that crosses the coupler again acquires a phase shift of $\pi/2$, so that when the beams combine, one has a total phase shift of zero while the other is shifted by π. No light is seen at the output, and by conservation of energy, all the light reflects back to the input.

As expected, the pulse-to-pulse spacing has decreased to 100 ns. As a consequence, the repetition rate has increased to 10 MHz. Figures 2c and d reveal that the bandwidth of these pulses is 10 times larger than that of the pulses formed in Figs 2a and b. This is because the loop is functioning as a periodic filter when there is some birefringence induced in the loop.

Typical autocorrelations of a number of laser pulse traces measured with the InGaAs photodiode are shown in Fig. 3. This fibre laser produces pulses about from 1 to 1.54 ps in duration depending on interplay between the modulated signal and nonlinearity generated in the Ge-doped fibre which represents the combination of active and passive mode locking.

4. Conclusions

We have demonstrated an APM-based nonlinear loop mirror ring laser producing different repetition rates and pulse durations with an average output power of –8 dBm at 1300 nm. The results indicate that the Ge-doped optical fibre is a useful passive fibre element for the construction of short-pulse lasers. The dynamical behaviour of the laser that includes a NOLM is sensitive to the repetition rate and pulse duration.

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