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Letter

Mode-locked fibre lasers with an adjustable drop-shaped cavity

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Abstract
We report the first implementation of a new cavity topology for mode-locked fibre lasers. This new 'drop-shaped' cavity topology employs a dual-fibre optical collimator and allows for a relatively simple cavity design with continuously adjustable length. It combines the advantages of the conventional ring cavity topology with the adjustment capabilities of hybrid ring-linear cavities (e.g. σ-cavities). Reliable femtosecond pulsed lasing was demonstrated in the experimental drop-shaped Er-doped fibre lasers, which were mode-locked in two different ways—by exploiting nonlinear polarisation evolution (NPE) and by means of a semiconductor saturable absorber. In the case of NPE-based mode locking, the shortest pulse duration was ~450 fs. The pulse repetition rate could be continuously varied within $\pm$3 kHz around ~25 MHz in the NPE-mode-locked lasers when the distance between the dual-fibre optical collimator and the cavity mirror was adjusted. This feature could, in principle, allow active stabilisation of the pulse repetition rate. Thus, mode-locked fibre lasers with the proposed drop-shaped cavity topology could be applied in metrology and other fields where a high stability of pulse repetition rate or its synchronization with an external clock is required.

Keywords: fibre lasers, mode locking, optical resonators

(Some figures may appear in colour only in the online journal)

1. Introduction

Currently, fibre-optic mode-locked lasers are preferable to bulk solid-state pulsed lasers because fibre-optic technologies provide a completely new level of convenience when working with short-pulse lasing. This is mainly due to their tuning- and alignment-free optical layout, which is either completely or predominantly implemented within optical fibres. This current phase in mode-locked fibre laser development relies, to a great extent, upon the expansion of the fibre-optic element base and new configurations or topology of the resonators of such lasers to make the desired parameters of output pulses achievable. It is often a novel cavity topology of a mode-locked fibre laser that proves to be the key in achieving target output parameters. Examples of this approach include ring-linear cavity layouts [1–5], configurations with figure-eight or dumbbell-shaped cavities [6–11], Y-, θ-, γ-shaped geometries [12–15], 'yin-yang' configurations [16] and others [17–20].

Here, we demonstrate a new cavity topology of mode-locked fibre lasers, which we call 'drop-shaped' because of its schematic resemblance to the outline of its namesake object. It could also be represented and referred to as a 'B-shaped' cavity. This cavity topology was implemented on the basis of a commercial dual-fibre optical collimator, which allowed for a relatively simple modified ring cavity design with a free-space delay line whose length could be continuously adjusted within several millimetres.

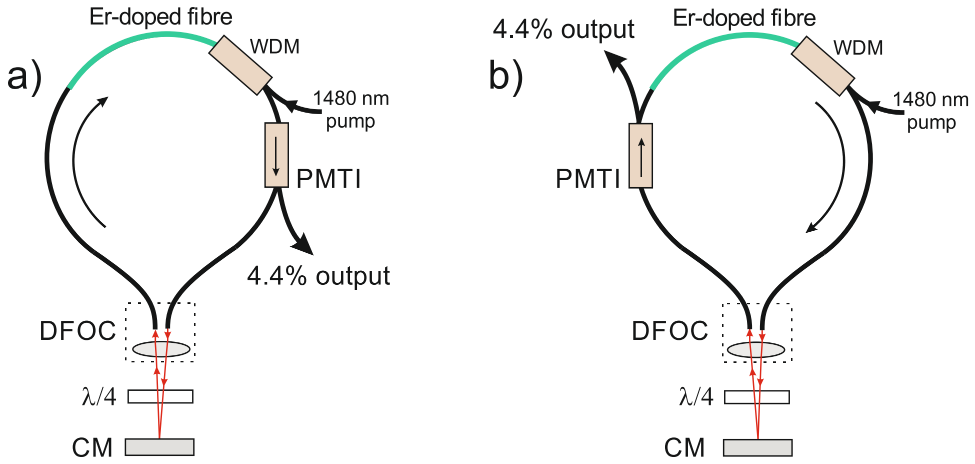

Figure 1. NPE-mode-locked fibre lasers featuring a drop-shaped cavity topology with right-hand (a) and left-hand (b) layouts. DFOC—dual-fibre optical collimator, PMTI—polarisation-maintaining TAP isolator, CM—copper mirror, WDM—wavelength division multiplexer. Arrows indicate the pulse propagation direction.

2. Experimental

2.1. NPE-mode-locked lasers

The schematic layout of the proposed drop-shaped cavity implemented in fibre lasers mode-locked via nonlinear polarisation evolution (NPE) is shown in figure 1. The left- and right-hand versions of the cavity only differed in the location of their fibre-optic isolators with built-in output coupler: in the right-hand configuration (figure 1(a)), it was positioned after the active fibre; and in the left-hand configuration (figure 1(b)), the isolator is positioned before the active fibre (following the pulse propagation direction). As it will be demonstrated later, the output parameters of lasers built according to the schematics shown in figures 1(a) and (b) exhibit certain differences.

The laser cavity contained a piece of Er-doped active fibre, a polarisation-maintaining TAP isolator (PMTI), which combined the functions of a polarisation-sensitive optical isolator and a tap coupler, a dual-fibre optical collimator, and a metallic mirror made of copper. The active fibre (nLight Liekki Er 80-8/125) was core-pumped in the direction opposite to that of pulse propagation through a wavelength division multiplexer (WDM). The pump source was a fibre-coupled diode laser emitting up to 400 mW at 1480 nm. Hybrid fibre element PMTI (AFR PMTI-2-55-05-2-L-P-0.25-F) not only ensured unidirectional circulation of radiation around the ring cavity and its coupling out of the resonator, but also acted as a polarisation discriminator necessary for mode locking due to NPE.

The key element of the proposed and studied drop-shaped cavity was a dual-fibre optical collimator (commercial component OPNETI CL-D-15-B-10-1-10-C-FA), the design of which allowed both extraction of collimated radiation from the embedded fibres and also back-coupling into these fibres with relatively low optical losses of the radiation exiting the collimator and reflected from the mirror. The mirror used in our experiments was made of copper and had a reflection coefficient of 0.96 at the operating wavelengths of the laser. It is necessary to point out that although this component is called a collimator, for minimisation of the optical losses it introduces, it was necessary to position the mirror in the vicinity of the focal plane of the short-focus lens of the collimator. Such positioning made it possible to redirect the radiation beam from one fibre into the other, as shown in figure 1. The focal length of the lens in the employed collimator amounted to approximately 2 mm and the lens-to-mirror spacing was variable within 1.5–5 mm. Moving the mirror further than 5 mm from the lens led to optical losses introduced by the collimator exceeding 50%. The existence of a gap between the collimator lens and the mirror not only allowed variable spacing between them, but also provided the option of inserting a discrete optical element there. In the proposed layout, this gap was used to add a quarter-wave achromatic phase plate, which was rotated in order to trigger mode-locked operation.

In general, a single quarter-wave plate is not sufficient for triggering mode-locked operation of a fibre laser by using the NPE effect [21]. Complete definition of the radiation polarisation state requires a set of several phase plates [22]. Nevertheless, such a set may be reduced to just a single plate, provided that the necessary state of the radiation polarisation is created by bending and twisting the cavity fibre in the process of laying and securing it. This cavity fibre manipulation procedure allowed us to reliably trigger mode-locked operation by rotation of a single discrete phase plate installed within the air gap between the collimator lens and mirror. Since the radiation passed the quarter-wave plate twice during a single round trip of the cavity, this plate acted as a half-wave one and thus allowed rotation of the plane of radiation polarisation.

Mode-locked operation was triggered by adjustment of the intra-cavity radiation polarisation with the phase plate at a pump radiation power in the range of 250–300 mW. It should be noted that adjustment of radiation polarisation via a single optical element allows triggering of mode-locked operation with reproducible parameters. As a rule, when using several elements for this purpose, a significant variability of radiation parameters is observed in systems mode-locked using NPE [23].

When the polarisation state of the laser radiation is defined by a set of independent tuneable components, the relation between the mode-locking parameters and the settings of

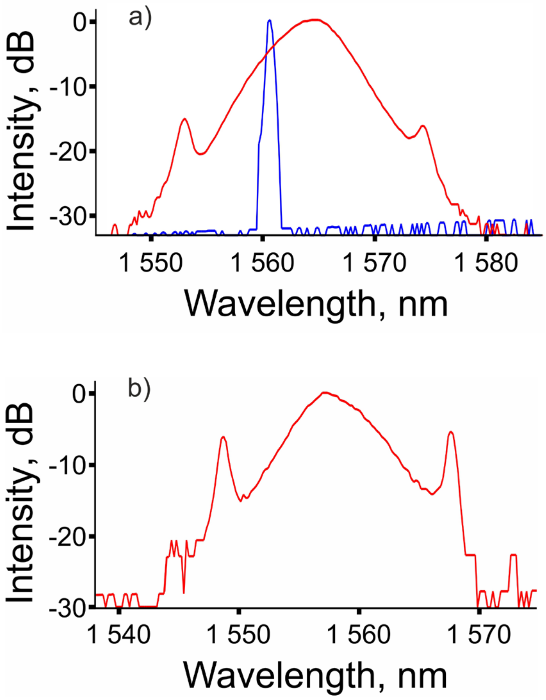

Figure 2. Output radiation spectra generated by the two studied cavity configurations (a) and (b). Red curves correspond to output spectra in the mode-locked regime. The blue curve shows the continuous wave generation spectrum.

the polarisation-controlling elements becomes complicated. Various artful approaches have been used to address this problem [24–27] with the aim of starting mode-locked operation with pre-determined parameters. However, these approaches involve relatively complicated intelligent systems for radiation parameter control including the application of machine-learning algorithms. The present work proposes a substantially simpler approach that relies on preliminary one-time permanent adjustment of the laser radiation polarisation via bending and twisting of the cavity fibre as it is laid and secured. This approach makes it possible to set the required polarisation state by adjusting a single cavity element and to reproduce the laser radiation parameters in successive initiations of mode-locked operation. Moreover, in the proposed method, a liquid crystal element [28, 29] may be used instead of a mechanically rotated phase plate, thus allowing complete electronic control over the mode-locked operation of the studied laser.

The average output radiation power in both studied laser configurations reached 1.5–2.0 mW. In both cases, the laser cavity featured all-anomalous dispersion (in excess of 0.1 ps nm^{-1} at 1560 nm), thus giving rise to soliton pulses generated during mode-locked operation. The spectral widths of the output of both laser configurations were quite similar (nearly 6 nm at −3 dB), even though the spectral shapes were different (figure 2).

The optical spectrum generated by the laser with cavity configuration (b) featured significantly more visible sidebands (Kelly sidebands [30]) appearing due to periodic perturbation of soliton pulses as they circulated around the cavity and the dispersion waves [31] accompanying this process.

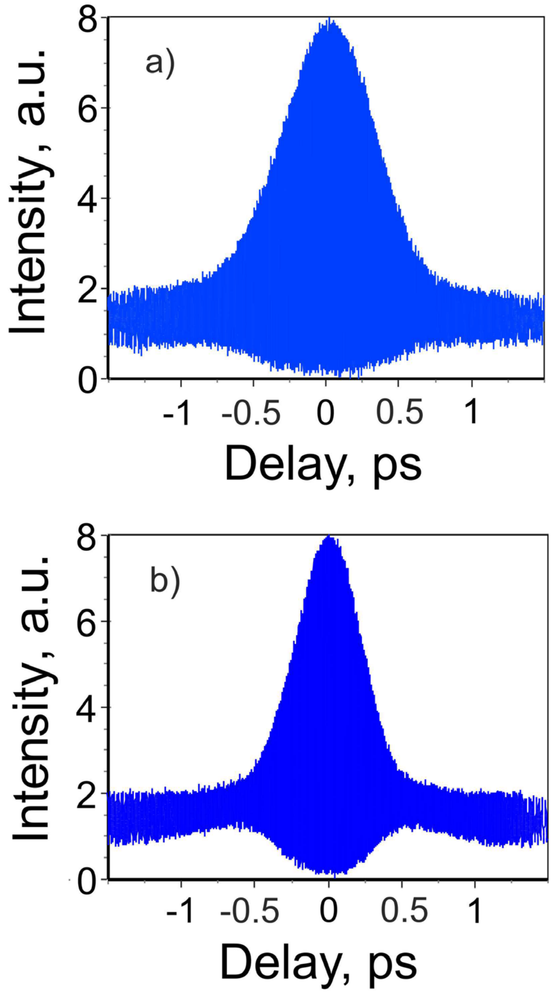

Figure 3. Interferometric autocorrelation functions of pulses from cavity configurations (a) and (b).

The measured interferometric autocorrelation functions (figure 3) of the pulses generated in lasers with cavity configurations (a) and (b) corresponded roughly to pulse durations of ~630 fs (a) and ~450 fs (b) in the approximation of $sech^2$-shaped pulses.

The autocorrelation traces revealed residual chirp in the measured pulses that was mainly due to the external Er-doped fibre amplifier used to match the laser output power to the sensitivity of the autocorrelator input. This complicated precise evaluation of the pulse duration.

Variation of the distance between the dual-fibre optical collimator and the copper mirror within 1.5–5.0 mm led to a corresponding variation of the output pulse repetition rate by ±3 kHz around ~25 MHz. The possibility of continuous variation of the pulse repetition rate of the proposed laser with a drop-shaped cavity is valuable in metrological applications [32, 33]. Therefore, it was important to estimate the quality of mode-locking in both cavity configurations of the studied laser. To do that, RF spectra of the intermode beats of the laser output were measured both around the fundamental pulse repetition frequency and in the vicinity of the 10th harmonic of the fundamental frequency. The recorded spectra are shown

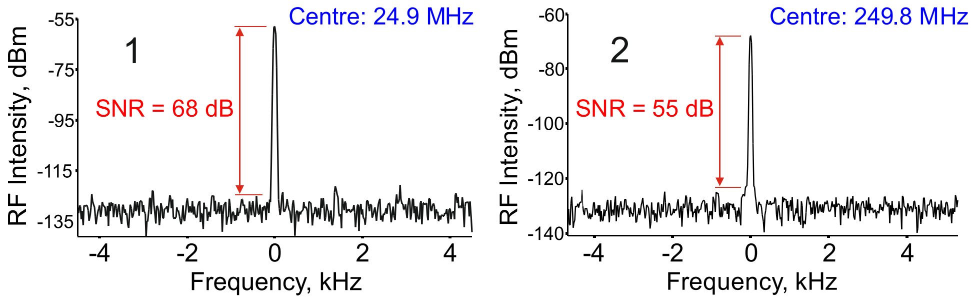

Figure 4. RF spectra of the intermode beats from the cavity configuration (a). (1) Spectrum measured around the fundamental pulse repetition frequency. (2) Spectrum measured around the 10th harmonic.

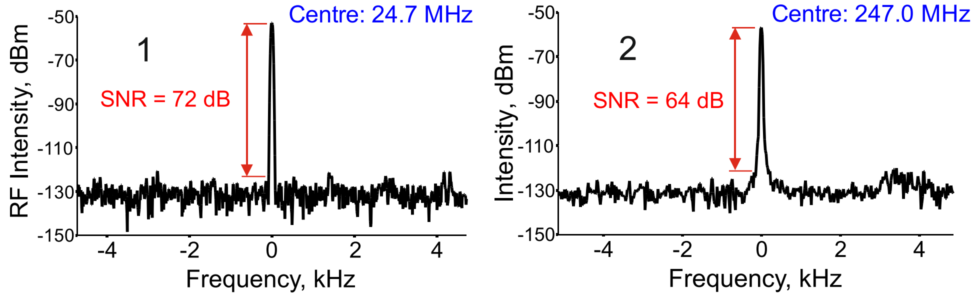

Figure 5. RF spectra of the intermode beats from the cavity configuration (b). (1) Spectrum measured around the fundamental pulse repetition frequency. (2) Spectrum measured around the 10th harmonic.

in figures 4 and 5. The resolution bandwidth of the used spectrum analyser was 30 Hz.

The measured spectra demonstrated that the signal-to-noise ratio was within 55–72 dB, thus indicating the relatively high quality of the obtained mode-locked generation regimes.

Therefore, both tested configurations of the proposed drop-shaped cavity offered the possibility of high-quality NPE-mode-locked lasing with an added benefit of relatively simple triggering of mode-locked operation and reproducible output parameters. Passive mode-locked operation in both configurations was also demonstrated to be highly stable: the laboratory prototypes of the lasers with drop-shaped cavities operated continuously throughout a working day, without mode-locking collapse and in the absence of any special measures to isolate the laser cavities from ambient perturbations.

Although it may seem obvious that the optical isolator PMTI and the dual-fibre optical collimator (DFOC) used in the demonstrated lasers could be replaced with a fibre-optic circulator and a conventional fibre-optic collimator (thus reducing the cavity design to a conventional ring-linear one [1]), the proposed novel cavity design is nevertheless preferred. It provided benefits such as a reduced number of intracavity elements, minimized total intracavity loss and, potentially, a very short cavity length. Indeed, the insertion loss of a fibre-optic circulator exceeds the typical loss of a single-stage fibre-optic isolator by almost a factor of two, while the losses of conventional and dual-fibre collimators are comparable. Moreover, if in the NPE-mode-locked lasers the optical isolator PMTI and the DFOC were replaced with a fibre-optic circulator and a conventional fibre-optic collimator, it would be necessary to incorporate a fibre-optic output coupler (or beam splitter), thus increasing the number of intracavity elements and the cavity length.

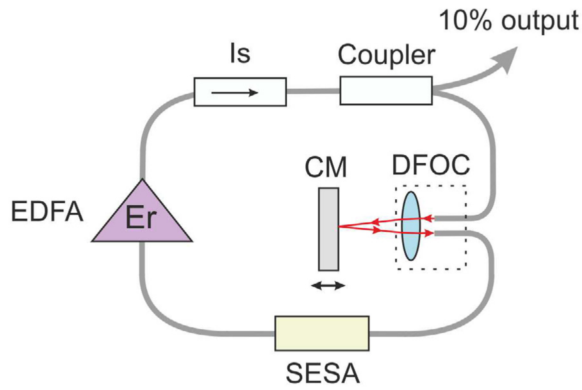

Figure 6. SESA-mode-locked fibre laser featuring the new 'B-shaped' cavity topology. DFOC—dual-fibre optical collimator, CM—copper mirror, SESA—semiconductor saturable absorber, EDFA—Er-doped fibre amplifier, Is—polarisation-insensitive isolator. Arrows indicate pulse propagation direction.

Therefore, development of very compact NPE-mode-locked lasers with a relatively high fundamental pulse repetition rate stabilized to an external frequency reference (or synchronized with an external clock) for metrological purposes can be advanced by the application of the proposed novel cavity topology.

2.2. *SESA-mode-locked laser*

The new cavity topology was also implemented in an Er-doped fibre laser, in which mode-locking was achieved and sustained by means of a semiconductor saturable absorber (SESA).

The schematic layout of the SESA-mode-locked fibre laser is shown in figure 6. Although this laser's cavity layout looks B-shaped, its topology was, in fact, identical to that presented

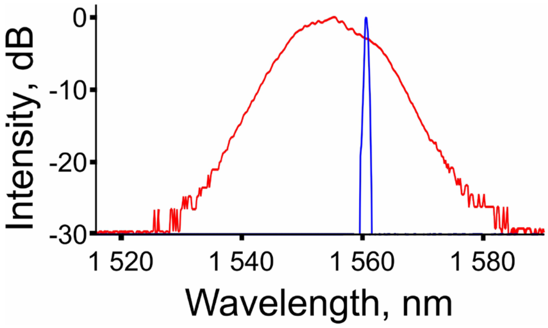

Figure 7. Output radiation spectra generated by the SESA-mode-locked laser. The red curve corresponds to the output spectrum in mode-locked regime. The blue curve shows the continuous wave generation spectrum.

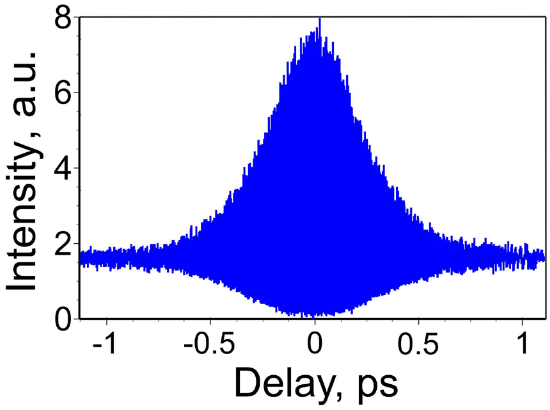

Figure 8. Interferometric autocorrelation function of pulses from the SESA-mode-locked laser.

in the previous section. The laser cavity incorporated the same Er-doped active fibre pumped in the same way by means of a WDM combiner and a fibre-coupled diode laser. In figure 6, these elements are jointly indicated as an EDFA (Er-doped fibre amplifier).

The hybrid element PMTI in the SESA-mode-locked laser was replaced by a polarisation-insensitive fibre-optic isolator and a fused fibre coupler. Additionally, a commercial fibre-coupled SESA (Batop SA-1550-58-2ps) was inserted into the cavity in order to achieve mode-locked lasing. The key part of the cavity which allowed implementation of the proposed topology consisted of the same DFOC and terminating CM as in the previously tested NPE-mode-locked lasers. Only non-polarisation-maintaining single-mode fibres were employed in the described SESA-mode-locked laser.

Proper mode-locked operation was self-triggered upon setting the pump power within the range of ~230–340 mW. The most stable and cleanest mode-locked performance of the laser was achieved when a 4 m long piece of dispersion-compensating fibre (Thorlabs DCF-38) was also inserted into the cavity. This fibre features strong normal dispersion at the lasing wavelength (nearly $-40\,\mathrm{ps\,(nm \cdot km)^{-1}}$). However, the net cavity dispersion remained slightly anomalous. Thus, pulse shaping in this laser was more similar to that of stretched-pulse mode-locked fibre lasers [34] rather than to the soliton lasing of the previously tested NPE-mode-locked lasers.

The average output radiation power of the SESA-mode-locked laser reached 4.5 mW at a pump power of 340 mW.

The optical spectrum of the laser output became very broad in the mode-locked operation mode: the spectral width reached nearly 12 nm at −3 dB (figure 7). No Kelly sidebands were observed.

The measured interferometric autocorrelation function (figure 8) of pulses generated in the SESA-mode-locked laser corresponded roughly to a pulse duration of ~480 fs in the approximation of Gaussian-shaped pulses. The autocorrelation trace revealed residual chirp in the measured pulses which was mainly due to an external Er-doped fibre amplifier being used to match the laser output power with the autocorrelator input sensitivity. This complicated precise evaluation of the pulse duration.

To evaluate the quality of mode-locking, RF spectra of intermode beats of the laser output were measured both around the fundamental pulse repetition frequency and in the vicinity of the 10th harmonic of the fundamental frequency. The recorded spectra are shown in figure 9. The resolution bandwidth of the spectrum analyser used was 30 Hz. The acquired spectra demonstrated a signal-to-noise ratio within 53–69 dB, thus indicating the good quality of the obtained mode-locked generation regime.

Therefore, the tested laser configuration offers the possibility of reliable SESA-based mode-locked lasing with the added benefits of self-triggering of mode-locked operation and reproducible output parameters. The SESA-mode-locked fibre laser with the proposed cavity topology also provides the possibility of continuous adjustment of the cavity length, which could be used for active stabilisation of the pulse repetition rate or for its synchronization with an external clock.

2.3. Remarks on results

It is necessary to point out that the relatively low fundamental frequency of pulse repetition in the demonstrated implementations of mode-locked fibre lasers with the new cavity topology was obtained due to a relatively long active fibre and relatively long pigtails of the used fibre-optic elements. By reducing their length, one could significantly increase the fundamental pulse repetition rate (up to ~100 MHz and higher in the case of NPE-mode-locked lasers).

In addition, it would probably be possible to replace a fibre-coupled SESA with a bulk semiconductor saturable mirror (SESAM), which will substitute for the terminating copper mirror in the laser configuration shown in figure 6. In this case, the pulse repetition rate would be significantly increased.

The proposed cavity topology features remarkable advantages over hybrid ring-linear fibre cavities with a length-adjustable linear arm [1, 33] due to simplification of the laser cavity design, reduced total insertion loss and a potentially shorter optical length when a very large adjustment range is not required.

The main goal of the presented work was to prove, for the first time, the feasibility of mode-locked fibre lasers based on the proposed new cavity topology. Therefore, more

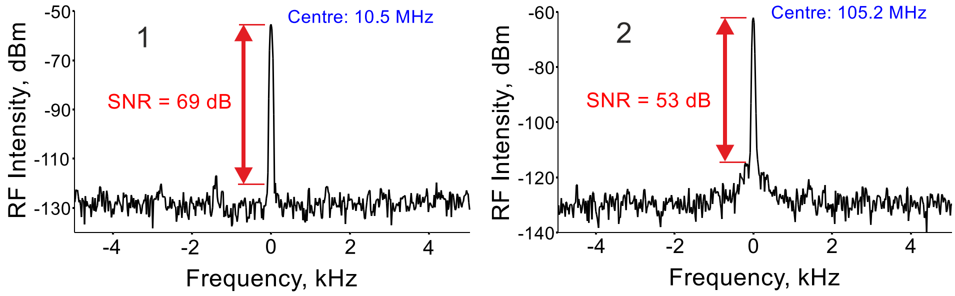

Figure 9. RF spectrum of intermode beats of the SESA-mode-locked laser. (1) Spectrum measured around the fundamental pulse repetition frequency. (2) Spectrum measured around the 10th harmonic.

comprehensive consideration and optimisation of laser performance lie rather beyond the scope of this paper and are subjects for further studies.

To a wide extent, the topological approach to the development of novel mode-locked fibre lasers cannot be reduced just to variation of the geometrical features of the laser cavity design. Many other methods, such as incorporation of fibres with specific waveguide properties [35], intra-cavity dispersion or power management [36, 37], polarization evolution management [38], and particular ordering of intra-cavity optical elements [39] are also effective for achieving particular pulse shaping regimes or improving lasing performance.

3. Conclusions

The present work discusses the results of the development and preliminary study of mode-locked fibre lasers with cavities based on a new topology. Their advantages include the possibility of continuous pulse repetition rate adjustment by employing a simpler and more reliable cavity design as compared with traditional length-adjustable mode-locked fibre lasers. The high quality of mode-locked operation and reproducible parameters of femtosecond pulses when repeatedly stopping and starting the mode-locked operation were demonstrated in these new 'drop-shaped' cavity lasers.

Thus, owing to the fruitful synergy of modern fibre-optics technology and advanced cavity design, we created a compact NPE-mode-locked femtosecond fibre laser whose pulse repetition frequency could be continuously adjusted by up to ± 3 kHz around the mean fundamental frequency (~25 MHz in this work) while providing relatively high-quality mode-locking. The signal-to-noise ratio of RF beat spectra in the vicinity of the fundamental repetition rate and its 10th harmonic reliably exceeded 50 dB. We also demonstrated self-triggered SESA-based mode locking in a fibre laser with the proposed cavity topology.

The developed drop-shaped laser cavity layout (which can be also represented as a 'B-shaped' one) features a reduced number of fibre-optic elements as compared with conventional cavity configurations of femtosecond fibre lasers with adjustable cavity length. Another important advantage of the proposed layout is that its key components are inexpensive commercially available items, thereby ensuring that the proposed configuration can be easily reproduced.

The demonstrated new type of mode-locked fibre lasers can be applied in metrological and other fields where high stability of pulse repetition rate or its synchronisation with an external clock is required.

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