Femtosecond 78-nm Tunable Er:Fibre Laser Based on Drop-Shaped Resonator Topology

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***Abstract*—We report for the first time on study of a passively mode-locked Er-doped fibre laser with ultra-wide tuning (from 1524 to 1602 nm) of the central wavelength of its femtosecond output (503–940 fs). The recently proposed drop-shaped cavity topology for fibre lasers enabled a compact widely tuneable femtosecond laser with a single discrete element, a reflective diffraction grating used for wavelength tuning of the output radiation. The key features of the proposed laser are: spectral tuning does not require adjustment of any other cavity elements; stable generation with a single pulse per round trip is provided over the entire wavelength tuning range; and the output pulses are close to transform limited and feature relatively high (>58 dB) signal-to-noise ratio of laser inter-mode beats indicating high quality of mode locking across the entire wavelength tuning range. The proposed laser configuration relying on the new drop-shaped cavity topology simultaneously delivers stability and reliability of mode locking, possibility of broad-range wavelength tunability, and adjustability of the output pulse repetition rate of the laser (which is important in various metrological and other applications).**

***Index Terms*—Fibre lasers, laser cavity resonators, laser mode locking, laser tuning.**

I. Introduction

WAVELENGTH tuning of laser radiation considerably widens its functional capabilities, enabling research and industrial laser applications requiring spectral selectivity. Active media using optical fibres doped with rare-earth elements feature gain profile widths of 100 nm and even wider [1], thus enabling tunability of laser radiation over these ranges [2]–[4]. Unfortunately, implementation of broad tuning of the fibre laser output wavelength is often constrained by cavity elements with relatively narrow spectral working range (pump combiner, output coupler, etc.). Moreover, in mode-locked lasers, additional limitation may be imposed by spectral dependence of cavity parameters affecting mode locking (dispersion and nonlinearity of the fibres, parameters of the saturable absorber, either natural or artificial, and the fraction of radiation coupled out of the cavity). Therefore, the wavelength tuning range of a mode-locked fibre laser is usually inferior to that of the same laser in continuous-wave (CW) mode. For example, the broadest demonstrated range of central wavelength tuning in a femtosecond Er:fibre laser did not hitherto exceed 75 nm [5], even though spectral tuning led to variation of the pulse duration from femtosecond up to picosecond range. Additionally, during wavelength tuning it was always necessary to manually adjust two fibre-based polarisation controllers in order to restart mode-locked lasing, and each time this led to unstable multi-pulse generation with a different number of pulses over the cavity round trip. Because of significant difficulty in achieving broad wavelength tuning in mode-locked fibre lasers, this term is sometimes used to refer to tuning ranges as narrow as ∼30–40 nm [6]–[9]. Identification of methods for broadening output wavelength tuning in mode-locked fibre lasers is further complicated by the general requirement that they should be compatible as much as possible with the fibre laser concept, that is ideally they should not use discrete optics or at least limit such use to a minimum.

It is pertinent to point out that along with the methods allowing direct leveraging of the spectral potential of a fibre laser active medium (we will call them “active-medium-based methods”), other approaches are being developed that broaden the output wavelength tunability in mode-locked fibre lasers owing to nonlinear transformation: harmonic generation [10], parametric conversion [11], self-phase modulation [12]/super-continuum generation [13], Cherenkov radiation [14], or cascaded Raman conversion [15]. These approaches lead to dramatic (sometimes, more than by an order of magnitude) enhancement of the output wavelength tuning range in mode-locked fibre lasers in comparison with the performance of the active-medium-based methods. Nevertheless, the development of these latter methods is also of significant interest, since they often happen to be simpler and less demanding than those based upon nonlinear conversion, meanwhile delivering higher output power in many implementations. It is also important that the tuning range available through some nonlinear methods depends on the initial range obtained through an active-medium-based method and can be further broadened thereby.

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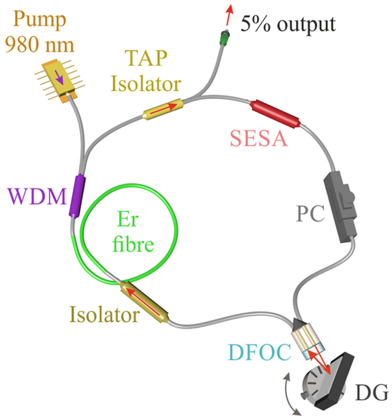

Fig. 1. Layout of the studied tuneable Er:fibre laser based on drop-shaped resonator topology: SESA–semiconductor saturable absorber, PC–in-line polarisation controller, DFOC–dual-fibre optical collimator, WDM–wavelength division multiplexer, DG–diffraction grating.

This work for the first time presents the results of research into an active-media-based method of central wavelength tuning in a mode-locked fibre laser featuring the recently developed drop-shaped cavity topology [16]. The single discrete element used in the studied laser, a diffraction grating, was adjusted to achieve a record-setting broad spectral tunability of the generated femtosecond pulses within a 78-nm range, from 1524 to 1602 nm, while maintaining the pulse duration between 503 fs and 940 fs without additional adjustment of any other cavity elements in the process of wavelength tuning and delivering stable generation with a single pulse per round-trip over the totality of the ultra-broad wavelength tuning range.

II. EXPERIMENT

The proposed laser layout is presented in Fig. 1. The laser's ring cavity contains Er-doped fibre pumped into the core through a wavelength-division multiplexor (WDM), semiconductor saturable absorber (SESA), two optical isolators (one of them having a 5% port for coupling the radiation out of the cavity), a dual-fibre optical collimator (DFOC) allowing a discrete reflector (diffraction grating) within the cavity, and a radiation polarisation controller used to maximise reflection from the diffraction grating.

The active section of the laser used commercial highly doped erbium fibre (LIEKKI Er40-4/125) pumped with a fibre-coupled semiconductor laser at ~980 nm. Active fibre with high concentration of erbium ions (in our case, the Er-doped fibre had absorption of 40 dB/m @ 1530 nm) allows efficient amplification and generation within the L-band [17], [18] at sufficient fibre length (2.7 m in the proposed laser).

The pump radiation was guided into the active fibre core through the WDM in the direction opposite to that of the generation radiation. The lasing wave circulation direction within the cavity was set by two optical isolators completely blocking amplification of the intra-cavity radiation in the opposite direction.

For passive mode locking, we used a commercial fibre-pigtailed semiconductor saturable absorber by Batop Co. (SA-1550-58-2ps). In the vicinity of 1.55 μm, this material had absorption of 58%, non-saturable loss of 23%, and relaxation time of 2 ps.

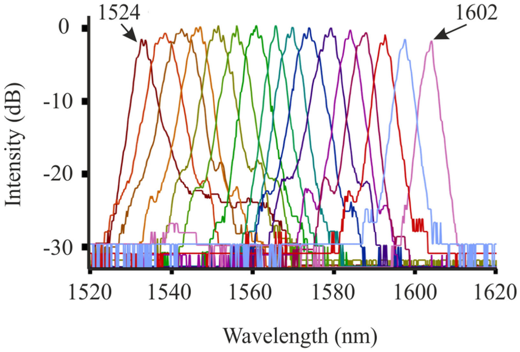

Fig. 2. Output pulse spectra of the proposed laser at different wavelengths within the tuning range of 1524–1602 nm.

The special feature of this laser, which forms the drop-shaped cavity and makes it unusual, is utilisation of DFOC. This type of collimators is available from different manufacturers. We used a DFOC from Opneti Communications Co, which is based upon two closely-spaced optical fibre ends with a short-focus (2 mm) lens in front of them. Therefore, it is possible to redirect radiation emitted from one of the DFOC ports into the other with a reflector positioned in the vicinity of the lens' focal plane. The spectrally selective reflector used in the present work was a rifled aluminium diffraction grating (300 lines/mm, 1300 nm blaze wavelength) with reflectivity 70–65% corresponding to wavelength tuning from 1500 to 1600 nm. This diffraction grating was set in a Littrow configuration [19] and could be rotated via a high-precision manual actuator Thorlabs PR01/M with resolution of 0.7 mrad/div and spectral precision of grating rotation of 2.2 nm/div.

The DFOC and the diffraction grating formed a tuneable spectral filter. We measured this filter's transmission band with an ASE light source. Around 1.55 μm, it amounted to approximately 10 nm (FWHM). The measured filter pass band is sufficient to avoid spectral deformation of pulses over ~400-fs long. Such filter can be used for output wavelength tuning of the studied laser, because earlier [16] it was shown that this laser generated pulses with duration within 450–630 fs.

In order to ensure the widest possible tuning range of the pulsed lasing spectrum, all the cavity elements were chosen for as broad as possible working spectral range. According to the specifications, the narrowest working bandwidth was that of the isolators (1530–1570 nm). Nevertheless, in our experiments the isolators operated normally at wavelengths of up to 1610 nm. The specified working spectral range of the WDM pump combiner was somewhat broader, 1530–1580 nm. The semiconductor saturable absorber featured a very broad working range (1.4–1.6 μm), albeit exhibiting significant variation of absorption (61–48%) and transmittance (34–45%) across the range of 1520–1600 nm. The parameters of the saturable absorber and the gain of the active fibre in the developed laser configuration experienced the most significant changes across

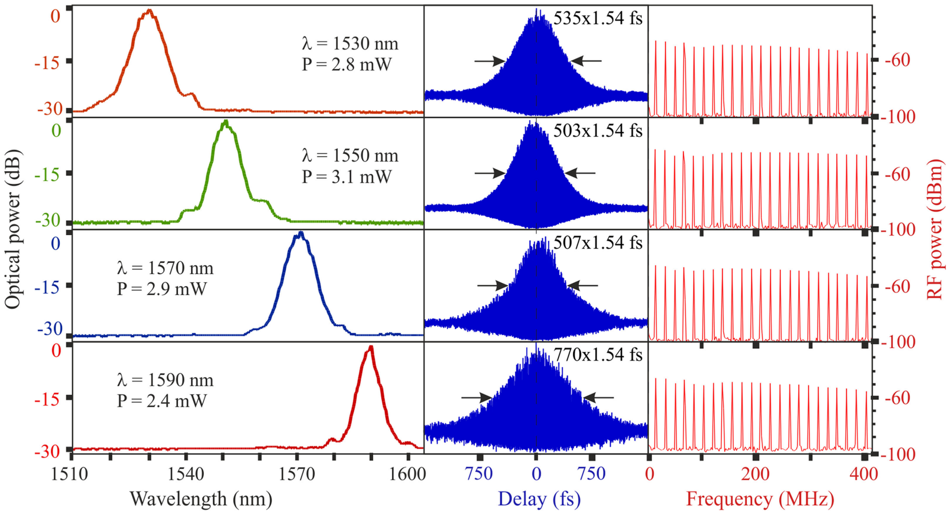

Fig. 3. Parameters of mode-locked generation in the studied laser at different wavelengths: left—optical output spectra with the central wavelength and average output power indicated; center—corresponding interferometric auto-correlation functions of the output pulses with their duration indicated in the approximation of sech^2 shape; right—respective RF spectra of the output pulse trains measured in a broad frequency band.

the wavelength tuning range. Spectral variation of dispersion and nonlinearity of the passive fibre were comparatively small within the 1520–1600-nm range.

The length of all fibre components of the laser cavity totalled about 11.5 m, of which the length of passive SMF-28e fibre was approximately 8.5 m. Factoring in the dispersion of the active and passive fibres used in the cavity, the total group velocity dispersion of the laser resonator was anomalous over the entire wavelength tunability range and changed from -0.102 ps^2 (1524 nm) to -0.167 ps^2 (1602 nm).

In order to study the optical parameters of mode-locked laser output, we used the following measurement equipment: optical spectrum analyser Avesta ASP-IRF along with interferometric autocorrelator Avesta AA-10DDM. We also used a fast InGaAs PIN photodetector connected to an RF spectrum analyser Rohde & Schwarz FSP, and a Keysight DSO-X 3052T oscilloscope with a 1-ns time resolution.

III. Results and Discussion

Rotation of the diffraction grating allowed continuous tuning of the central wavelength of output pulses within the range of 1524–1602 nm. It is important to emphasise that this tuning could be consistently done without disturbing mode-locked generation over the entire indicated range. Another key point is that no additional adjustment of any cavity elements (other than the grating) was necessary in the tuning process. Only the pump level had to be raised at the very long-wavelength edge of the tuning range (around 1600 nm). Within the output wavelength range of 1524 to 1595 nm, the most stable mode locking was observed at the pump power of 270 mW, the average output power ranging from 2.4 to 3.1 mW in the process of wavelength tuning. In order to maintain this level and quality of output at the long-wavelength extremity of the tuning range, the pump power had to be increased to 370 mW.

Fig. 2 shows the registered output pulse spectra at different wavelengths within the tuning range of 1524–1602 nm.

The spectra shown in Fig. 2 were measured 5–6 nm apart, and it follows from this Figure that the pulse spectrum evolves in the process of wavelength tuning, its FWHM breathing between 3 and 6 nm. The spectral pedestals visible in Fig. 2 below –20 dB arise from ASE contribution to the output.

In our preceding work [16], this laser was studied without aspectrally selective element (a mirror was installed instead of a diffraction grating) and exhibited a broader optical spectrum.

It is evident that the greatest limitation of the generation spectrum in the studied laser comes from the spectral filter formed by the diffraction grating and DFOC.

A similar output spectrum limitation in passively mode-locked fibre lasers down to approximately 1/2 FWHM of the intra-cavity band-pass spectral filter was reported in [20]–[22].

Fig. 3 presents measurements of various parameters of the observed mode-locked regime at four different wavelengths: 1530, 1550, 1570, and 1590 nm.

It can be seen that the output radiation spectrum becomes narrower when tuned towards longer wavelengths, whereas, conversely, the pulse duration grows. In the centre of the tuning range within 1530–1590 nm, the output pulse duration varies between 503 and 770 fs, whereas at its edges, the pulse duration rises to 850 fs (1524 nm) and 940 fs (1602 nm).

Analysis of the pulse time-bandwidth (TB) product at different wavelengths demonstrates that the output is near transform-limited across the entire tuning range in the sech^2 shape approximation. Fig. 4 presents the measured dependence of the pulse TB product upon the radiation wavelength. As shown, the TB product swings within 0.35–0.4 range across the totality of the wavelength tunability domain.

It is essential to point out that the degree of pulse duration variability in the studied laser (507–940 fs) is lower than that observed in [5] (within 0.64–1.3 ps) and much lower yet than the results reported, for instance, in [20] where wavelength detuning across 34 nm led to a higher than an order of magnitude pulse duration variability ranging from 545 fs to 6.1 ps.

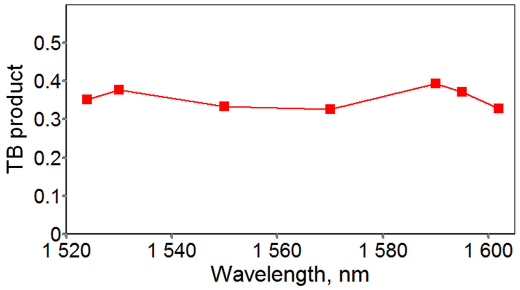

Fig. 4. Dependence of the pulse time-bandwidth product upon the radiation wavelength.

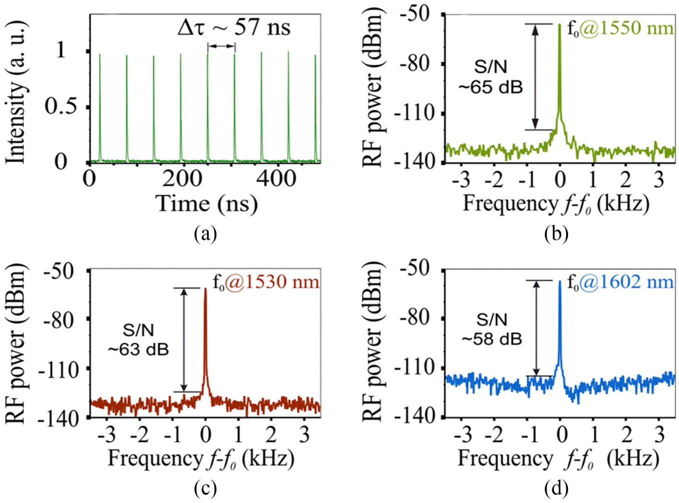

Fig. 5. (a) Typical time trace of the output pulse train generated by the laser in mode-locked regime; (b, c, d) RF spectra of the output pulse trains measured at 10-Hz resolution in the vicinity of the fundamental intermode frequency ($f_0 \approx 17.5$ MHz) at different wavelengths.

The RF spectra shown in Fig. 3 (right) were measured by means of the aforenamed photodetector and RF spectrum analyser. These spectra are an evidence of almost equally good quality of mode locking at different output wavelengths.

More detailed studies of RF spectra at different wavelengths are summarised in Fig. 5. Comparatively high measured signal to noise ratio (>58 dB) indicates high quality of mode locking provided by the chosen saturable absorber.

The pulse repetition rate in the studied laser corresponded to the fundamental value 17.5 MHz at the all demonstrated lasing wavelengths as indicated by the oscillogram in Fig. 5(a). The presence of a variable air gap between the DFOC and diffraction grating enables adjustment of the pulse repetition rate. The available range of distances between the grating and the DFOC was around ±0.2 mm, beyond which it was impossible to start mode-locked operation. This grating displacement corresponds to the output pulse repetition rate tunability of ±0.42 kHz around the central frequency of 17.5 MHz. The possibility of pulse repetition rate adjustment may be used in a pulse frequency lock-in system for laser stabilisation.

Very importantly, the proposed laser also features high long-term stability of the generation parameters. In laboratory conditions, instability of the average output power did not exceed 4% over several hours. High stability and reliability of radiation mode locking is also borne out by reproducibility of the generation parameters from day to day.

To identify the potential for further broadening the wavelength tunability of femtosecond pulses generated in the studied laser, we also measured its wavelength tuning range in CW operation. We replaced the saturable absorber with a standard fibre and at the same pump intensities (270 mW across the large majority of the range and 370 mW around 1600 nm), the CW tuning range extended to 1522–1610 nm. This means that at the short-wavelength end, the maximal tuning range is practically achieved (taking into consideration the spectral width of the output), whereas at the opposite end, tunability could still be improved by a few nanometres.

IV. CONCLUSION

The proposed passively mode-locked Er-doped fibre laser with drop-shaped resonator topology delivers broadest tunability of the central wavelength of the output femtosecond pulses within the range of 1524–1602 nm without disturbing the mode-locked regime in the process of wavelength tuning. During live wavelength tuning, the laser provides uninterrupted stable mode-locked generation with a single pulse per round-trip across the totality of the wavelength tuning range. The output pulse duration varies between 503 and 940 fs and at all available wavelengths, the output pulses remain close to transform-limited, the TB product being measured within 0.35–0.4 over the entire wavelength tunability range.

The developed mode-locked fibre laser on the basis of a drop-shaped cavity topology features a simple cavity configuration with a low optical element count, close to the lowest possible for lasers of this type. The developed configuration contains only one discrete element, a diffraction grating, used for output wavelength tuning. The freedom from additional element adjustments and comparatively small variation of the TB product while tuning make the proposed laser stand out among other ultra-short pulse tuneable Er-doped fibre lasers.

A discrete reflector used in the laser cavity makes it possible, as it did in [16], to adjust the pulse repetition rate of the laser. In combination with the possibility of broad-range wavelength tunability, this opens new application prospects for the developed unique radiation source.

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