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Harmonically mode-locked fibre laser: stabilisation of and control over the pulse repetition rate using a narrow spectral component

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Abstract. **This paper examines a soliton fibre laser with harmonic mode locking via nonlinear polarisation rotation. A characteristic feature of its spectrum is the presence of a narrow-band component. We show that, as the wavelength of the narrow-band component approaches that of a Kelly peak, the supermode noise level in the radiofrequency spectrum of the laser can be reduced by 27 – 32 dB at pulse repetition rates from 275 to 1230 MHz. In addition, we demonstrate the feasibility of tuning the pulse repetition rate with the highest possible accuracy, equal to the fundamental cavity frequency, throughout the range of its variation, up to the highest value of 1760 MHz. Such tuning is possible if the wavelength of the narrow-band component lies in a certain resonance region of the soliton spectrum.**

Keywords: *soliton, fibre laser, mode locking, pulse repetition rate.*

1. Introduction

The ease of tuning and use, comparatively low cost, high output beam quality, and a number of other qualities make fibre lasers a consumer-oriented alternative to solid-state and semiconductor lasers in many applications [1]. The last decade has seen rapid advances in pulsed fibre sources with a pulse repetition rate (PRR) of up to tens of gigahertz owing to their potential applications in optical comb generators and telecommunication systems [2 – 4]. Since the fundamental PRR of a standard fibre laser does not exceed tens of megahertz, gigahertz pulse trains are generated using harmonic mode locking (HML), a technique in which many pulses should be uniformly distributed over the laser cavity [5, 6]. Possible types of HML fibre lasers include actively mode-locked lasers [7] and lasers with an intracavity high-Q comb filter [8], but the most widespread are lasers with a fibre ring cavity, in which a periodic sequence of pulses is ensured by their mutual repulsion [6, 9].

The main drawback of HML fibre lasers is noise deviations of the pulse amplitude and spacing from their average levels – amplitude and timing jitter considerably exceeding that in lasers at the fundamental PRR [10]. The magnitude of jitter in an HML laser is directly related to the level of supermode noise. Suppression of the latter corresponds to pulse train stabilisation, i. e. approach to an ideal periodic signal. A number of approaches to HML laser stabilisation have been reported to date [11–14]. Most of them rely on a combined action of additional modulators and filters, which reduces the supermode noise level.

Another rather important issue in the technology of HML fibre lasers is PRR tuning [15]. In most of the known HML lasers, varying the pump power causes sharp changes in PRR. The magnitude of the changes considerably exceeds the minimum step, equal to the fundamental cavity frequency, and is of the order of hundreds of megahertz at PRRs in the multigigahertz range [16 – 18]. Besides, in accord with hysteresis effects characteristic of soliton lasers, 'upward' and 'downward' PRR jumps occur at different pumping levels [19]. Thus, PRR tuning with the highest possible accuracy, equal to the fundamental frequency, turns out to be a rather nontrivial problem. Recent work [20, 21] has shown that supermode noise suppression and PRR tuning in an HML soliton laser can be ensured by a universal method: injection of light from an external narrow-band laser into the cavity. The point of crucial importance in the proposed method is the position of the external cw source wavelength relative to the soliton spectrum of the HML laser. If the external cw component is located immediately near a Kelly peak, an interesting effect is observed: Kelly peak lock-in by the external cw light, accompanied by a shift of the optical spectrum and a considerable reduction in the supermode noise of the HML laser. Basic to this effect is four-wave interaction of solitons and cw light, which leads to the formation of a single structure of solitons and background cw light, with a constant phase difference between them [22].

In contrast to the above effect, which stabilises the system, the change in PRR in response to injection of external cw light is related to a destabilisation process and soliton creation or annihilation in the HML laser cavity. The physics of this process is associated with the possibility of controlling dissipative effects of saturable gain and absorption in the ring laser cavity with the use of a small external cw signal. As shown earlier [21], if the wavelength of the cw signal being injected lies at certain resonance points in the soliton spectrum, varying the signal power allows one to control soliton creation and annihilation processes in the HML laser cavity, setting the PRR with the highest possible accuracy, equal to the fundamental frequency and corresponding to a single soliton creation or annihilation.

Turning to the formulation of the purposes of this study, it is worth recalling some features of mode-locked fibre lasers. A frequently encountered characteristic feature of their spectrum is an intrinsic narrow-band component, whose intensity may be polarisation-dependent [2, 18, 23]. Owing to the diver-

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sity of soliton dynamics, especially in the case of multipulse operation, when there is a large number of pulses in the cavity, the intrinsic cw component can both attest to imperfect mode locking [24] and act as a mediator of interpulse interactions [2, 22, 25]. The latter is confirmed by the frequently encountered presence of an intrinsic cw component in the spectrum of HML lasers [18, 23]. In this work, we draw parallels between results we obtained previously for HML lasers under external cw injection and our recent observations concerning HML lasers with an intrinsic cw component in their spectrum. Analysis of these observations allowed us to formulate a number of recommendations concerning noise characteristics and PRR tuning of HML lasers with an intrinsic cw component in their spectrum and make significant advances in understanding the processes involved.

2. Experimental setup

In our experiments, we used a standard fibre ring soliton laser configuration with mode locking via nonlinear polarisation rotation (Fig. 1). The laser cavity includes two types of optical fibre: heavily erbium-doped normal dispersion (–48 ps nm^{-1} km^{-1}) fibre (0.8-m length) and standard anomalous dispersion (17 ps nm^{-1} km^{-1}) single-mode fibre. The total cavity length is ~15.5 m, which corresponds to a fundamental PRR f_0 = 13.3 MHz. In addition, the cavity includes a fibre isolator suppressing one of the polarisation components, a 5% fibre coupler, and a polarisation controller (PC). The laser is diode-pumped at a wavelength of 980 nm and maximum power of 550 mW. The output signal is detected by a spectrum analyser (Yokogawa 6370D) with a 0.02-nm resolution and an RF spectrum analyser (R & S FSP40) equipped with a 30-GHz photodetector.

The threshold pump power of the laser is about 30 mW. Above the threshold, it switches to cw operation at a wavelength of ~1562 nm (Fig. 3, dashed lines). In the case of accurate adjustment of the PC, raising the pump power to about 80 mW leads to mode locking at the fundamental frequency f_0. In this regime, a single pulse circulates in the cavity. As the pump power is raised, the laser switches to multipulse operation. Accurate adjustment of the PC then makes it possible to switch to the HML regime with a periodic distribution of N pulses over the cavity. In this regime, the laser emits a pulse train with a PRR $f_{\mathrm{rep}} = Nf_0$. Raising the pumping level leads to an increase in PRR.

3. Lowering the supermode noise level

As mentioned above, a key stability indicator of an HML laser is its supermode noise level. It can be determined from the RF spectrum of the laser, which has a characteristic shape. The repetition frequency of the main peaks in the RF spectrum is $f_{\mathrm{rep}} = Nf_0$. In addition, they are surrounded by weaker peaks (supermodes), with a spacing equal to the fundamental frequency f_0 (Fig. 2a). The ratio of the main peak amplitude to the maximum supermode intensity determines the supermode suppression level (SSL). Even though a pulse train jitter is determined by the joint contribution of all supermodes [10], the SSL can be regarded as a key parameter for assessing HML laser output signal periodicity. According to our experiments, the SSL depends on the relative position of the soliton spectrum and the intrinsic cw component of the fibre laser. This effect will be considered below in greater detail for HML lasing with a pulse centre wavelength near λ = 1567 nm. A distinctive feature of this lasing mode is that the optical spectrum of the soliton laser contains a well-defined cw component at a wavelength λ = 1562 nm, corresponding to narrowband lasing at low levels of pumping.

At a constant pump power near 450 mW, we observe HML lasing at a PRR of 1230 MHz. The RF spectrum of the laser is represented by blue lines in Fig. 2a. Note that supermode amplitudes fluctuate over time in a relatively narrow range (1 – 2 dB), with the average SSL being near 24.5 dB. The shape of the optical spectrum is typical of soliton lasers with

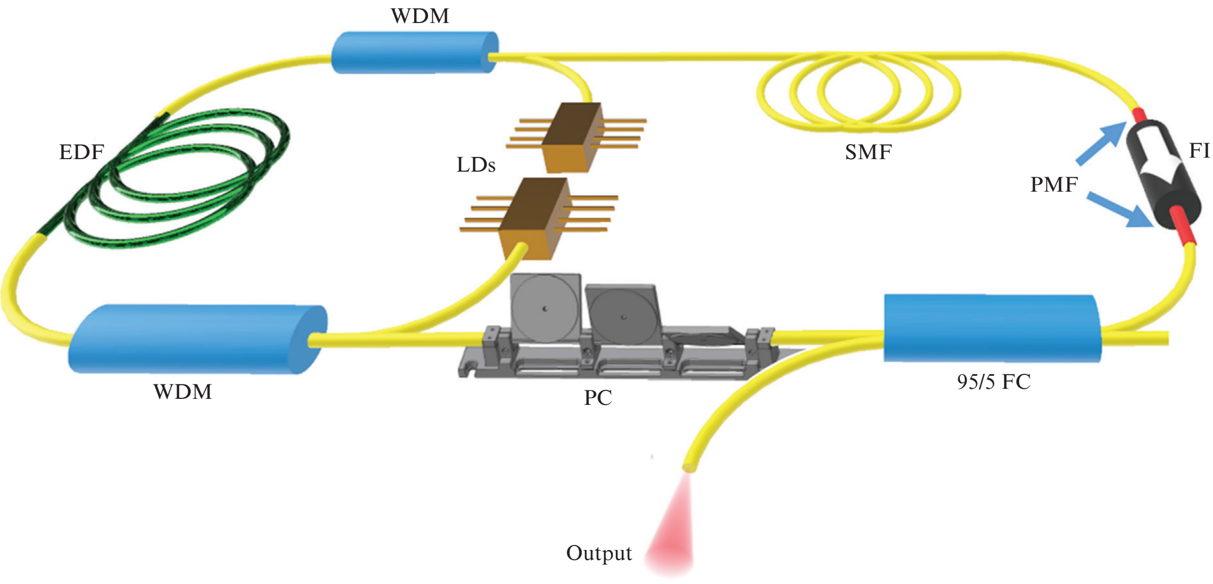

Figure 1. (Colour online) Experimental configuration of the fibre ring laser:
(EDF) Er-doped fibre; (WDM) wavelength-division multiplexer; (LDs) pump laser diodes; (605SMF) single-mode fibre; (PMF) polarisation-maintaining fibre; (FI) fibre isolator suppressing one of the polarisation components; (FC) fibre coupler; (PC) polarisation controller.

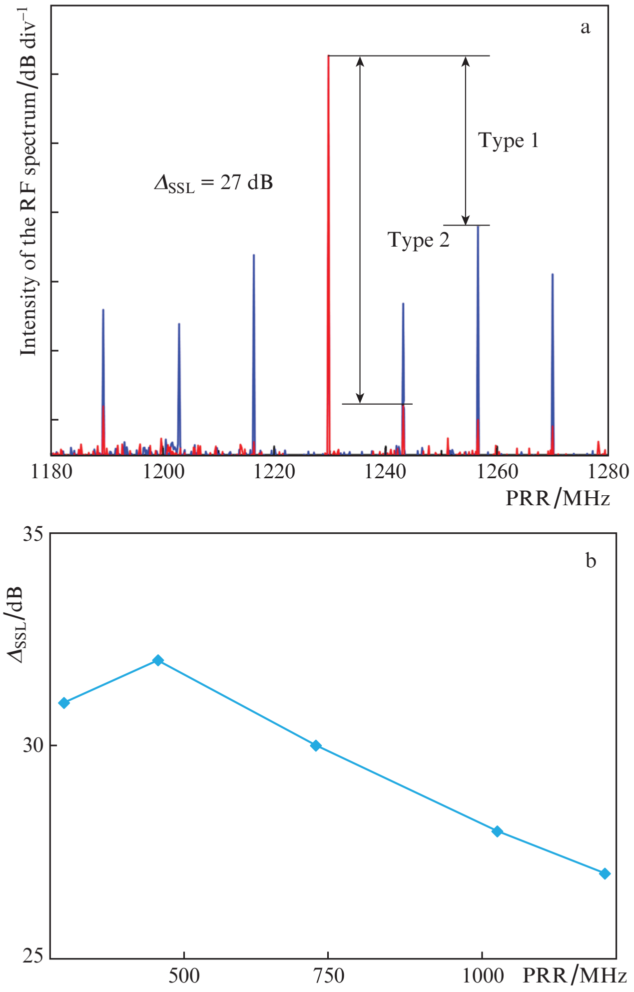

Figure 2. (Colour online) (a) RF spectra of the HML laser at a PRR of 1230 MHz; type 1 (blue lines): RF spectrum in the case where the cw component differs in wavelength from the Kelly peak (corresponds to the optical spectrum in Fig. 3a); type 2 (red lines): RF spectrum in the case where the wavelength of the cw component coincides with that of the Kelly peak (corresponds to the optical spectrum in Fig. 3c); (b) effect of the HML laser PRR on the change in SSL in the case where the wavelength of the cw component coincides with that of the Kelly peak (type 2).

well-defined Kelly peaks. To the above noise level there correspond an initial position of the cw component between the top of the optical spectrum and the strongest short-wavelength Kelly peak (Fig. 3a).

Fine tuning of the quarter-wave plate of the polarisation controller allows one to vary the pulse centre wavelength in the range 1563–1570 nm, while maintaining the HML regime and keeping the pulse repetition rate unchanged. Shifting the soliton spectrum and approaching the Kelly peak to the cw component, we revealed an interesting effect: after the separation between them decreased to some critical level ($\sim$0.5 nm) (Fig. 3b), further shift of the spectrum occurred spontaneously, without PC tuning, and caused the Kelly peak and cw component to merge (Fig. 3c). As a result of this process, the supermode noise level drops, and the SSL rises to 51.5 dB (Fig. 2a, red lines). Thus, after the absorption of the Kelly peak, the supermode noise level decreases by Δ_{SSL} = 27 dB, attesting to HML laser stabilisation. Direct measurements with a Yokogawa AQ 7750 oscilloscope showed that, as a result, the rms timing jitter decreased from 7.7 to 2.1 ps. Next, we examined the influence of the intensity of the cw component on the magnitude of the observed effect. Tuning the central half-wave plate of the PC was shown to allow one to control the intensity of the cw component in a certain range (at

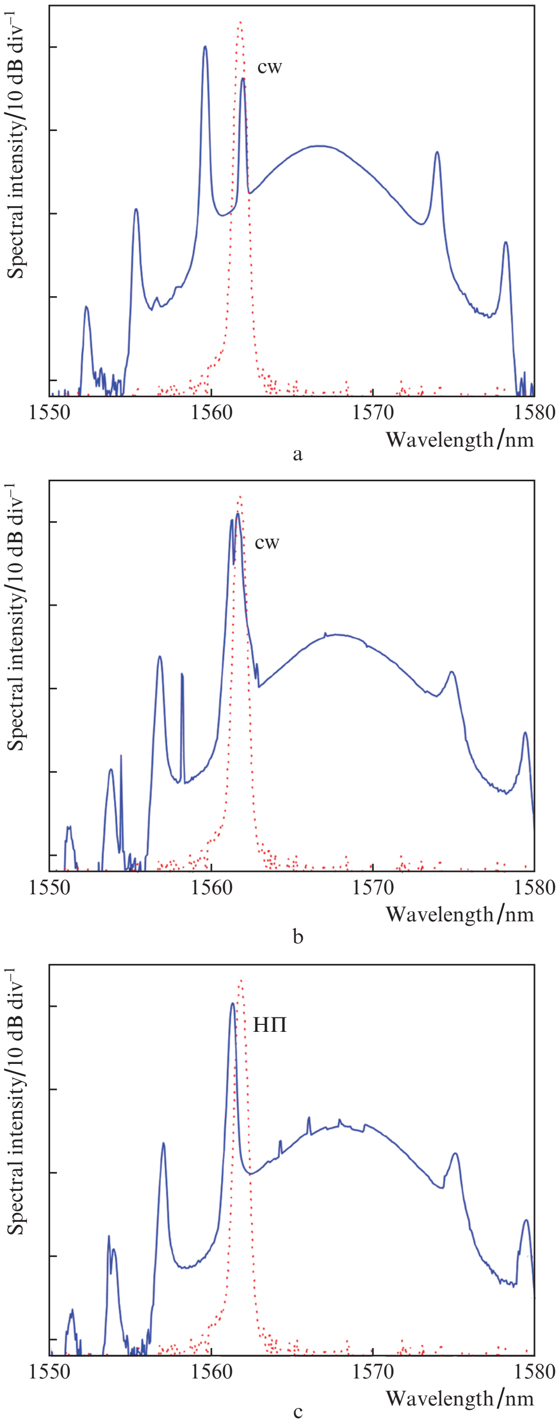

Figure 3. (Colour online) Sequential changes in the optical spectrum of the HML laser as the Kelly peak approaches the wavelength corresponding to the cw component: (a) initial shape of the optical spectrum, with well-seen Kelly peaks and isolated position of the cw component; (b) optical spectrum after a shift of the soliton spectrum as a result of PC tuning; (c) final shape of the optical spectrum after the Kelly peak and cw component merged. Pump power, near 450 mW; pulse repetition rate, 1.23 GHz. The dotted line represents the narrow-band lasing peak at a pump power near 40 mW.

least when the cw component was noticeable in comparison with the soliton spectrum), while keeping the centre wavelength and pulse repetition rate of the HML laser unchanged. Experimental data show that tuning the intensity of the cw component in the indicated range has essentially no effect on the SSL.

Similar results were obtained in several analogous experiments at other pump power levels and, hence, other PRRs: after the Kelly soliton peak approached the cw spectral component, they merged, which was accompanied by a drop in SSL. It can be seen from Fig. 2b that $\Delta_{\rm SSL}$ decreases with increasing PRR. The highest value, $\Delta_{\rm SSL} = 32$ dB, was reached at a PRR of 440 MHz. At PRRs above 1230 MHz, no supermode noise suppression in the HML laser was detected.

4. Pulse repetition rate tuning

The key approach to tuning the PRR of an HML laser is to vary the pump power, thereby changing the number of pulses in the cavity. However, the use of this method has to face the fact that creation and annihilation of solitons in the cavity occurs by groups of tens of pulses, rather then gradually, one by one. This is illustrated by Fig. 4, which shows how the PRR of the laser under consideration varies in response to changes in pump power at a constant position of the polarisation controller for a centre laser wavelength of ~1567 nm. Gradually raising the pump power to ~530 mW causes several jumps in PRR (red lines), from its original level f_0 = 13.3 MHz to its highest value, ~1.75 GHz. In accord with the known soliton hysteresis effect [19], the reverse process – a stepwise decrease in PRR with decreasing pump power – follows a different trajectory (blue lines). It follows from Fig. 4 that there are considerable ranges (several hundred megahertz) of intermediate PRRs that cannot be obtained by merely manipulating laser pumping.

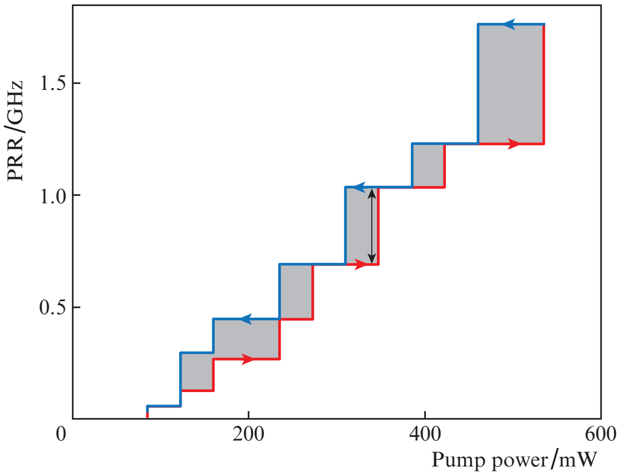

Figure 4. (Colour online) Effect of pump power on the PRR of the HML laser. The red and blue lines correspond to an increase and decrease in pump power, respectively. In the shaded regions, PRR tuning is possible. The two-headed black arrow represents the tuning range described in text.

As shown in our experiments, these intermediate PRRs can be obtained by shifting the optical spectrum relative to an immobile narrow-band component. As an example, consider PRR tuning at a pump power of ~340 mW (Fig. 4, two-headed black arrow). The initial state of the laser was obtained by raising the pump power, i. e. by moving from left to right along the hysteresis trajectory. The initial PRR is ~720 MHz. As pointed out above, accurate adjustment of the quarter-wave plate of the PC allows the optical spectrum to be shifted within some range (1563–1570 nm), without disturbing the HML state. In such a case, variations in spectral bandwidth

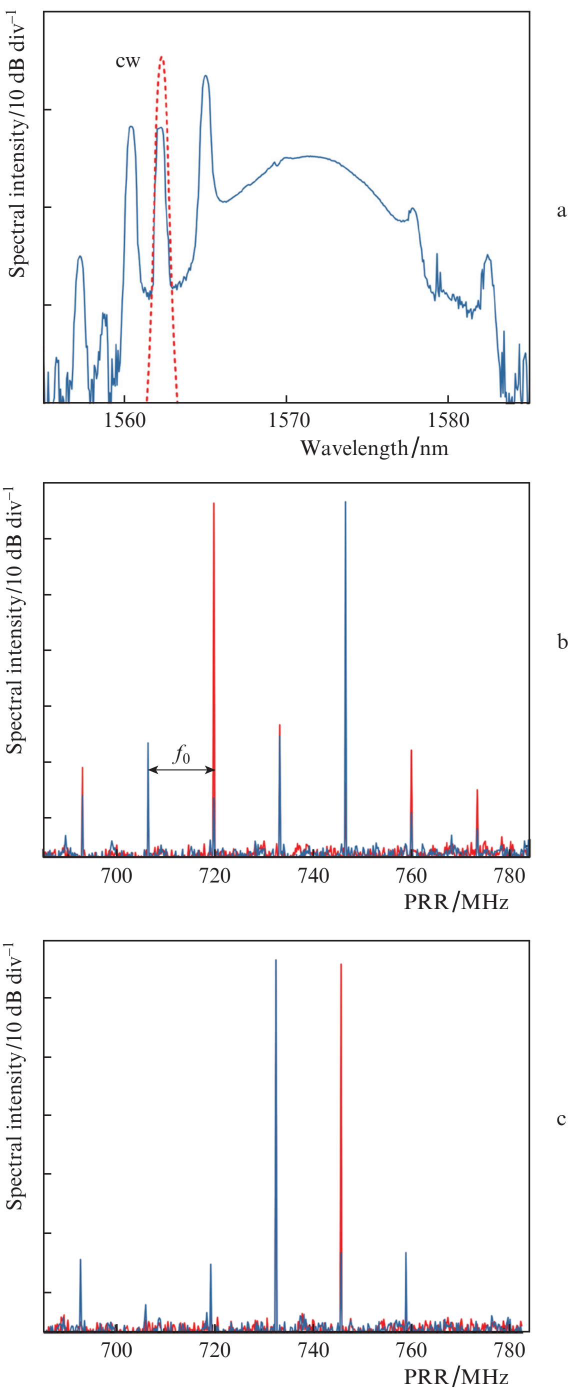

Figure 5. (Colour online) (a) Optical spectrum of the HML laser in the PRR tuning regime. The dashed line represents the narrow-band lasing line at a pump power near 40 mW. (b, c) RF spectra of the HML laser before (red lines) and after (blue lines) PRR tuning at a pump power of 340 mW: (b) PRR tuning by $2f_0$, from 720 to 748 mHz; (c) PRR tuning by $-f_0$, from 748 to 734 mHz. The resolution of the RF spectrum is 100 kHz.

and average output power are insignificant, i.e. the duration and energy of an individual soliton remain unchanged. In this way, shifting the optical spectrum to longer wavelengths with the use of the PC, we found a narrow spectral region where the PRR changed spontaneously, with the cw component located between two strong short-wavelength Kelly peaks (Fig. 5a). The change in PRR can be noticed from variations in the RF spectrum: after the shift of the optical spectrum to the resonance region, the main peak in the RF spectrum begins to randomly shift in the range 720–1030 MHz. This range lies within the shaded region in Fig. 4 and corresponds to a change in PRR between the 54th and 77th harmonics of the ring cavity. To keep the final PRR constant, it is sufficient to shift the optical spectrum, using the PC, to beyond the resonance region. After that, the position of the main peak in the RF spectrum remains unchanged, whereas the amplitude of side supermodes decreases. As an example, Fig. 5b shows PRR tuning from 720 to 748 MHz with a step of two fundamental frequencies, $2f_0$ (the initial and final states of the RF spectrum are shown), and Fig. 5c shows a change in PRR from 748 to 734 MHz, caused in a similar manner, with the minimum step, $-f_0$. Note that PRR tuning has essentially no effect on the SSL, which confirms that the pulse train remains stable after the tuning. Similar experiments at other pump powers showed that such changes in PRR occur in all the ranges corresponding to the shaded regions in Fig. 4. The maximum PRR reached by tuning coincides with its highest value: 1760 MHz. Thus, the method under consideration allows one to set the PRR throughout the range of its variation with the highest possible accuracy, equal to the fundamental frequency f_0.

5. Discussion and conclusions

The present experimental data are closely related to previously reported results on the stabilisation [20] and PRR tuning [21] of HML lasers via external narrow-band injection. On the one hand, the use of an intrinsic cw component significantly limits the spectral range where stabilisation of and control over the PRR are possible. Indeed, in the laser configuration under consideration, with polarisation control, HML operation can be achieved in several unconnected regions in the range 1545–1590 nm. However, the proposed method for controlling laser parameters is only possible in a narrower range, 1565–1572 nm, where a necessary overlap of the soliton spectrum and the cw component can be ensured. On the other hand, the obvious advantages of the approach under consideration – the simplified experimental setup and the ability to do without an external narrow-band source, an expensive additional component – of course make it viable.

The physics of the processes involved is rather interesting, and separate investigation is needed to analyse it in detail. In this work, we consider only their key points and discuss similarities and distinctions between the observed effects, caused by either external narrow-band injection or an intrinsic cw component. As shown earlier by examining control over parameters of an HML laser via external injection [20], the resonance character of the observed processes is associated not only with the small external source linewidth, but also with the fact that the external cw component should be injected at the peak transmission wavelength of the Lyot polarising filter coupled to the ring cavity. The key role in its formation is played by the polarisation-maintaining fibre segments (Fig. 1), and adjustment of the PC has essentially no effect on the spectral position of transmission peaks. Our findings show that the internal cw component is also generated in one of such fixed peaks. The use of only visual evaluation of the intensity of the intrinsic cw component (from the optical spectrum) significantly limits the capabilities of the proposed technique. Nevertheless, the present results have led us to the following conclusions: The experimental configuration with external narrow-band injection is designed so that external cw light passes through the coupler and its intracavity power is ~ 0.1 mW, which is almost two orders of magnitude lower than the intracavity intensity of the intrinsic cw component at the beginning of the lasing process. We showed that the magnitude of the effects observed under external narrow-band injection is a linear function of the injected light intensity. If an intrinsic cw component is used, there is no such relation, which suggests that the intracavity intensity of the intrinsic cw component should surpass some threshold and that there is its 'saturation'.

The physical foundations underlying HML laser stabilisation and supermode noise suppression under external narrow-band injection persist in the case of stabilisation with the use of an intrinsic cw component. In both cases, the physics of the process is connected with interaction between pulses and the continuous background formed either upon injection or directly in the laser cavity. Effectiveness of this interaction is ensured by the spectral proximity of the cw component to a Kelly peak. Four-wave interaction between pulses and the cw component causes the soliton spectrum to shift so that the cw component absorbs the Kelly peak, and the solitons and cw light in the cavity form a single phase-matched structure [22]. In collective dynamics of such structure, it is worth noting a decrease in pulse position fluctuations originating from the initially random phase difference between the pulses. As mentioned above, HML is due to interpulse repulsion. According to current views, the key role in this process is played by interaction between pulses as a result of gain saturation and relaxation [6]. The presence of a cw background between pulses may cause additional repulsion [22], which increases interaction through gain saturation and relaxation and stabilises the harmonic distribution of pulses over the cavity, thus reducing jitter [9].

PRR tuning with the use of a narrow-band background implies the possibility of some control over dissipative processes related to the saturable absorption and saturable gain in the HML laser cavity. Gaining insight into the physics of the processes involved in PRR tuning in an HML laser via interaction with a cw component will ensure deeper understanding of the physics of soliton fibre lasers and can be the subject of separate, extremely interesting research.

In conclusion, note that we have considered approaches to stabilisation and PRR tuning of an HML soliton fibre laser with the use of an intrinsic cw component. The SSL has been shown to decrease by 27–32 dB at PRRs in the range 275–1230 MHz as the wavelength of the cw component approaches a Kelly peak. We have demonstrated the feasibility of tuning the PRR with the highest possible accuracy, equal to the fundamental frequency, throughout the range of its variation, up to the highest value of 1760 MHz, which is possible if the wavelength of the intrinsic cw component lies in a certain resonance region of the soliton spectrum. The present results have been compared to analogous data obtained previously using external injection of narrow-band light into the cavity of an HML fibre ring laser.

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