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High-order harmonic noise-like pulsing of a passively mode-locked double-clad Er/Yb fibre ring laser

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Abstract

In this paper, we study noise-like pulse generation in a km-long fibre ring laser including a double-clad erbium–ytterbium fibre and passively mode-locked through nonlinear polarization evolution. Although single noise-like pulsing is only observed at moderate pump power, pulse energies as high as 120 nJ are reached in this regime. For higher pump power, the pulse splits into several noise-like pulses, which then rearrange into a stable and periodic pulse train. Harmonic mode locking from the 2nd to the 48th orders is readily obtained. At pump powers close to the damage threshold of the setup, much denser noise-like pulse trains are demonstrated, reaching harmonic orders beyond 1200 and repetition frequencies in excess of a quarter of a GHz. The mechanisms leading to noise-like pulse breaking and stable high-order harmonic mode locking are discussed.

Keywords: double-clad fibre lasers, passive mode locking, noise-like pulses, harmonic mode locking

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

1. Introduction

Passively mode-locked fibre lasers are versatile and low-cost sources that have long been studied for the generation of a wide variety of optical pulses [1–8]. Although non-fibre-based saturable absorbers [9–11] are sometimes used, all-fibre schemes using an artificial saturable absorber effect based on the fibre nonlinearity is usually preferred, due to its very fast time response, enhanced flexibility and higher damage threshold. The so-called figure-eight laser [1] and the ring cavity [2, 3] both fall into this category, the latter design often being chosen for its simplicity.

Taking advantage of the availability of high-power pump diodes and of the progress in double-clad fibre technology and stimulated by a renewed understanding of the pulse dynamics in the dissipative soliton framework [12], significant advances have been made and are still in progress today in two main directions: towards the generation of breaking-free, high-energy pulses and towards the production of dense, periodic pulse trains at very high harmonics of the cavity frequency, in the GHz range and beyond (harmonic mode locking).

Although single pulse energy has long been limited by the well known soliton quantization effect [13] in the anomalous dispersion regime, the discovery of dissipative soliton regimes in strongly normal dispersion cavities triggered the generation of very long, strongly chirped pulses with unprecedented high energies [5, 9, 11, 14]. On the other hand, harmonic mode locking is a particular multiple pulsing regime which requires the pulses to be maintained at equidistant intervals along the cavity, in order to produce a stable train of periodic pulses. Until recently, multi-pulsing regimes were of limited interest for practical applications due to the tendency of multiple pulses to either drift randomly with respect to each other or bunch together in the cavity; however, it has since been realized that several mechanisms of inter-pulse interaction can be exploited to produce stable trains of regularly spaced pulses [7, 15–19]. Although currently the dissipative four-wave mixing technique holds the record of the highest repetition rates obtained from fibre lasers [20], values beyond 20 GHz were recently demonstrated in passively mode-locked schemes [7] and even much higher frequencies are predicted for the near future [17].

One strong mechanism of stabilization in passive harmonic mode-locked lasers is provided by a direct, close-range interaction between pulses, which takes place when the skirts of individual pulses overlap, leading to the formation of bound states of solitons [17]. Long-range interaction mechanisms also exist, although weaker, which are mediated by dispersive waves or wavelength-shifted CW components [15, 21, 22]. Another important long-range mechanism involves electrostrictive effects [15]: the intense electric field of the pulses distorts the material and excites weak transverse acoustic waves in the fibre, which perturb the refractive index and imposes phase modulation on the next pulse. At particular pulse repetition frequencies that closely match one of the resonant frequencies of the transverse acoustic wave, the effect is strongly enhanced and is sufficient to stabilize the temporal position of the pulses. Finally, a mechanism based on gain dynamics has also been proposed [23].

Recently, there has been growing interest in the production of original types of pulses, the noise-like pulses, due to their potential applications [8, 24–35]. Originally studied in the 1.0 and 1.5 μm wavelength ranges, the noise-like pulsing regime has since been discovered in the 2 μm region as well [36, 37]. Noise-like pulses are large and compact collections of thousands of ultrashort (ps or sub-ps) inner pulses, with randomly varying amplitudes and durations, which are commonly observed in long lasers in any dispersion regime. Their total duration ranges from a few tens of ps to 1 μs. In spite of the large variability of their inner details, their global properties (like the total duration of the bunch, its energy or the average spectrum) remain stationary. Being composed of a large number of ultrashort pulses, noise-like pulses intrinsically possess a high energy [8]. They also display a wide, smooth optical spectrum [32] and low temporal coherence, so that these pulses do not vanish even after propagation through km-long dispersive fibre [24]. These characteristics make them attractive for sensing, supercontinuum generation and metrology, among other applications [38–40]. Another typical signature of noise-like pulses is a double-scaled autocorrelation, in which a narrow coherence peak is surrounded by a strong, wide and smooth pedestal.

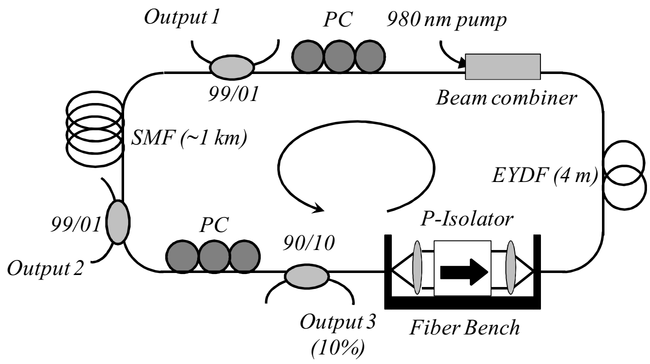

Figure 1. Scheme of the laser under study.

In nearly all references dealing with noise-like pulses, only one pulse circulates in the cavity (fundamental mode locking). This means that the sub-pulses remain stuck together, independently of their number in the bunch. In general, if pump power is increased, the pulse duration and thus the number of sub-pulses in the packet, increases proportionally [26]. In [33], a single noise-like pulse as long as ~ 1 μs (thus extending over ~200 m of fibre) could be obtained, so that the temporal extension of such pulses could seem boundless. Nevertheless, a few cases of multiple noise-like pulses have also been reported [25, 33–35]. In [35], up to 12 simultaneous noise-like pulses were observed in a figure-eight laser. Although single noise-like pulsing was the most usual mode of operation in this scheme, multiple pulsing appeared when the pulse duration was extended beyond ~20 ns through adjustment of the nonlinear switching power. Multiple pulsing thus appeared at the long-duration, low-peak-power limit of single pulsing, when the sub-pulses become so numerous and the nonlinear effects so weak that the cohesion of the bunch is no longer maintained, leading to noise-like pulse breaking. Although a stable pattern of multiple identical pulses could be obtained, the pulses were not uniformly distributed along the cavity, so that harmonic mode locking was not observed in [35]. To the best of our knowledge, the only example of high-order harmonic mode locking achieved with noise-like pulses is provided by [33]. In this reference, a repetition frequency as high as 1 GHz was obtained from a 5 km long Raman fibre laser, which is more than 24 000 times the cavity fundamental frequency.

In this paper, we study a passively mode-locked Er/Yb-doped fibre ring laser producing noise-like pulses and in which harmonic mode locking appears to be the most usual mode of operation. Fundamental mode locking can also be achieved; however, it is confined to moderate levels of pump power. Stable harmonic mode locking up to the 1270th order is demonstrated.

2. Experimental setup

The laser under study is depicted in figure 1. It is a ring configuration and is composed by 4 m of Er/Yb-codoped double clad fibre (EYDF) backward-pumped at 980 nm by a multimode high-power source through a beam combiner, a fibre bench containing a free-space single-polarization isolator

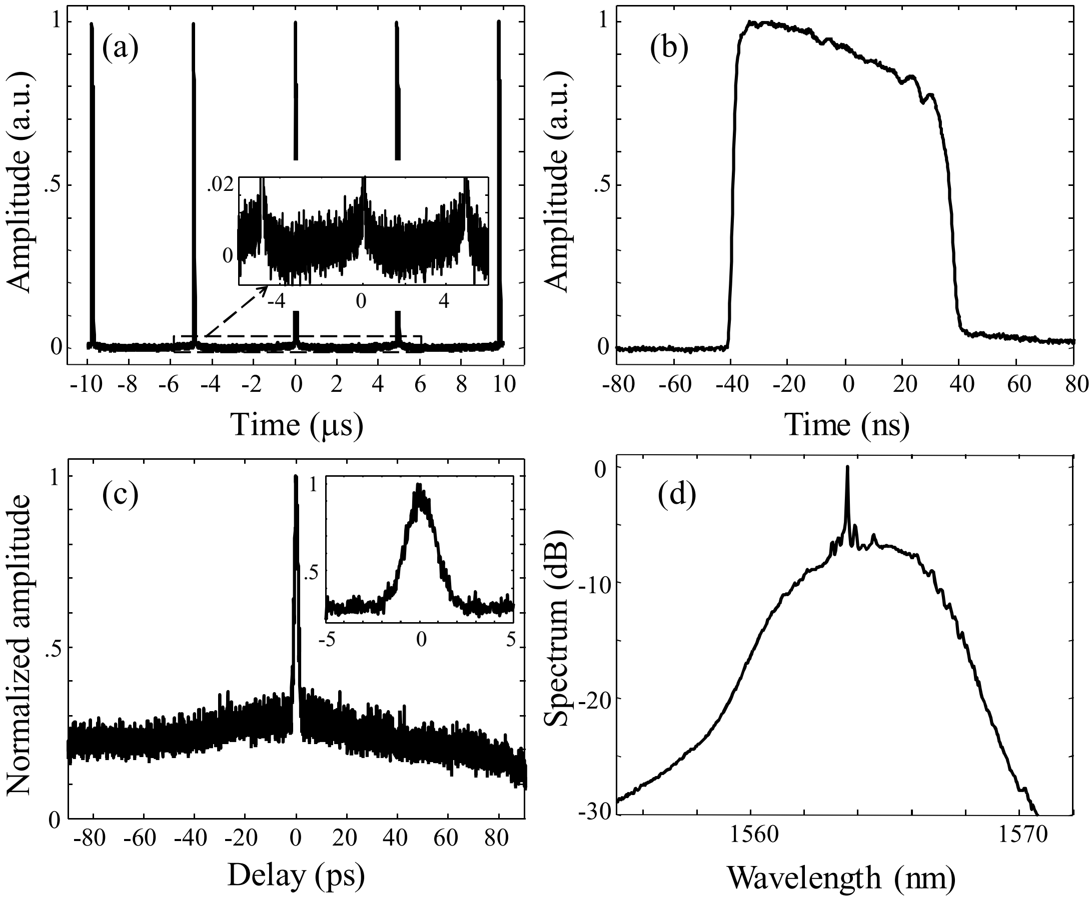

Figure 2. Fundamental mode locking; (*a*), (*b*) scope traces obtained using a 2 GHz photodetector and a 200 MHz oscilloscope; (*c*) autocorrelation (inset: close-up on central spur); (*d*) optical spectrum.

(insertion loss ~3 dB) which also acts as polarizer and a 1 km spool of standard single-mode fibre (SMF, dispersion = 18 ps nm^{-1} km^{-1}). The ring also includes two fibre polarization controllers (PC) and three output couplers (two 99/01 and one 90/10) for signal measurement and monitoring. With this setup, we are able to couple up to ~2 W of pump power at 980 nm into the doped fibre, this limit being set by the damage at the splice between beam combiner output and doped fibre.

For proper adjustments of the PCs, mode locking is obtained through nonlinear polarization evolution and polarization selection [2]. Mode locking is self-starting and is first observed for a pump power of about 10% of the maximum. As pump power is increased and through PC adjustments, fundamental mode locking and harmonic mode locking of growing order are successively observed.

3. Experimental results and discussion

The measurements of fundamental mode locking are shown in figure 2. Figure 2(*a*) shows a stable pulse train with a period of 4.9 μs (repetition rate = 204 kHz), which matches the round-trip time of the 1000 m long cavity. The pulse duration is of several tens of ns and grows with pump power, reaching a maximal value of ~80 ns (figure 2(*b*)). The autocorrelation function (figure 2(*c*)) shows a double-scaled structure, with a narrow, ~2 ps coherence peak riding a wide, smooth pedestal, and the optical spectrum is smooth (except for a spike) and has a full width at half maximum (FWHM) bandwidth of 5 nm (figure 2(*d*)). These features are the typical signature of noise-like pulses. Fundamental mode locking is restricted to relatively low values of pump power, for which an average power not higher than 25 mW is measured at output 3. In spite of this, the single pulse energy at this point is estimated to be ~120 nJ at output 3 (and 1.2 μJ inside the cavity), which is more than twice the previously reported highest noise-like pulse energy from a double-clad fibre laser [8]. However, it has to be noted that the pulses in [8] were much shorter, and that 20 ns pulses with energies reaching several μJ have already been extracted from a km-long fibre laser [6].

If the pump power is further increased, the single 80 ns pulse splits into multiple pulses. Hence, there seems to be an upper limit of pulse duration, beyond which the cohesion between an increasing number of sub-pulses becomes insufficient to keep the pulses together. Repulsive interactions between sub-pulses mediated by dispersive waves or a CW component may play an important role in the pulse breaking process. Indeed, such a CW (or quasi-CW) component is clearly visible as a spur in the optical spectrum. From figure 2(*d*), its energy can be estimated as ~6% of the total intracavity energy. This component is also present on the scope as a wide pedestal or tail accompanying the pulses. An estimation of the energy carried by the background shown in the inset of figure 2(*a*) yields

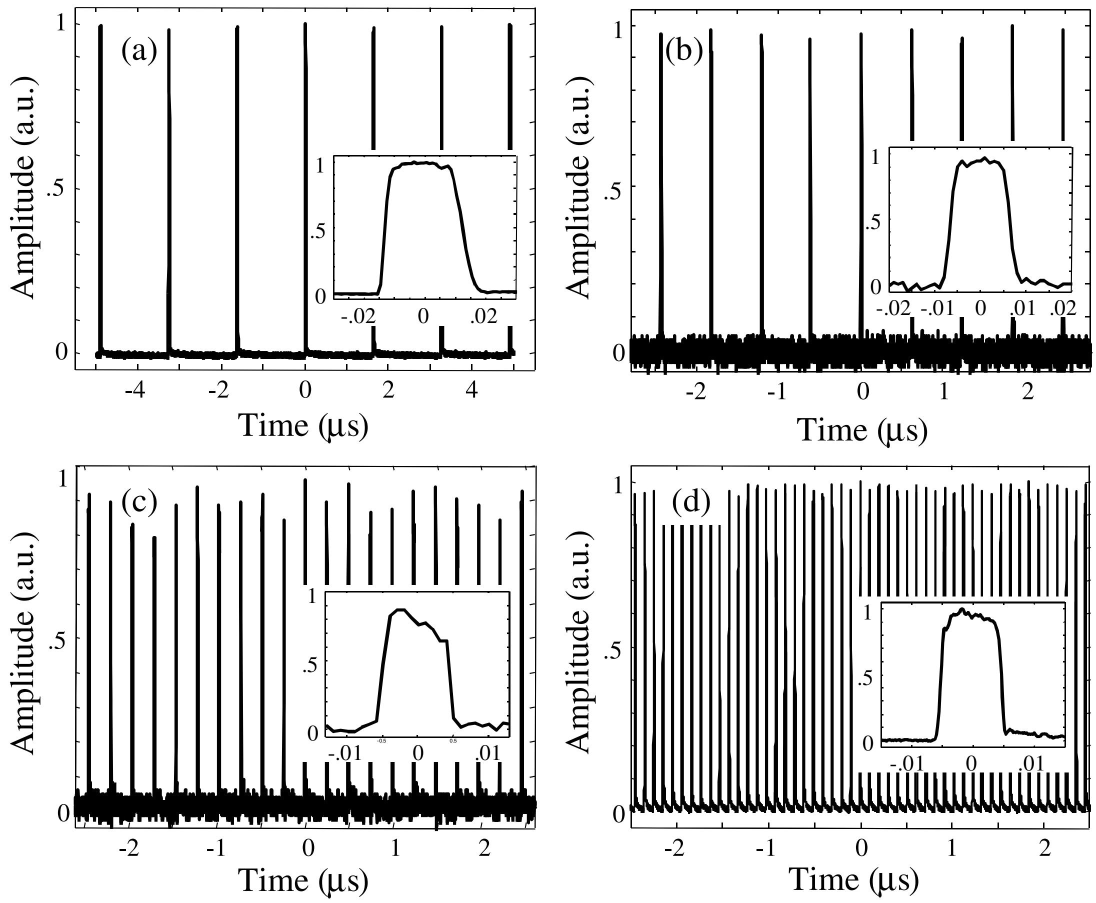

Figure 3. Scope traces of harmonic mode locking of orders 3 (*a*), 8 (*b*), 20 (*c*) and 48 (*d*). Insets show close-ups on one pulse.

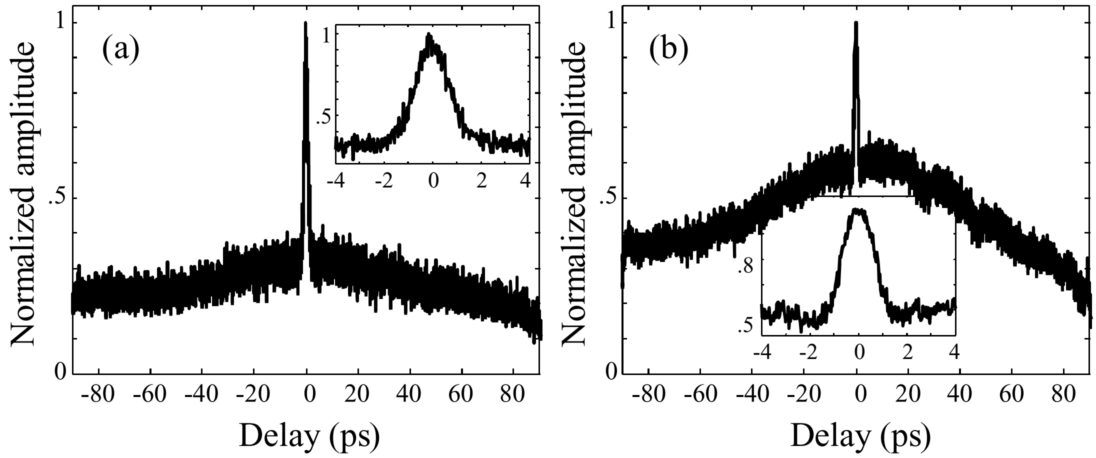

Figure 4. Autocorrelation traces for harmonic mode locking of orders 2 (*a*) and 11 (*b*). Insets show close-ups on central spurs.

roughly the same result as the value calculated from the optical spectrum. It has been recognized [15, 21, 22] that the interaction between the pulses in a bunch and such a background component may induce small shifts in the central wavelength of the individual pulses. Subsequently, these sub-pulses would tend to move apart in the dispersive cavity, which eventually breaks the noise-like pulse. Hence, we believe that dispersion compensation, at least partial, would mitigate this effect and constitutes a necessary step towards improving the highest achievable noise-like pulse energy with this scheme. In [33], using a 5 km long cavity with a dispersion value close to zero, fundamental mode locking with the generation of noise-like pulses as long as ~1 μs was demonstrated.

Beyond the limits of fundamental mode locking, multiple pulses tend to form in the cavity. In some instances, multiple pulsing is unstable: the pulses appear to be randomly distributed in time and are drifting rapidly with respect to each other, so that the scope trace is completely filled in persistent mode. In most cases however, after slight PC adjustments, it takes a few seconds for a stable pattern of uniformly distributed

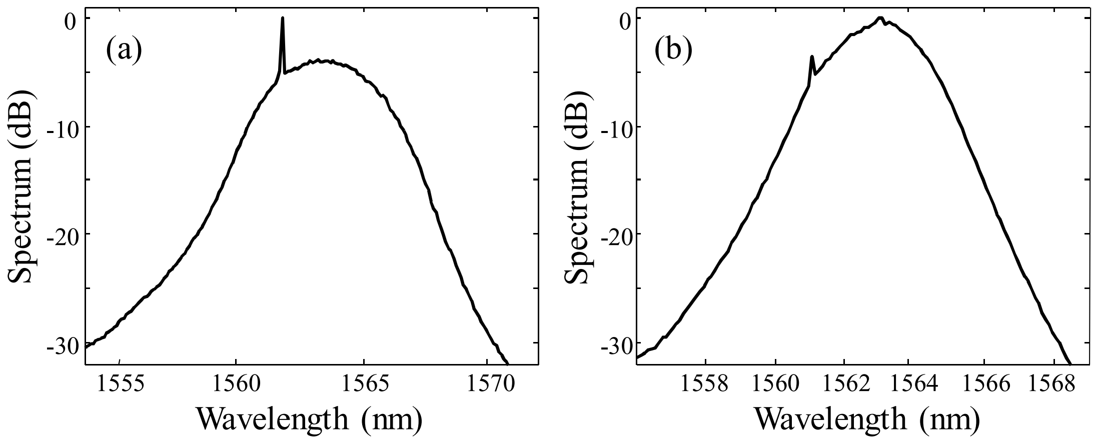

Figure 5. Optical spectra for harmonic mode locking of orders 11 (*a*) and 24 (*b*).

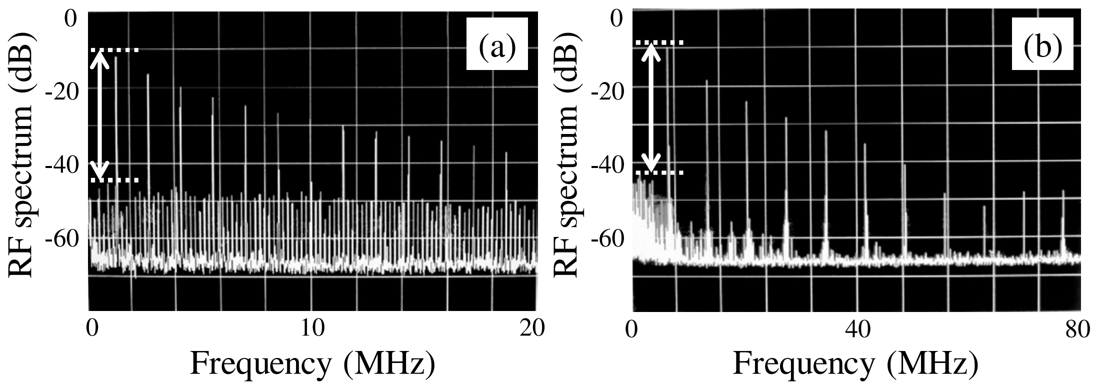

Figure 6. RF spectra for harmonic mode locking regimes of orders 7 (*a*) and 34 (*b*). Double arrows show supermode suppression ratios.

pulses to emerge, which corresponds to harmonic mode locking. Stable harmonic mode locking of order 2, 3,... and up to 48 (repetition rates = 0.4–9.7 MHz) are readily obtained, the order depending on PC adjustments and typically increasing as the pump power is gradually raised up to ~50% of its maximal value. Figure 3 presents a selection of scope traces obtained in those regimes. The pulse durations were found to be in the range 10–60 ns, typically increasing as pump power is raised and decreasing with increasing harmonic order.

Figure 4 shows autocorrelation traces measured for a few harmonic mode locking orders. These results do not differ substantially from the case of fundamental mode locking (figure 2(*c*)), although the peak-to-background ratio is variable. The optical spectra are typically smooth and several nm wide, although they usually present one or a few spikes shifted from the centre (figure 5). These features confirm that the noise-like nature of the pulses is conserved in the harmonic mode locking regime.

As already mentioned, a small wavelength-shifted spike is usually present in the otherwise smooth optical spectrum of the pulses. This spike is associated with a temporally extended background which, although weak, is usually observable on the scope as a tail accompanying the pulses, like in the case of fundamental mode locking. It has been recognized that a CW component slightly shifted from the centre of the pulse spectrum is able to mediate a repulsive interaction between the pulses [21, 22]. This mechanism was proposed to explain the spontaneous synchronization of several hundreds of solitons in fibre lasers [15, 16, 18], although a discrepant result was also published [7]. We believe that a similar mechanism is operating in the present scheme and that such long-range repulsive interactions are at play between the noise-like pulses. This type of interaction is weak, as confirmed by the relatively long time required, after PC adjustments, to get stable harmonic mode locking (from a few seconds to a few minutes [18]). In spite of this, a stable state is eventually reached in which the overall interaction is minimized, which corresponds to the regular arrangement of harmonic mode locking.

Figure 6 shows the radiofrequency (RF) spectrum of the detected pulse trains, measured using an electrical spectrum analyzer, for a few orders of harmonic mode locking. The level of ‘supermodes’ [41] typically lies 30 dB or more below the peak at the repetition frequency, which attests that proper harmonic mode locking is obtained.

When the pump power is increased to values close to the maximum, corresponding to powers of 150–200 mW at output 3, two additional regimes of harmonic mode locking are observed, characterized by very high harmonic orders: 673 and 1270. These regimes are illustrated in figure 7. The pulse trains generated in these regimes display periods of 7.29 and 3.86 ns, which correspond to repetition frequencies of 137 and 259 MHz, respectively. Contrary to the previous harmonic regimes, these two regimes stabilize very quickly after adjusting the PCs. Again, the dual-scale autocorrelation traces and

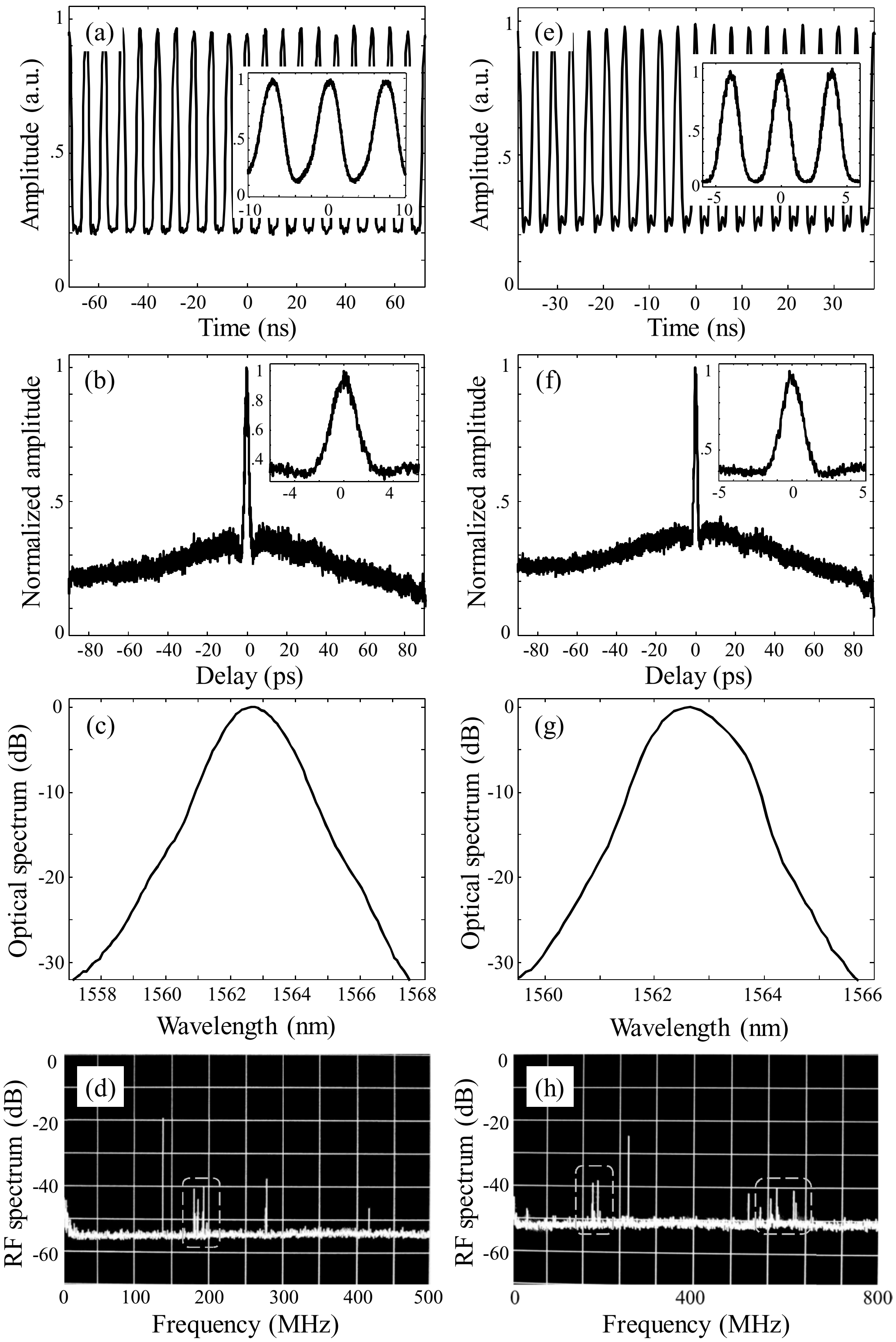

Figure 7. (*a*), (*e*) Scope traces (inset: using a 10 GHz photodetector and sampling scope), (*b*), (*f*) autocorrelation traces (insets: close-ups on central spurs), (*c*), (*g*) optical spectra and (*d*), (*h*) RF spectra for harmonic mode locking regimes of orders 673 (*a*)–(*d*) and 1270 (*e*)–(*h*).

the smooth power spectra leave no doubt on the noise-like nature of the pulses. The optical spectra have a FWHM bandwidth below 2 nm and no CW spike is visible in these cases. Although harmonic orders in excess of 20 000 have already been demonstrated in a Raman fibre laser [33], this is probably the first experimental observation of stable harmonic mode locking (covering both solitons and noise-like pulses) beyond the 1000th order in a rare-earth-doped fibre laser.

It appears clearly on the scope and sampling scope traces of figure 7(*a*), (*e*) that the signal does not reach zero between adjacent pulses, which means that the pulses present some degree of overlap. Hence, a kind of strong direct interaction between overlapping pulses is believed to play an important part in the formation of a stable and regular pattern of so many pulses, in a manner similar to what happens with bound solitons [17]. On the other hand, the onset of high-order harmonic mode locking at only two particular values of the repetition frequency (137 and 259 MHz, within roughly a factor of two) also advocates for a stabilization mechanism through electrostrictive effects. This mechanism involves acoustic waves induced transversally in the fibre by the intense optical field of the pulses: for some particular pulse repetition frequencies, in the 100s of MHz range, that match some harmonic of the acoustic resonance frequency, the acoustic response is enhanced and induces a refractive index perturbation that is strong enough to stabilize the pulse train [15]. It has to be noted however that the observed repetition rates do not exactly match the resonant frequencies predicted in [15]. Electrostrictive effects could also be responsible for the series of spurs observed in the RF spectra (dashed boxes in figure 7(*d*), (*h*)), in the 200 and 600 MHz regions. Although noticeable, these features still lie 15–20 dB below the main peak at the pulse repetition frequency.

4. Conclusions

We studied noise-like pulse generation in a km-long fibre ring laser including a 4 m Er/Yb-doped double-clad fibre and mode-locked through nonlinear polarization evolution. Single noise-like pulse generation (fundamental mode locking) is only observed at moderate pump powers, if power is further increased, the 80 ns pulse breaks into multiple pulses. This demonstrates that, contrary to the common belief, the increase in duration and energy of the noise-like pulse is not boundless. We believe that the long pulse is eventually torn apart by a repulsive interaction between inner pulses in the bunch, which is mediated by a CW component that is observed to accompany the pulses. In spite of this, single pulse energies as high as 120 nJ are obtained at the 10% laser output. Once single pulsing is lost, the multiple pulses usually evolve towards a stable train of equally spaced identical pulses, corresponding to harmonic mode locking. A repulsive force mediated by a CW component is again believed to play an important part, acting in this case between the multiple noise-like pulses and stabilizing the uniform pulse pattern. Through pump power and PC adjustments, harmonic mode locking orders spanning from 2 to 48 are readily obtained. For pump power levels close to the damage-free limit of operation, two additional harmonic mode locking regimes, with orders 673 and 1270, are obtained, corresponding to repetition rates of 137 and 259 MHz, respectively. The overlap between successive pulses suggests direct pulse-to-pulse interactions as a possible mechanism of pulse train stabilization, although electrostrictive effects could also be involved. Besides providing insight into the noise-like pulse dynamics in long fibre lasers, these results could be useful in the quest for higher pulse energies and higher repetition rates that is currently going on in passively mode-locked fibre lasers.

Acknowledgments

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