Appl. Phys. B 81, 507–509 (2005)
DOI: 10.1007/s00340-005-1894-2

Applied Physics B
Lasers and Optics

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2-GHz passive harmonically mode-locked Yb-doped double-clad fiber laser

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Received: 10 November 2004 / Revised version: 4 May 2005
Published online: 28 June 2005 •

ABSTRACT We report passive harmonic mode locking of a high-power Yb-doped double-clad fiber laser. 680-fs, 48-pJ pulses are emitted at the repetition rate of 2.13 GHz, while the free spectral range of the cavity is 23.4 MHz. Results indicate a supermode suppression of more than 25 dB.

PACS 42.55.Wd; 42.65.Re

The generation of ultra-short pulses from fiber lasers near the 1-μm wavelength region has been under high investigation in recent years [1–6]. Since the first demonstration of femtosecond pulses in an Yb-doped fiber laser in 1997 [1], significant progress has been realized. Indeed, it has been demonstrated that pulses with durations as short as 36 fs [5] and energies as high as 5 nJ [4, 6] could be obtained from the stretched-pulse ytterbium-doped fiber systems and, more recently, generation of self-similar high-energy parabolic pulses could be further observed [7]. An intense effort is now directed toward high repetition rate femtosecond laser development. These sources are interesting for many applications including biological imaging, micro-machining and optical parametric oscillator pumping. A technique allowing high repetition rate generation is the so-called harmonic mode locking, where the laser operates at a multiple of its fundamental frequency. This can be realized actively using a modulator driven at a harmonic of the round-trip cavity frequency [8]. It can also be obtained by passive methods like the nonlinear polarization rotation mode-locking technique [9, 10]. It is well known that, for high pumping power, a passively mode-locked fiber laser features multiple pulsing operation, where many pulses are emitted per cavity round trip. This operating regime manifests itself either with the emission of bunches of close pulses, or the emission of largely separated pulses. In this latter case, pulses can rearrange themselves to occupy the cavity uniformly, leading to harmonic mode locking. Passive harmonic mode locking with hundreds of megahertz has been reported in erbium- and ytterbium-doped fiber lasers. Further scaling up of repetition rates to the gigahertz range was achieved with semiconductor saturable absorbers [11, 12]. Recently, we have reported harmonic mode locking with an ytterbium-doped double-clad fiber laser operating at 1050 nm, both in normal and anomalous dispersion regimes [9]. The repetition rate did however never exceed 400 MHz. In the present letter, we report the obtaining of much higher repetition rates exceeding 2 GHz in an additive pulse-mode-locking fiber laser.

The experimental setup has been detailed in [4]. The amplifying medium is an Yb-doped double-clad fiber side pumped using the V-groove technique. Mode locking is achieved through nonlinear polarization rotation [13]. A grating pair is inserted into the cavity to control the total cavity group velocity dispersion (GVD) [2]. For the results reported here, the distance between the gratings has been adjusted to obtain a near-zero total cavity GVD estimated to be about $-0.004\,\mathrm{ps}^2$. We expect this cavity to operate in the anomalous dispersion regime usually named the 'soliton' regime [13, 14]. This was confirmed by the presence of the commonly observed spectral sidebands due to periodic perturbations. The free spectral range of the cavity is 23.4 MHz. As previously mentioned, multiple pulsing can occur in very different forms, particularly in high-power fiber lasers. An important regime is the emission of bound pulses, whose control currently attracts much attention [15, 16]. For example, with our double-clad fiber laser, binding of multiple pulses is often observed spontaneously by slightly reducing the pumping power [16]. When looking for harmonic mode locking, the problem is opposite since pulses must repulse themselves to occupy the cavity uniformly and not bind together. We have now identified a reproducible method that allows us to avoid pulse binding and leads to passive harmonic mode locking at very high repetition rate. Harmonic mode locking is achieved through the following operation mode: the output coupling coefficient is first adjusted to a low value such that the laser works in continuous-wave regime. On increasing the output coupling coefficient, mode locking occurs and single-pulse emission per round trip is observed. On further increasing the output coupling coefficient, this regime of emission is no longer stable [9]: actually, the pulse splits up into a very great number of pulses, which rearrange themselves automatically to occupy the cavity uniformly. In this case where the total cavity dispersion approaches zero-order dispersion, the number of pulses per round trip is very high (91). The repetition rate achieved when harmonic mode locking is obtained is thus just above 2 GHz. This can be viewed on the radio-frequency (RF) spectrum presented in Fig. 1. The peak at 2.13 GHz is

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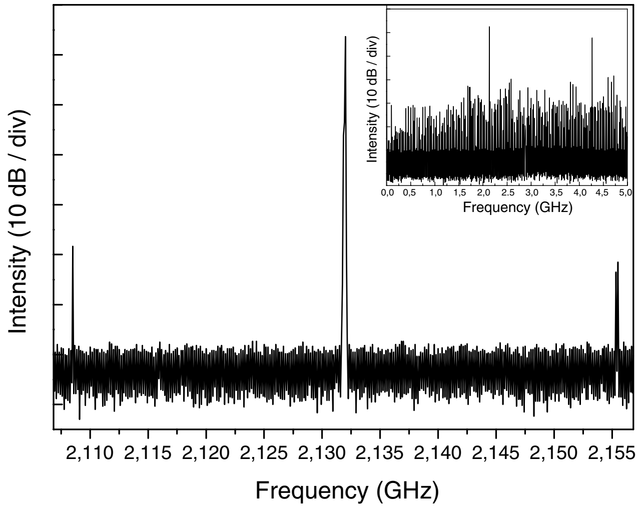

FIGURE 1 RF spectrum in the harmonic mode-locking soliton regime

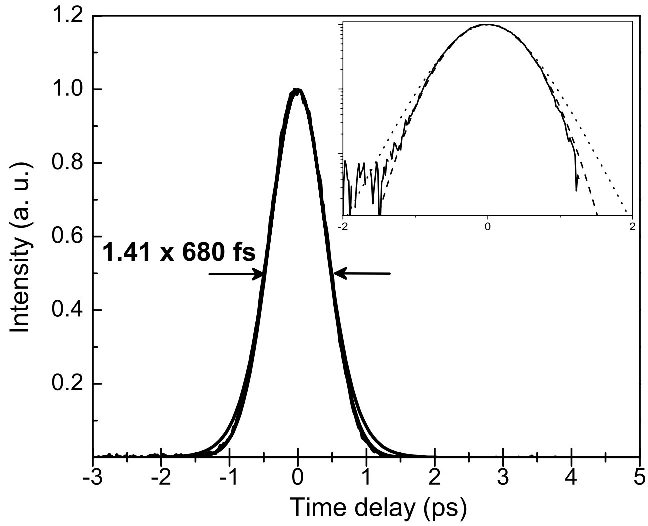

FIGURE 2 Autocorrelation trace. Theoretical fits assuming sech^2 (*dotted line*) and Gaussian (*dashed line*) profiles

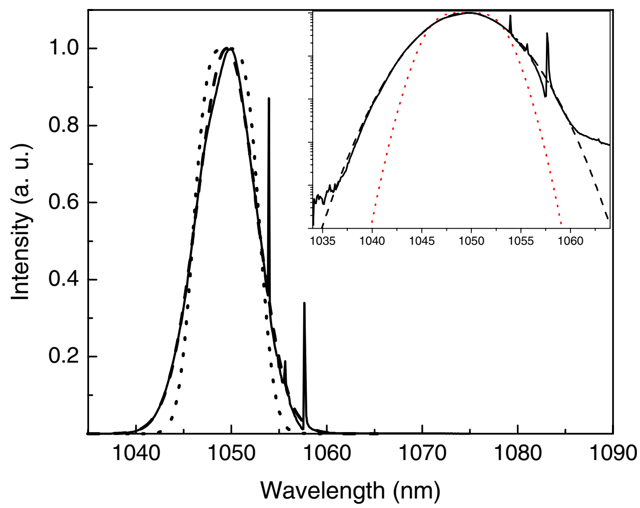

FIGURE 3 Optical spectrum. Theoretical fits assuming sech^2 (*dotted line*) and Gaussian (*dashed line*) profiles

clearly evidenced while suppression of the adjacent modes exceeds 45 dB. Observation of the whole spectrum (inset of Fig. 1) shows that the suppression of all supermodes is higher than 25 dB. As shown in the inset of Fig. 1, the different supermode noise peaks present different amplitudes. This is a consequence of the existence of correlations between pulses inside the cavity [17]. Let us note that supermode suppression has been enhanced recently using a semiconductor saturable absorber in a colliding configuration [18]. Figure 2 shows the autocorrelation trace of the output pulses and the theoretical fits with Gaussian and sech^2 profiles. As shown in the inset of Fig. 2, the best fit is obtained assuming a Gaussian pulse profile with 680 fs full width at half-maximum (FWHM). The corresponding optical spectrum is presented in Fig. 3. The fit of the experimental spectrum confirms a better agreement with the Gaussian profile. The best fit is obtained for a spectral FWHM of 7.1 nm, which corresponds to a time–bandwidth product of 1.3. It is about three times higher than the theoretical limit for Gaussian pulses. This is not a surprise since it is well known in stretched-pulse fiber lasers that the pulse width undergoes large changes along the cavity round trip even for anomalous total GVD [14, 15]. In particular, experimental and theoretical investigations of the pulse dynamics in stretched-pulse fiber lasers have shown that the pulse-stretching factor (defined as the ratio of maximum to minimum pulse widths within the loop) in the anomalous dispersion regime is around 3–4, while it can be more than 20 in the normal dispersion regime [14, 15]. In addition, Tamura et al. have already shown that, in the anomalous dispersion regime, the reduction of the total net GVD results in the deviation of the pulse shape from the sech^2 form to a Gaussian one [14].

The output power is 100 mW for 2-W pump power. The energy per pulse is thus 48 pJ while their peak power is 68 W. This is very important for an Yb-doped fiber laser operating in passive harmonically mode-locked regime at such high repetition rates. The main modification in this configuration compared to previous works [9] is the low total cavity dispersion value that is close to zero. In the case of our laser operating in the anomalous dispersion regime, pulses can be described in terms of 'average solitons' [13]. The soliton area theorem states that the product of the peak amplitude A_0 and the pulse width τ is fixed by the averaged dispersion and nonlinearity. This means that any modification of the total cavity dispersion will induce a modification of the pulse characteristics. The results reported in Ref. [9] were obtained for a negative dispersion value of $-0.1\ \text{ps}^2$ and the pulse width was 1 ps. The total cavity dispersion is presently reduced by more than an order of magnitude to $-0.004\ \text{ps}^2$, while the pulse width is modified by only 30% (to 680 fs). This can explain to a certain extent the 91 pulses per round trip obtained in the present configuration. Note, however, that a real quantitative estimation of the number of pulses would require a complete numerical analysis of pulse splitting that takes into account the different elements of our laser cavity. Let us note for example that we could obtain passive harmonic mode locking at higher repetition rates (around 3.51 GHz) for the same cavity dispersion but with another orientation of the polarization controllers. However, suppression of supermodes was not satisfactory (lower than 15 dB) and results are not reported here.

In conclusion, we have reported for the first time to our best knowledge passive harmonic mode locking of a high-power Yb-doped double-clad fiber laser operating near 1050 nm with repetition rate above 2 GHz. 680-fs, 48-pJ pulses are emitted.

The authors wish to thank Stephane Le Masson and Jean-Marie Debraux from France Telecom R/D Lannion for lending them a HP8562E RF spectrum analyzer.

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