Optics Communications 283 (2010) 113–117

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

High frequency pulse trains from a self-starting additive pulse mode-locked all-fiber laser

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ARTICLE INFO

Article history:
Received 21 April 2009
Received in revised form 21 August 2009
Accepted 24 September 2009

PACS:
42.55.Wd
42.55.Xi
42.60.Fc
42.81.Wg

Keywords:
Fiber lasers
Mode-locking
Bragg gratings

ABSTRACT

In this paper, a coupled-cavity Er-doped fiber laser is experimentally developed and analyzed. The proposed scheme has the advantage of an all-fiber configuration. Two similar fiber Bragg gratings are employed as reflective components of the main cavity containing the gain medium. The second cavity is generated, in one side, by the reflective flat end of a standard fiber optic pigtail of variable length and, in the other, by one of the Bragg gratings belonging to the main cavity. Depending on the ratio between the lengths of both cavities, trains of stable and short pulses were obtained with a repetition frequency larger than the frequency of the main cavity. The repetition rate of the pulse trains experimentally obtained was as high as 780 MHz (15 times the main cavity frequency) and the pulse width was ~110 ps. Prediction of the possible repetition rates for each cavities lengths ratio and the upgrading possibilities of this laser system are analyzed.

1. Introduction

Mode-locked fiber lasers have become an important optical source for many applications and their potential is increasing. These lasers have received much attention due to their low cost, low power consumption, long term robustness, and ease of long distance transmission (through single-mode fiber). Applications range from micro-machining metals to very precise frequency measurements. Related to the first application, subpicosecond pulse trains of 40 kW peak power with an average output power of near 1 W have been achieved with double clad fiber lasers [1]. Based on the many proposals for new technologies that utilize very short pulses, it is clear that these systems are invaluable tools for future developments [2–4].

Because its intrinsic stability, fiber laser are a real alternative to solid-state lasers to generate very short pulses at infrared wavelengths. Conventional designs for producing short pulses are the use of active or passive elements such as electro- or acousto-optic modulator, or a saturable absorber medium (SESAM) [5,6]. Active techniques can provide pulses with high repetition rate and ps temporal widths. Under this regime, pulse widths are much longer than those obtained by passive mode-locking.

A promising way to create such type of optical sources is related to harmonic passive mode locking of fiber lasers with non-linear techniques. Through Additive Pulse Mode-Locking (APM), Non-linear Optical Loop Mirror (NOLM) or Non-linear Polarization Rotation (NPR), it is possible to produce very short pulses without the use of active optical devices [7,8]. Various synchronizing schemes have also been demonstrated on passive harmonic mode-locked fiber lasers in order to achieve high repetition rates with very short pulses. Recently, a passive harmonic mode-locked femtosecond Yb-doped fiber laser produced 380-fs pulses at 605 MHz repetition rate employing a semiconductor saturable absorber in a colliding-pulse configuration [9–11].

Although, molecular transitions in dyes were the first method discovered to passively mode-lock a laser, this method is by no means the only way. In 1984 Mollenauer and Stolen demonstrated that the saturable absorber effect can be simulated by optical phenomenon [12]. This approach has several advantages including the fact that the recovery time of an optically based saturable absorber can be extremely fast (few optical cycles) since it does not depend on an atomic/molecular resonance. In particular, APM (in coupled-cavity bulk or fiber optic systems) have been widely used with many types of laser materials including Nd:YAG, color-center,

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0030-4018/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2009.09.064

Ti:sapphire, and Er-doped fiber lasers to obtain ultrashort mode-locked pulses. APM is a non-linear technique based on the interference between two overlapping pulses coming from two coupled cavities on a central mirror acting as beam-splitter. Usually one of the cavities contains the laser gain medium and the other a non-linear medium, where the beam acquires a power-dependent phase modulation, which finally leads to pulse compression [13–16].

Glas et al. [17] have investigated the mode locking of a Nd doped fiber laser with a linear external cavity and obtained high repetition rates (up to 10 GHz) by employing bulk elements in the experimental setup, what has important drawbacks as reduced mechanical stability and high insertion losses. Because of the interferometric nature of this mode-locking technique, a critical adjustment for matching the optical lengths of the two cavities is typically required in bulk schemes. A larger cavity mismatch can be tolerated in fiber optic based systems [18]. This technique was successfully proved with other configurations of all-fiber laser systems, including "figure eight" and unidirectional ring cavity configurations [5,6].

Recently, a self-controlled short pulse laser was obtained from a CW pumped ytterbium fiber laser employing two coupled Fabry–Perot cavities without any devices for polarization control and birefringence compensation [19]. The reflectivity of the three fiber Bragg gratings used as cavity mirrors were 67%, 8.2% and 42.8%. When the main cavity length was an integer multiple of the other, self-pulse operation at 1033.6 nm was achieved. For equal cavities lengths, the repetition rate was about 13.9 MHz (the main cavity frequency), the average output power was 0.9 mW and the pulse duration was 800 ps. When the total length of laser cavity was about 11 times longer than the auxiliary cavity length, the repetition rate of pulse trains was 77 MHz, but the pulse duration was about 1.2 ns.

Under a similar approach, in this paper we analyze a very simple scheme for a coupled-cavity APM erbium-doped fiber laser, and present a general consideration for obtaining high repetition rates, that is not only the case where the cavities lengths ratio is an integer number. The main cavity, containing the gain medium, employed two similar fiber Bragg gratings as reflective elements. The additional resonator was formed by splicing a pigtail, of variable length conventional single-mode fiber, to the end of one of the mentioned gratings, and employing the Fresnel reflection at the other end of the pigtail. Depending on the cavities lengths ratio, stable short pulses trains with a pulse repetition larger than the main cavity frequency were obtained. The repetition rate of the pulsed laser experimentally obtained was as high as 15 times the main cavity frequency. We also found that the pulse width varies inversely with the pulse repetition rate. The mentioned scheme has many advantages since it is simple, compact and robust, insensitive to environmental instabilities, and it has no need of any polarization controller device inside the cavity.

2. Experimental setup

The experimental set-up is illustrated in Fig. 1. Two uniform fiber Bragg gratings (FBG1 and FBG2) centered approximately on 1553.4 nm were employed as the main cavity mirrors. These gratings have similar reflection coefficients and spectral bandwidths (∼0.75 and ∼0.2 nm at 3 dB, respectively). A single-mode erbium-doped fiber of 1.286 m long, with numerical aperture NA = 0.22, mode field diameter MFD = 6.8 μm and 125 μm cladding diameter, was used as gain media. Roughly 0.35 m of single-mode standard fiber (SM-SF) was maintained around the gratings for splicing purposes in order to complete the 1.976 m length (L_c) of the main cavity. The auxiliary cavity contains a pigtail of SM-SF spliced to FBG2. The free end of the pigtail was cut perpendicular to the fiber axis producing a Fresnel reflection of around 4%. The length L_a of the auxiliary cavity was appropriately selected, mostly shorter than the main cavity length. The gain fiber (erbium-doped fiber) had a positive group velocity dispersion $D_M \sim 0.01\ ps^2/m$, while the dispersion of the standard single-mode optical fiber was $D_S \sim -0.02\ ps^2/m$. The net total cumulative dispersion of the main cavity was approximately $-0.0012\ ps^2$. Dispersion of the auxiliary cavity depends of the pigtail length and it can be calculated as $D_A = D_S \times L_A$.

The APM fiber laser was pumped by a semiconductor laser diode emitting at 976 nm (maximum optical power 280 mW). A 980/1550 nm wavelength division multiplexer (WDM) was employed to couple the pump beam and to extract the generated fiber laser beam. Temporal distributions of light were obtained by employing a LeCroy WaveExpert 100H sampling oscilloscope with a 10 GHz optical module. Spectral characteristics of the sources were obtained by using a monochromator of 0.5 m focal distance, and an electrical spectrum analyzer of 26.5 GHz bandwidth was also employed in order to perform a frequency-domain analysis of electrical signals obtained by a 3 GHz optical detector.

3. Results and discussion

As was previously mentioned, in our experiment the main cavity length was $L_c = 1.976$ m, with a corresponding repetition rate $f_c \cong 52$ MHz. We employed different auxiliary cavity lengths (L_a) in order to analyze the behavior of the APM fiber laser. We define the cavities lengths ratio k as:

$$\frac{L_c}{L_a} = \frac{N}{M} = k \qquad (1)$$

where N and M are positive integers.

Now we will consider the case where L_a is shorter than L_c ($N > M$) and satisfies Eq. (1). Under these conditions, it is possible to obtain stable short pulses trains with a repetition frequency several times larger than the main cavity frequency. Under stable mode-locking regime, there will be N pulses circulating in the main laser cavity and M pulses circulating in the auxiliary cavity.

Fig. 2a shows the laser output obtained for $L_a = 1.1856$ m ($k = 5/3$) with a repetition frequency of 260 MHz (five times the main cavity frequency f_c) and a pulse width of ∼340 ps. Fig. 2b shows the radio-frequency analysis of the fiber laser emission, where this component is clearly observed as well as its harmonics. Variations lower than 2 MHz were observed in the fundamental frequency. When we avoided back-reflection from the pigtail end by immersing it in alcohol, no coupling of the cavities were obtained and the laser emission frequency was $f_c = 52$ MHz, as is shown in Fig. 3. In

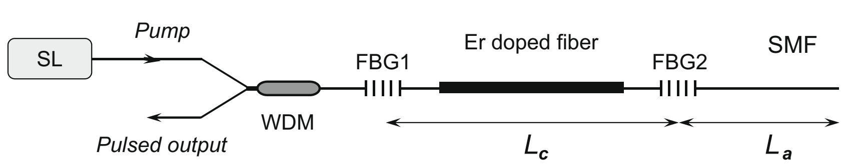

Fig. 1. Experimental set-up. WDM, wavelength division multiplexer 980/1550 nm; FBG, fiber Bragg grating; SL, semiconductor laser; SMF, standard single-mode fiber.