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Passively mode-locked fiber laser with kilohertz magnitude repetition rate and tunable pulse width ☆

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ABSTRACT

We propose and demonstrate a strictly all-fiber, erbium doped passively mode-locked figure-eight fiber laser (EDFL). In the laser structure, we use the nonlinear optical loop mirror combination with a variable ratio coupler (VRC-NOLM) to achieve mode-locking. Due to the nonlinear effect in the nonlinear fiber, stable self-starting pulse is obtained. In order to reduce the repetition of pulse, a segment of nonlinear fiber (NLF) has been incorporated into the VRC-NOLM. The laser generates stable rectangular pulses with a low repetition rate (kilohertz magnitude) by extending the length of the cavity. Furthermore, the output pulse width of the fiber laser can be varied by changing the coupler ratio of the variable ratio coupler.

1. Introduction

In recent years, there has been a great growth in the research of optical pulse source. This kind of source could be used in many applications. When the source is used in ultrafast optical sampling [1], optical continuum generation [2], or high-speed optical communication [3], the repetition rate of the pulse should be high [4]. However, scientists are interested in the low repetition rate optical pulse train for some other applications such as bio-medical science diagnostics, micromachining, optical probing, ranging lidar systems, and chirped-pulse-amplification systems [5]. It can be explained that the reduction of repetition rate may reduce thermal parasitics, sample damage problems, and recovery time artifacts [6].

In the past few years, many efforts have been made to reduce the repetition rate. Tian demonstrated one of this kind fiber lasers with 397 kHz fundamental repetition rate and 910 ps pulse width using a semiconductor saturable absorber (SESAM) [7]. Sayinc reported on a passively mode-locked ytterbium-doped fiber laser with a repetition rate of 1.8 MHz [8]. As we known, they are not all-optical fiber resonator configurations. Usually, extended cavity length is the most effective method to reduce the repetition rate [9]. In 1989, mode-locking in a long cavity laser was demonstrated by Tarroja et al. [10]. They increased the cavity length up to 66 m for Fabry-Perot xenon lasers [10]. In 1990, Cho reported on a low repetition Kerr-lens mode-locked Ti:Al_2O_3 laser including a multiple-pass cavity (MPC). They obtained pulse with 0.7 mW of power at a repetition rate of 15 MHz [6]. As the laser is not an all-fiber laser, it requires careful design and cannot be effectively coupled to the fiber. Kobtsev reports on a passively mode-locked fiber laser with optical length of the resonant cavity amounting to 3.8 km. Then the pulse with low repetition rate (77 kHz) and duration of 3 ns is obtained [11]. However, the shape of the pulse is not rectangular and the width of pulse is difficult to adjust. In the present work, we propose and demonstrate experimentally a stable passively mode-locked fiber laser utilizing a VRC-NOLM to produce nonlinear phase shift for the first time. Here, the VRC-NOLM played the role as a saturable absorber. The VRC-NOLM consists of a NOLM with a 50/50 coupler, a variable ratio coupler and 1 km nonlinear fiber (NLF). This configuration can generate the rectangular pulse with low repetition rate. Meanwhile, it is easy to tune the width of the pulse by adjusting the coupler ratio of the variable ratio coupler.

2. System configuration and principle

The structure of a VRC-NOLM is shown in Fig. 1. Input optical field is split into two counter propagating waves by the 50:50 optical coupler. The power of the optical beam which propagates counter clockwise is reduced by the variable ratio coupler before it propagates through the whole fiber loop. At the same time, another beam propagates through the whole fiber loop without any loss. The nonlinear phase shift that is produced during

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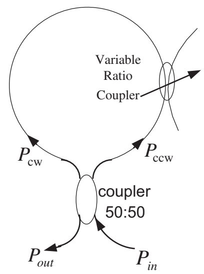

Fig. 1. Configure of VRC-NOLM.

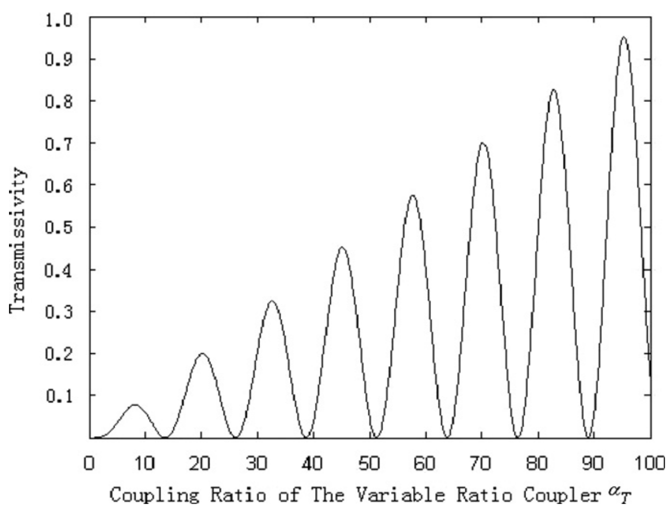

Fig. 2. Transmissivity versus coupler ratio of VRC-NOLM.

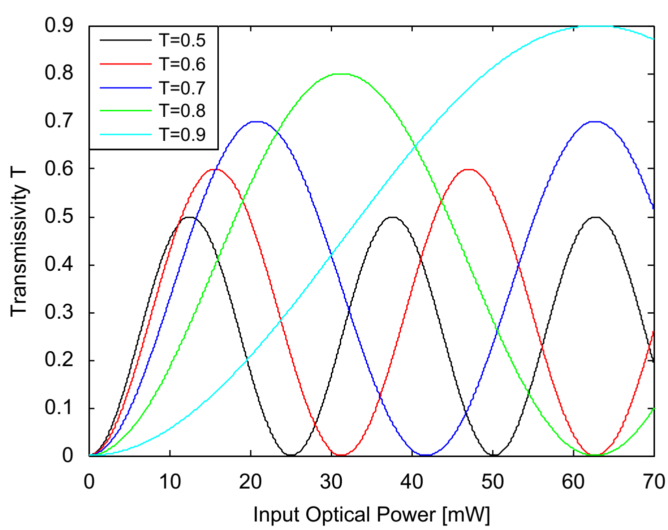

Fig. 3. Switching characteristics of VRC-NOLM.

transmission can be expressed as [12,13]

$$\phi_{NL} = \frac{k_0 n_2 L P_0}{A_{eff}} \tag{1}$$

Where P_0 is the input optical power, L the length of the whole loop, k_0 the free space propagation constant of light, n_2 the nonlinear refractive index coefficient, A_{eff} the effective area. Based on the above equation, the difference power will create difference phase shift. And the accurate difference can be written as [12,14]

$$\delta\phi = \frac{(1-\alpha_T)k_0 n_2 L P_0}{2A_{eff}} \tag{2}$$

where α_T is the coupling ratio of the variable ratio coupler. Then, the transmissivity of this VRC-NOLM can be written as [12,14]

$$T = \frac{\alpha_T}{2}\left\{1-\cos\left[\frac{(1-\alpha_T)\phi_{NL}}{2}\right]\right\} \tag{3}$$

When $(1-\alpha_T)\phi_{NL}/2$ is $(2n+1)\pi$, T is maximum. When $(1-\alpha_T)\phi_{NL}/2$ is $2n\pi$, T is minimum. Fig. 2 shows the calculated switching characteristics of a VRC-NOLM when input power is constant and $k_0 n_2 L/A_{eff} = 1[1/W]$. It can be found from Fig. 2 that to improve the transmissivity we should increase the value of α_T. Fig. 3 shows the relationship between transmissivity and input

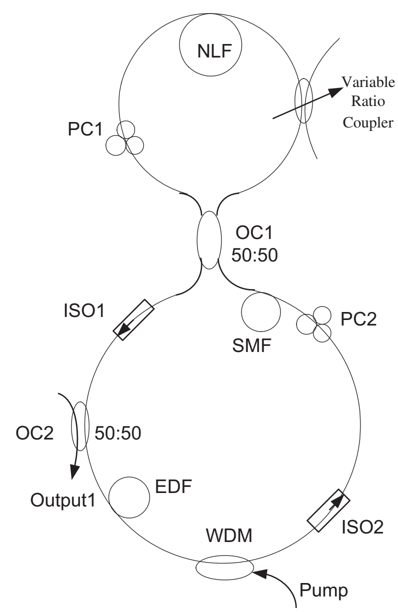

Fig. 4. Experimental setup of the proposed passively mode-locked fiber laser. NLF: nonlinear fiber; PC1, PC2: polarization controller, SMF: single mode fiber. EDF: Er-doped fiber; ISO1, ISO2: isolator; OC1, OC2: optical coupler.

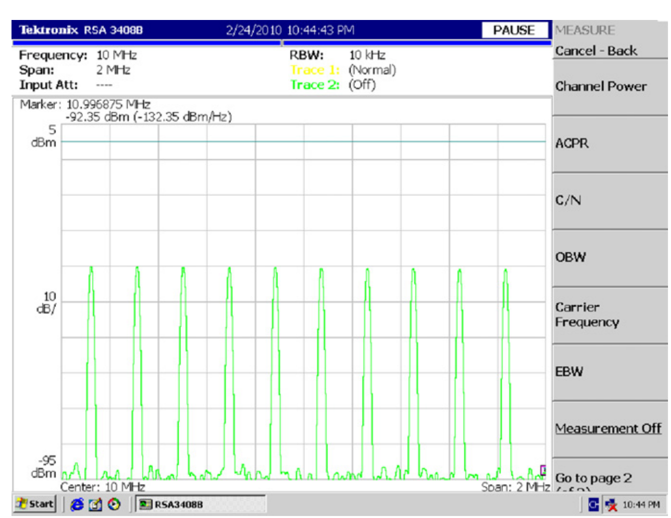

Fig. 5. RF spectrum of the mode-locked pulses.