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Tunable 12 × 10 GHz mode-locked semiconductor fiber laser incorporating a Mach-Zehnder interferometer filter

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ABSTRACT

A stable multiwavelength mode-locked semiconductor fiber ring laser incorporating a fiber Mach-Zehnder interferometer (MZI) filter was proposed and experimentally demonstrated. A semiconductor optical amplifier (SOA) serves as an optically controlled mode-locking element due to gain exhaustion caused by external injected optical pulses. Another SOA severs as a constant-gain medium. A fiber MZI filter with a temperature control is incorporated into the fiber ring cavity to acquire a stable and tunable multiwavelength oscillation. Twelve wavelengths are synchronously mode-locked at 10 GHz, pulse width of mode-locked pulse are about 30 ps. Proposed multiwavelength mode-locked semiconductor fiber ring laser has some distinct advantages, such as simple and compact structure, easy integration, convenient tuning, good stability, potential high repetition rate operating, which has potential application in the future WDM communication system.

1. Introduction

The rapid growth in bandwidth and speed demand from optical fiber network systems has intensified research for high repetition rate multiwavelength laser sources. Actively mode-locked fiber ring lasers can generate multiwavelength short pulses with high repetition rate, are a potential candidate source in the future optical communication system. A large number of approaches have been taken to increase the product by channel number and repetition rate of multiwavelength mode-locked output. A multiwavelength fiber ring laser source incorporating a $LiNbO_3$ Mach-Zehnder (MZ) intensity modulator (IM), semiconductor optical amplifier (SOA) and Fabry-Pérot (FP) filter was demonstrated, which generated 10 synchronized wavelengths and each mode-locked at 10 GHz pulses [1]. A multiwavelength fiber ring laser source using cross gain modulation (XGM) effect of SOA and rational harmonic mode locking technique was demonstrated, which generated pulse train with 10 wavelength channels, simultaneously mode-locked and synchronized at 30 GHz [2]. A 16-wavelength polarization-maintaining fiber laser including a 16-channel 100-GHz-spaced arrayed waveguide grating (AWG), actively mode-locked at 10 GHz, was proposed and demonstrated [3]. Simultaneous mode locking of more than 24 wavelengths at 3 GHz in an actively mode-locked erbium-doped fiber laser with a frequency shifter, an all-fiber 50 GHz periodic filter and an amplitude modulator operating at room temperature was demonstrated [4]. A wavelength-tunable 4 × 10 GHz optically mode-locked semiconductor fiber ring laser incorporating a SOA used as a gain medium and optically controlled modelocking element and four superimposed linearly chirped fiber Bragg gratings (FBGs) was demonstrated [5]. A 46-channel multiwavelength mode-locked erbium-doped fiber laser at 2.5 GHz with 25 GHz channel spacing and that output wavelength was tunable from 1545 to 1558 nm by exploiting four-wave mixing in a length of highly nonlinear fiber was reported [6]. A Lyot filter based actively mode-locked multiwavelength fiber ring laser with a hybrid gain medium consisted of an SOA and Erbium-doped fiber amplifier (EDFA), simultaneous mode locking of up to 8 wavelength channels at 10 GHz using a $LiNbO_3$ MZ-IM was proposed and demonstrated [7]. An active multiwavelength mode-locked fiber ring laser incorporating a length of dispersion-compensation fiber (DCF) by exploiting XGM in a reflective SOA was demonstrated, simultaneous tunable triple-wavelength 10 GHz mode-locking was implemented [8]. Recently, a multirate and dual-wavelength mode-locked semiconductor fiber laser that incorporates a multichannel nonlinear optical loop mirror (NOLM) functioning as a multichannel all-optical modulator was demonstrated [9]. More recently, a tunable L-band 16 × 200 GHz multiwavelength fiber laser using cascaded SOAs and optical slicer was proposed and demonstrated [10].

The need to extend the bandwidth of dense WDM systems has resulted in research of new transmission waveband, such as longer waveband (L-band, 1570–1610 nm) within the low-attenuation window, which effectively doubles the potential bandwidth. To increase the product of channel number and repetition rate of multiwavelength mode-locked output, two issues must be carefully addressed. Firstly, to acquire high repetition rate mode-locked

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pulse output, a high-speed IM is often employed. However, IM need to be driven by radio frequency (RF) signal, but, it is very difficult and costly to generate RF signal higher than 10 GHz. Moreover, $LiNbO_3$ modulator has strong polarization dependence, which is disadvantageous for achieving stabile multiwavelength operation. Since gain of SOA is exhausted by external injected optical pulses, it may serve as an optically controlled mode-locking element. Ultra-short optical pulses with high repetition rate can be readily obtained using this technique. Secondly, to acquire more lasing wavelength, employed gain medium is required to be able to provide a wideband high gain. EDFA can provide high flat gain with a bandwidth of more than 40 nm, which is very important for generation of multiwavelength mode-locked pulses. But, since EDFA has homogeneous gain character, special measures must be adopted to mitigate mode competition of multiwavelength operation, which results in system complication and cost increase [11]. In addition, fiber Raman amplifier (FRA) is also often employed in multiwavelength laser, which has an extremely large gain bandwidth spanning several wavebands [12]. However, efficiency of FRA is relative low compared to EDFA, and high-power semiconductor laser diodes fit for various wavebands as pump source still needs to be developed. Since SOA has primarily inhomogeneous broadening property, SOA-based multiwavelength fiber lasers can stably operating without any assisting measures; it is therefore a very nice choice [10].

In this paper, we propose and demonstrate a stable multi-wavelength mode-locked semiconductor fiber ring laser incorporating a fiber Mach-Zehnder interferometer (MZI) filter. An SOA serves as an optically controlled mode-locking element due to gain exhaustion caused by external injected optical signal. Another SOA serves as a constant-gain medium. A fiber MZI filter with temperature control is incorporated into the fiber ring cavity to acquire a stable and tunable multiwavelength oscillation. Proposed multi-wavelength mode-locked semiconductor fiber ring laser has some distinct advantages, such as simple and compact structure, easy integration, convenient tuning, good stability, potential high repetition rate operating, which has potential application in the future WDM communication system.

2. Experimental setup

Schematic diagram of proposed multiwavelength mode-locked semiconductor fiber ring laser is depicted in Fig. 1. The fiber ring cavity is formed by two SOAs, a fiber MZI filter, an optical circulator (Cir), an optical isolator (ISO), two polarization controllers (PCs), a tunable optical delay line (TODL) and a 10:90 optical coupler (OC). When a 10 GHz external optical pulse train located at 1549 nm is injected into the ring cavity via a variable optical attenuator (VOA)

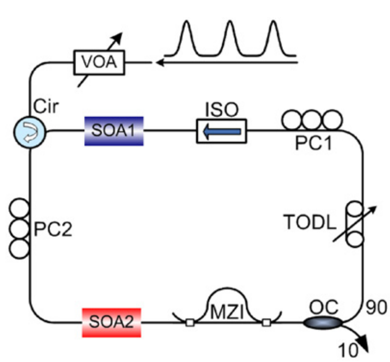

Fig. 1. Experimental setup. VOA: variable optical attenuator; Cir: circulator; SOA: semiconductor optical amplifier; MZI: Mach-Zehnder interferometer; ISO: isolator; PC: polarization controller; TODL: tunable optical delay line; OC: optical coupler.

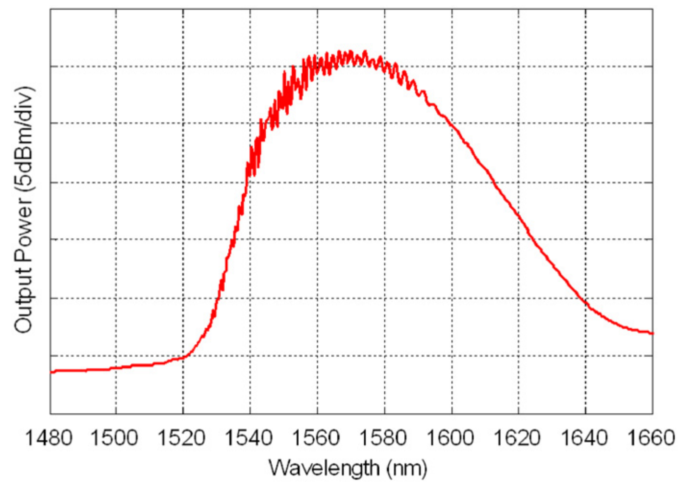

Fig. 2. Measured gain spectrum of the SOA2.

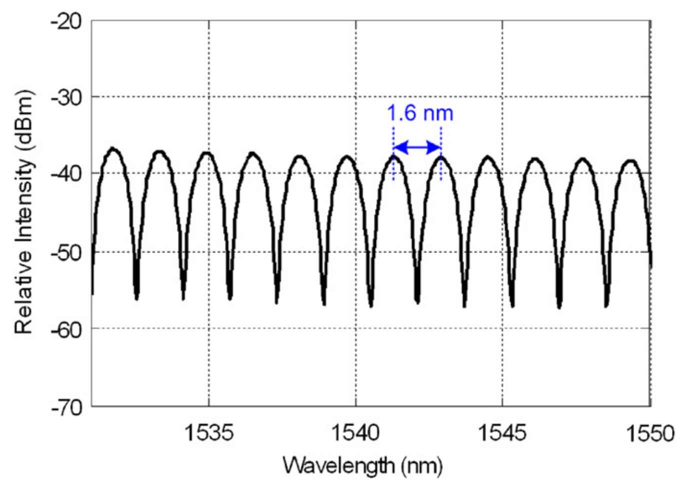

Fig. 3. Measured transmission spectrum of the fiber MZI filter.

and a Cir, the amplified spontaneous emission (ASE) fields of the SOAs are modulated in the SOA1 due to SOA-XGM effect. It induces gain-depletion (or loss) modulation as well as mode locking of the SOA fiber laser at various wavelengths. The injection rate is therefore sufficiently high to saturate the SOA and to deplete its excited-state electrons. In this case the SOA1 is employed as a loss modulator for a SOA fiber laser [13,14]. The Cir and the ISO allow the light to propagate unidirectional in the ring cavity and ensure ASE fields being modulated only in the SOA1 by the injected external optical signal. The SOA1 (by CIP) driven by a 250 mA current can provide small signal gain of about 24 dB at 1554 nm. The SOA2 (by Kamelian) serves as gain medium and can provide small signal gain of about 26 dB at 1570 nm when it is driven by a 250 mA current. Measured gain spectrum of the SOA2 is depicted in Fig. 2. The two SOAs have a low polarization sensitivity of about 0.5 dB. A fiber MZI with temperature controller serves as a comb filter in multiwavelength lasing. To realize stable and tunable multiwavelength operation, temperature control to the fiber MZI is necessary. The measured transmission feature of the fiber MZI filter is shown in Fig. 3. Temperature of the MZI is maintained at 21 °C, and transmission spectrum of the fiber MZI filter is with a free spectrum range (FSR) of 1.6 nm (~200 GHz) and an extinction ratio (ER) of 19.8 dB. The two PCs are incorporated into the ring cavity to adjust polarization state of the light for optimizing operation. TODL