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Wavelength-stepped, actively mode-locked fiber laser based on wavelength-division-multiplexed optical delay lines

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A B S T R A C T

We propose a new scheme for an actively mode-locked wavelength-swept fiber laser that produces a train of discretely wavelength-stepped pulses from a short fiber cavity. Pulses with different wavelengths are split and combined by standard wavelength division multiplexers with fiber delay lines. As a proof of concept, we demonstrate a laser using an erbium doped fiber amplifier and commercially available wavelength-division multiplexers with wavelength spacing of 0.8 nm. The results show simultaneous mode-locking at three different wavelengths. Laser output parameters in time domain, optical and radio frequency spectral domain, and the noise characteristics are presented. Suggestions for the improved design are discussed.

1. Introduction

Lasers with time varying wavelength output are of great interest for their applications to optical imaging [1], testing for optical components [2], spectroscopy [3] and sensing [4,5]. One version of such lasers produces discrete wavelength steps that can provide simpler data acquisition electronics for high speed applications [5,6] compared to the continuously wavelength swept counterparts [7,8]. For the wavelength stepped lasers in [5] and [6], the laser cavities were very long (a few to tens of km) to accommodate long optical pulse duration or large dispersion requirement. The long fiber length requires careful management of dispersion in the fiber.

We note that a wavelength stepped laser with much shorter cavity length is possible by adopting short mode-locked pulses and the temporal–spectral-multiplexing (TSM) as originally demonstrated in [9]. In the report, two mode-locked pulses with closely spaced wavelength steps (0.7 nm) were produced using erbium doped fiber (EDF) as gain medium and fiber Bragg gratings (FBG) as digitized dispersion elements. The two pulses with different wavelengths were enforced to go through the amplifier at different times. This is to reduce the gain competition normally expected in a homogeneously broadened gain medium such as EDF in room temperature [9–11]. The separated pulses were recombined at the location of an intensity modulator used for mode locking. The separation and recombination of the optical pulses in time domain was realized by a matching pair of FBG's. Simultaneous lasing of two wavelengths was observed without significant gain competition. This result was unexpected since the temporal and spectral separation of the two pulses were much shorter than the gain recovery time and homogeneous linewidth of EDF, respectively. Also the potential impact of the gain competition on the noise characteristics of the laser output has not been addressed that would be critical for the application of such wavelength stepped lasers. Very recently, another mode-locked laser configuration with short cavity length was reported using a semiconductor optical amplifier and a very long chirped fiber Bragg grating [12].

In this paper we propose and demonstrate a novel configuration for the wavelength stepped mode-locked laser with short cavity length based on standard wavelength division multiplexers (WDM) used for communications. This approach provides additional advantages of individual control of optical parameters for each wavelength component such as polarization, insertion loss and dispersion. If needed, individual control of the timing, intensity and polarization of each pulses becomes possible. Since WDM's with a large channel number are commercially available in the optical communication wavelength bands (1300 to 1600 nm), this approach can potentially be used for various applications requiring few to 100's of wavelength channels. The cavity lengths using this approach can be less than several tens of meters. For the experimental demonstration of the operating principle of the proposed configuration, we built a wavelength stepped fiber laser with an EDF and WDM's. Simultaneous lasing of three wavelengths was observed. We also measured the noise characteristics of the different wavelength

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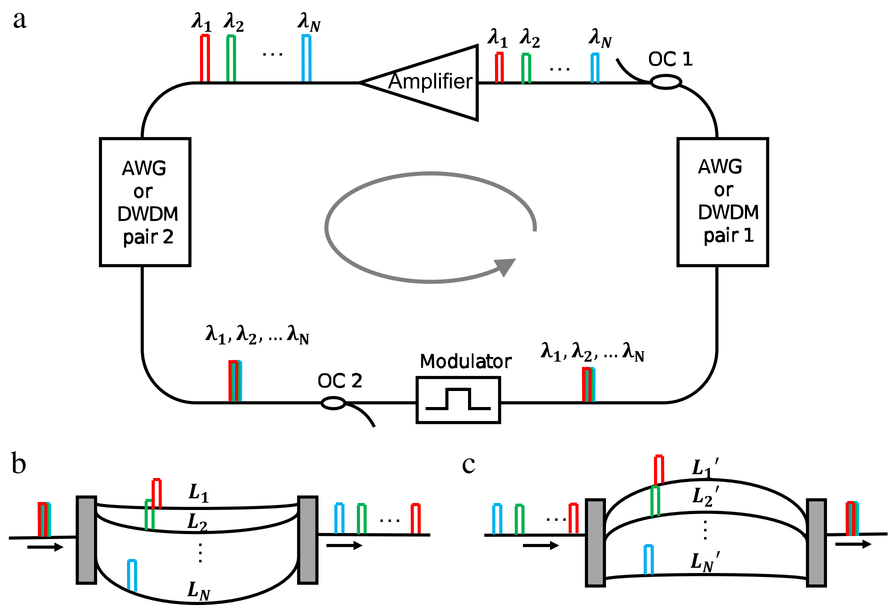

Fig. 1. Schematic diagrams of (a) operation principle of the laser, (b) fiber delay lines within the first pair of DWDM's (or arrayed waveguide gratings (AWG's)), (c) fiber delay lines within the second pair of DWDM's (AWG's). L_i (L_i') (i = 1, 2, …, N): the length of fiber delay lines inside the first (second) pair of DWDM's (AWG's) at wavelength λ_i. The sum of L_i and L_i' should be the same for all the wavelengths so that they experience the same cavity length.

components that have not been previously addressed. Based on the findings we suggest future improvements for practical use of such lasers.

2. Operating principle

Fig. 1(a) shows the functional schematic of the proposed construction of the wavelength stepped mode-locked laser. The fiber laser cavity consists of an optical amplifier, two pairs of dense wavelength division multiplexers (DWDM's), an intensity modulator and output couplers. The lasing wavelengths are selected by the N-channel DWDM's. Each DWDM pair splits signals at different wavelengths into N separate fibers having different lengths and recombines them into a single fiber as shown in Fig. 1(b) and (c). The delay between adjacent wavelengths in the DWDM pair is set to be larger than the pulse duration. A single pulse input containing different wavelengths converts to fully separated pulse train after passing the DWDM pair 1 (Fig. 1(b)). By making the delay difference in the first DWDM pair to be accurately compensated by the second pair (Fig. 1(c)), the cavity length for all wavelength components can be made identical. In this way, the pulses with different wavelengths can pass through the amplitude modulator at the same time while they pass through the amplifier at different times as shown in Fig. 1(a). This arrangement reduces cross gain saturation between closely spaced wavelengths in the amplifier. The output from output coupler 1 (OC1) is wavelength stepped pulse train while the output from OC2 is a single pulse with multiple wavelength components. In this laser, the amplitude modulation period coincides with the cavity roundtrip time and the output pulses are mode-locked.

3. Experimental setup

The experimental setup is shown in Fig. 2. For the optical amplifier, a 3 m-long EDF (Fibercore M-12) pumped by a laser diode at 980 nm was used. The pump power coupled to EDF was fixed at 208 mW. Although an amplifier with fast enough gain recovery such as semiconductor optical amplifier would provide better suppression of gain competition, we used an EDF amplifier currently available in our laboratory. Also the use of an EDF amplifier allows the analysis of the effect of gain competition and relaxation oscillation not addressed in earlier work [9] as described below. Four commercially available DWDM's were used to construct two matched DWDM pairs with carefully controlled delays

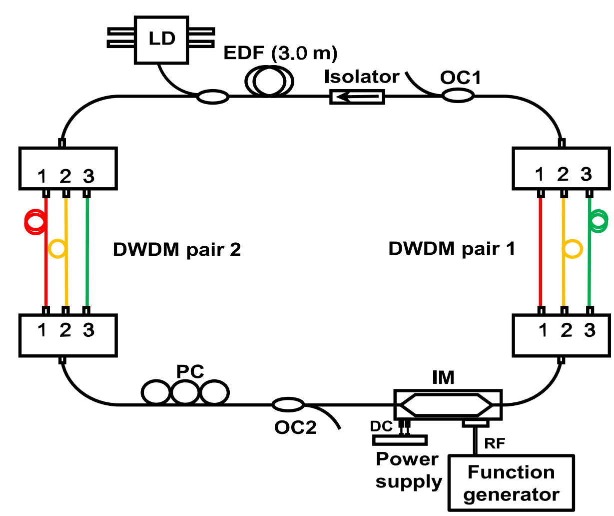

Fig. 2. Schematic of the experimental setup. LD: laser diode, DWDM: dense wavelength division multiplexer, PC: polarization controller, OC: output coupler, IM: intensity modulator.

between the wavelength channels. Three wavelength channels of the DWDM with 0.8 nm spacing at the center wavelengths of 1554.13 nm (channel 1), 1554.94 nm (channel 2) and 1555.75 nm (channel 3) were used. The 3-dB bandwidth of transmission at each channel was about 0.25 nm. The total fiber laser cavity length was about 31 m including the EDF that corresponds to the mode spacing of about 6.3 MHz and the roundtrip time of about 160 ns. The group delay difference between channel 1 and channel 2 of the DWDM pair 1 was about 18.0 ns, and that between channel 2 and channel 3 was about 14.8 ns. The fiber delay length difference between the channels in DWDM pair 1 would be on the order of 3–4 m. For DWDM pair 2, the group delay difference between channels were carefully adjusted to compensate for the delays in the DWDM pair 1 within about 50 ps. This arrangement makes the cavity lengths seen by the three wavelength components matched within 1 cm length difference. The group delay differences in the first DWDM pair were longer than the pulse-width theoretically