Multiwavelength Pulse Generation Using an Actively Mode-Locked Erbium-Doped Fiber Ring Laser Based on Distributed Dispersion Cavity

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***Abstract*—A simple design of a stable multiwavelength pulse generator was demonstrated using a dispersion-tuned actively mode-locked erbium-doped fiber (EDF) ring laser with distributed dispersion cavity. The distributed dispersion cavity in the fiber laser successfully reduced the cross-gain saturation in EDF, and thus, enabled multiwavelength operation. Simultaneous generation of wavelength-tunable 10-GHz pulses up to four different wavelengths was achieved with the same wavelength space of 2.94 nm. The extinction ratio of all wavelengths was above 30 dB. In addition, smooth wavelength tuning was achieved over more than 41 nm when the laser was working at dual-wavelength mode. The super mode noise was ~60 dB below the signal level at both wavelengths. The laser state was found to be very stable.**

***Index Terms*—Mode-locked lasers, multiwavelength lasers, optical fiber dispersion, optical fiber lasers, ring lasers.**

I. Introduction

STABLE multiwavelength mode-locked fiber lasers have wide applications in wavelength-division-multiplexing transmission systems, optical signal processing, fiber-optical sensing, optical instrumentation, and microwave photonic systems. The main challenges for erbium-doped fiber (EDF) ring lasers to achieve stable multiwavelength lasing at room temperature are the strong homogeneous line broadening and the cross-gain saturation. Previously, several approaches have been proposed [1]–[4]. Cooling the EDF to 77 K by liquid nitrogen can suppress the homogenous line broadening and the cross-gain saturation [1], but this technique is impractical in many applications. Room-temperature multiwavelength lasing was demonstrated by using multiple gain media in the laser cavity [2] or flattening the gain spectrum [3]. However, these designs are somewhat complex and costly. A novel gain competition suppression method using temporal-spectral multiplexing was put forward by Chen *et al.* By inserting a pair of nearly identical linearly chirped fiber Bragg gratings before and after EDF, respectively, they realized dual-wavelength actively mode-locked fiber laser [4]. Nevertheless, the two lasing wavelengths are not tunable. As an alternative way, a multiwavelength dispersion-tuned actively mode-locked EDF ring laser has been proposed [5]. A remarkable feature of the technique is that it allows "smooth" wavelength tuning. However, it does not overcome the problem of gain competition. Lee and Shu also suggested a novel scheme for dual-wavelength pulse generation using the dispersion tuning approach [6]. They have produced not only simultaneous but also alternating dual-wavelength tunable pulses. But the configuration is a bit complex and more wavelength lasing is not reported.

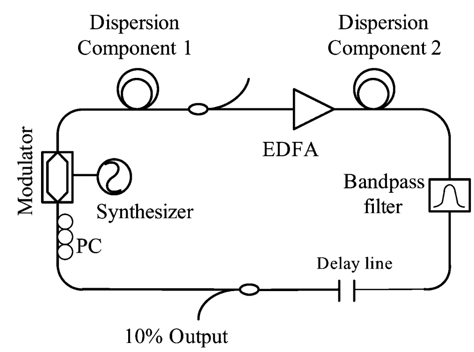

Fig. 1. Experimental setup.

In this work, we propose a simple technique to obtain room-temperature multiwavelength lasing by distributing dispersion before and after the EDF in the cavity of a dispersion-tuned actively mode-locked EDF ring laser. The dispersion cavity of the EDF ring laser allows multiwavelength operation with the same wavelength spacing [5]. Without distributed dispersion in the cavity, pulses at different lasing wavelengths that are injected into the EDF will superimpose so as to pass through a modulator with the least loss. Therefore, gain competition is serious among these wavelengths. In contrast, by properly setting the dispersion before and after the EDF, pulses at different wavelengths are separated in the time domain by the dispersion component before the EDF, and hence, they would get separated gain in EDF. The split pulses are then recombined or mismatched with exactly integral bit periods by the dispersion component after the EDF. This method is sufficient to reduce, though not eliminate, the cross-gain saturation in the EDF, thus enabling stable multiwavelength lasing in EDF ring lasers. With the above mechanism, simultaneous generation of 10-GHz short pulses at multiple wavelengths is obtained. The pulsing state of the laser is very stable.

II. Experimental Setup

A schematic of the experimental setup is shown in Fig. 1. The gain of the fiber laser was provided by an erbium-doped fiber amplifier (EDFA), whose output saturation power was

Manuscript received October 26, 2005; revised November 24, 2005. This work was supported in part by the National Natural Science Foundation of China (60444008904010247).

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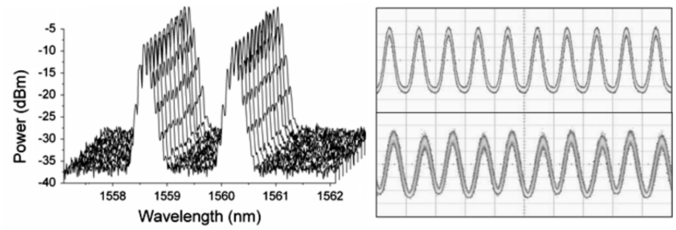
Digital Object Identifier 10.1109/LPT.2006.870149



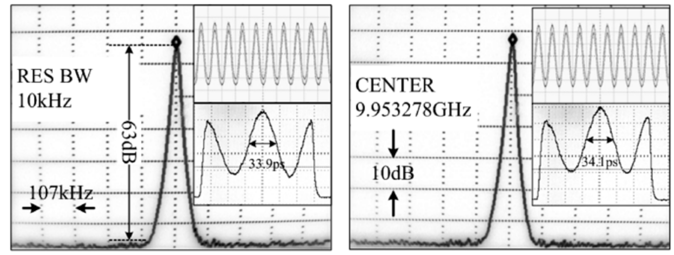
(a) (b)

Fig. 2. Dual-wavelength output from the laser. (a) Repeated scan of the output spectra. (b) Output pulse waveforms.

16.6 dBm. The EDFA included two polarization-independent isolators, which could ensure the unidirectional cavity. In our first setup, a tunable optical bandpass filter (OBPF) with a 3-dB bandwidth of 2.8 nm was inserted to restrict the work bandwidth of the laser. A $LiNbO_3$ Mach–Zehnder intensity modulator driven by a synthesized microwave generator at 10 GHz was biased at its half-wave voltage. Due to the polarization dependence of the $LiNbO_3$ modulator, a polarization controller (PC) was employed to adjust the polarization state of the pulses. A tunable optical delay line, ranging from 0.1 to 0.4 ns, was used to adjust the cavity length, which was also used for wavelength tuning. Intracavity group velocity dispersion was introduced by two dispersion components placed before and after EDFA. In our experiment, the dispersion components were implemented by segments of commercial dispersion-compensating fiber (DCF) or single-mode fiber (SMF) with different dispersion values. The total cavity dispersion and loss without dispersion components were 0.8 ps/nm and 12.9 dB at 1550 nm, respectively (including the OBPF). An optical spectrum analyzer (ANDO AQ6315B, resolution: 0.05 nm) and a 40-GHz photodetector connected to a digital sampling oscilloscope (Agilent 86 100A with module 83 484A) were engaged to observe the pulses at the EDFA input port or the laser output port.

III. Results and Discussion

At the first step, we investigated the dual-wavelength operation by implementing the dispersion component$_1$ with a segment of SMF (length: 2 km; dispersion value: 33 ps/nm at 1550 nm; loss: 0.7 dB), and dispersion component$_2$ with a segment of DCF (length: 0.6 km; dispersion values: -96.2 ps/nm at 1550 nm; loss: 2.8 dB). The corresponding wavelength spacing is 1.6 nm in theory. To evaluate the effect of gain competition suppression between two close wavelengths, we incorporated a tunable OBPF (3 dB bandwidth $= 2.8$ nm) in the cavity to avoid gain competition with other modes. Fig. 2(a) shows the repeated scan of the laser spectral output. As can be seen, the two lasing wavelengths have above 30-dB suppression over other nonlasing modes. Their wavelengths are 1558.62 and 1560.24 nm, respectively. The wavelength spacing is 1.62 nm, which agrees well with the theoretical result. Fig. 2(b) depicts the waveform of multiwavelength 10-GHz pulses. The upper trace provides the waveform at the laser output, while the lower one gives the waveform at the EDFA input. The pulses are well separated in the time domain before injecting into the EDF, where they would get separated gain. We confirmed the existence of pulses for the two wavelengths by inserting another



(a) (b)

Fig. 3. RF spectrum, sampling oscilloscope trace (upper inset), and autocorrelation trace (lower inset) of the pulses. (a) 1558.62 nm; (b) 1560.24 nm.

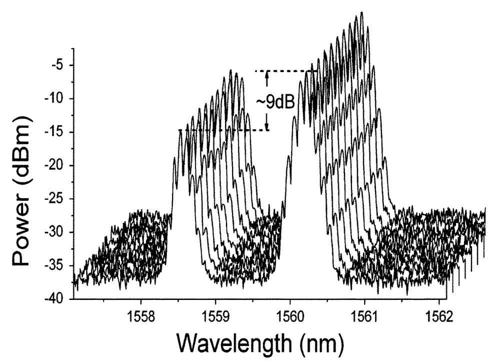


Fig. 4. Repeated scan of the output spectra when a power imbalance of $\sim$9 dB was induced between the two wavelengths.

tunable BPF (3-dB bandwidth $= 0.6$ nm) external to the laser. The results are shown in Fig. 3. The radio-frequency (RF) spectra were measured using a 20-GHz photodetector and an RF spectrum analyzer. For both wavelengths, the super mode noise was $\sim$60 dB below the signal level. For Guassian pulse shapes, the full-width at half-maximum (FWHM) pulsewidths were measured as 33.9 and 34.1 ps (see the lower inset in Fig. 3). The measured FWHM bandwidths were 0.120 and 0.114 nm, giving time bandwidth products 0.407 and 0.389 (nearly transform-limited). The output power of the laser could be adjusted from ~ -6 to ~ 2 dBm by changing the EDF pumping power.

Note that without gain competition suppression, dual-wavelength lasing could also be obtained by careful gain equalization. However, with slightly dithering of the fiber, one lasing wavelength would fade due to its failure in the gain competition. On the other hand, with some gain competition reduction mechanism in the cavity, the pulsing state should not be interrupted by gain variation under a certain extent. In our experiment, we rotated the PC and found that the two wavelengths held with only power variation. As shown in Fig. 4, we induced a power imbalance of $\sim$9 dB by the PC and found that the lasing state kept for more than an hour, which demonstrates the sufficient gain competition reduction.

As the gain competition between the two wavelengths reduced by the distributed cavity and that of other modes suppressed by the bandpass filter, the mode-locking state should be very stable. In our experiment, we observed the dual-wavelength mode-locked state for more than an hour without any stabilization mechanism. The wavelength varied within 0.2 nm and the relative change of the amplitude was smaller than 1 dB.

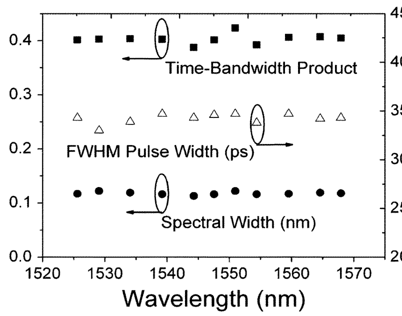


Fig. 5. Measured pulse characteristics during tuning process.

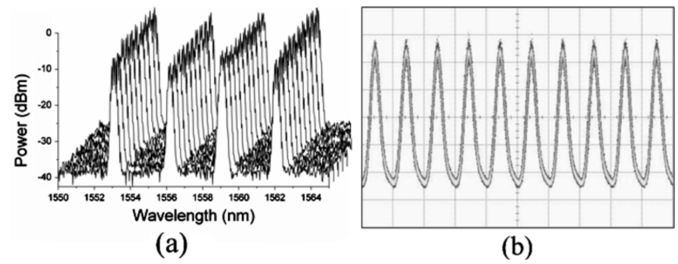


Fig. 6. Four-wavelength output from the laser. (a) Repeated scan of the output spectra. (b) Output pulse waveform of the superimposed four-wavelength pulses.

The variation of the amplitude is mainly caused by polarization fluctuation. The stability of the laser also shows the sufficient gain competition reduction. It should be emphasized that the polarization fluctuation can be prevented by using polarization-maintaining components or a polarization-insensitive modulator, and the drift of the wavelength can be eliminated by a cavity-length-stabilizing feedback system.

For a dispersion-tuned mode-locked laser, smooth wavelength tuning can be achieved by changing either the modulation frequency or the cavity length without interrupting the stable pulsing state [5]–[8]. In our experiment, we tuned the wavelength by adjusting the delay line so as to keep the repetition rate of the pulses fixed at 10 GHz. With the tunable filter tuning simultaneously, the two wavelengths can be tuned from $\sim$1527 to $\sim$1568 nm, which covers almost the entire gain bandwidth of EDFA. As a comparison, the lasing bandwidth (single or multiple wavelength operation) of the dispersion cavity without filter is only 11.5 nm (1556.5–1568.0 nm). The limited tuning range of the latter case is mainly caused by the gain spectrum profile of the EDFA and the gain competition of other oscillation modes [7]. Fig. 5 shows the measured pulse characteristics in time and frequency domains. It was found that the pulses kept stable during the tuning process. The time-bandwidth products were around 0.4, indicating near transform-limited pulses over the entire tuning range. During the tuning process, we also observed a power difference up to 12.1 dB between the two simultaneous lasing wavelengths. However, by adjusting PC, the power equalized state could be easily restored.

Based on the principle above, we obtained simultaneously stable operation of four-wavelength lasing. In this setup, both the dispersion components were implemented by DCF (length: 50 and 170 m; dispersion value: -7.8 and -27.2 ps/nm at wavelength 1550 nm; loss: 0.9 and 2.5 dB, respectively). As can be seen in Fig. 6, four wavelengths are lasing with a wavelength spacing of 2.94 nm. The four wavelengths almost occupy the whole lasing bandwidth (11.5 nm). Therefore, no filter is needed in the cavity. The pulsewidths vary from 24 to 25 ps, and 3-dB bandwidths from 0.16 to 0.18 nm. The maximum power variation among the four wavelengths is 3.2 dB, which compares favorably to other multiwavelength pulse sources, such as [9]. Also, the four wavelengths can be tuned among the whole lasing bandwidth. If PC was adjusted simultaneously, the power variation can be limited in 5 dB during wavelength tuning. It should be noted that, by properly configuring the dispersion value of dispersion component$_1$ and dispersion component$_2$, other amounts of wavelength lasing would be available. Moreover, wavelength spacing tuning can also be obtained by changing the whole cavity dispersion [5]. Therefore, if the two dispersion components are implemented by a dispersion-tunable device (e.g., wide-band dispersion compensator), both the wavelength spacing and the number of lasing wavelengths are tunable.

IV. Conclusion

We have demonstrated stable multiwavelength pulse generation in an actively mode-locked EDF ring laser by distributing dispersion in the cavity. By properly configuring the dispersion before and after the EDF, we have performed simultaneous generation of 10-GHz pulses up to four wavelengths. When the laser works at dual-wavelength mode, smooth wavelength tuning is achieved over more than 41 nm. The pulsing state of the laser is observed to be very stable. Furthermore, if the dispersion components are implemented by dispersion tunable devices, both the wavelength spacing and the number of lasing wavelengths are tunable. We believe the method can be used to obtain more wavelengths lasing by hybridizing it with other techniques.

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