Generation of tunable multi-wavelength optical short pulses using self-seeded Fabry-Perot laser diode and tilted multimode fiber Bragg grating

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We experimentally demonstrate the simultaneous generation of tunable multi-wavelength picosecond laser pulses using a self-seeding configuration that consists of a gain-switched Fabry-Perot laser diode (FPLD) with an external cavity formed by a tilted multimode fiber Bragg grating. Dual- and triple-wavelength pulses are obtained and tuned in a flexible manner by changing the temperature of the FPLD. The side mode suppression ratio larger than 25 dB is achieved at different dual- and triple-wavelengths and the typical pulsewidth of the output pulses is ∼70 ps. In the experiment, the wavelength separation can be narrowed to 0.57 nm.

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Dual- and multi-wavelength short pulses have attracted much interest over the years because of their many important applications, such as in optical fiber sensors, optical code division multiple access systems, and wavelength-division multiplexing (WDM) optical communication[1−6]. Self-seeding or external injection seeding of a gain-switched Fabry-Perot laser diode (FPLD) is a simple and inexpensive method for generation of multi-wavelength short pulses[7−10]. In a typical self-seeding scheme, multiple fiber Bragg gratings (FBGs) are typically used as wavelength selection elements, and multi-wavelength operation is achieved by selecting the different modes of a FPLD. Recently, a configuration consisting of a single-mode fiber (SMF) with a multimode FBG (MMFBG) has been developed to achieve the wavelength-switching of a fiber ring laser. The discrete lasing wavelengths were obtained over a wide wavelength range by changing the mode coupling condition in the multimode fiber (MMF)[11].

In this letter, we propose the use of a tilted MMFBG as the wavelength selection element for the generation of dual- or multi-wavelength short pulses from a self-seeded FPLD. The principle of wavelength selection is based on the mode coupling in a graded-index MMF caused by microbending. The fundamental core mode can be coupled to a specific high-order core mode of the MMF by inducing microbending of the fiber; the order of the dominantly coupled mode progressively increases as the amount of microbending is increased[12]. The wavelength of the FPLD modes varies as temperature changes, providing the possibility of generating multi-wavelength pulses and wavelength tuning of generated pulses when different FPLD modes are selected by the tilted MMFBG. With the simple reflection element based on the tilted MMFBG, three different kinds of dual-wavelength optical pulses and a group of triple-wavelength optical pulses were obtained using a self-seeding scheme. Wavelength tuning can be achieved by adjusting the temperature of the FPLD and changing the modal distribution in the reflection of the MMFBG using a mode scrambler. The side mode suppression ratio (SMSR) is higher than 25 dB and the pulsewidth is ∼70 ps. The narrowest wavelength separation is 0.57 nm.

The experimental setup of the self-seeded FPLD with a tilted MMFBG as the wavelength-selection element is shown in Fig. 1. A commercial 1.5-μm pigtailed FPLD with a mode separation of ∼1.12 nm was used, whose threshold current was 9.5 mA. A 15-m erbium-doped fiber (EDF), optically pumped by a 980-nm laser diode (LD) through a WDM coupler, was inserted in the linear cavity to amplify the light from the FPLD. An external cavity was constructed with the EDF, a 3-dB coupler, and the tilted MMFBG, which was terminated with an index-matching gel (IMG). A polarization controller (PC) was included in the external cavity to control the polarization state of light. The FPLD was modulated at a radio frequency (RF) of 1243.74 MHz, which corresponded to the 393rd harmonic of the fundamental frequency of the external cavity. The FPLD was biased at 8.6 mA and the RF power applied was 28 dBm. The gain-switching frequency was kept unchanged, which was determined by the fixed length of the external cavity. The output pulses were divided into two parts through a 20/80 coupler, 20% of which were measured with an optical spectrum analyzer with a

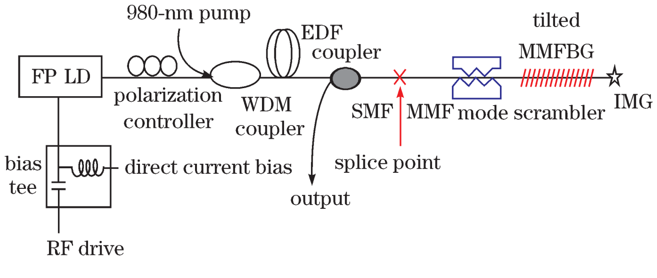

Fig. 1. Experimental setup of a self-seeded FPLD with a tilted MMFBG.

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resolution of 0.02 nm; 80% of the pulses were measured using a 35-GHz digital optical sampling oscilloscope.

The tilt angle of the grating was 1.6°. A mode scrambler (a three-teeth fiber deformer) was applied on the MMF near the splicing point between the tilted MMFBG and the SMF, as shown in the Fig. 1. A leverage was used for force operation. The force can be applied to the mode scrambler by hanging some weight on the free end of the leverage. Figure 2 shows the reflection spectra of the tilted MMFBG when no weight and a 300-g weight were applied on the leverage. As the weight is applied, micro-bending can be induced in the MMF, and then the higher-order modes can be coupled back into the SMF. Meanwhile, the light power coupled into the SMF decreases as the weight is applied on the leverage. Different FPLD modes can be selected when their wavelengths coincide well with the reflection peaks of the tilted MMFBG. To obtain stable multi-wavelength pulses and achieve wavelength tuning, we only need to adjust the PC in the laser cavity and the temperature of the FPLD to select different FPLD modes.

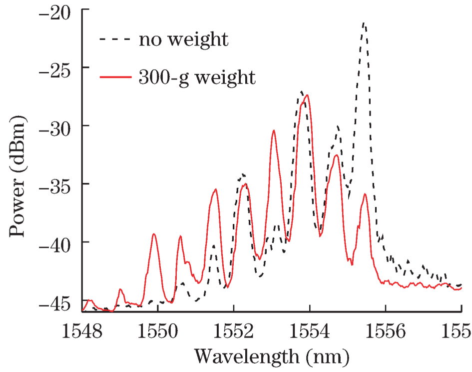

Fig. 2. Reflection spectra when no weight and a 300-g weight were applied on the leverage.

In the experiment, we applied a 300-g weight on the leverage to excite mode coupling in the MMF, and adjusted the temperature of the FPLD accordingly. When the temperature of the FPLD is adjusted to 23.7 °C, a group of dual-wavelength pulses are generated, as shown in Fig. 3. The laser output is stable at room temperature, as shown by the repeated scans of the output spectrum over a period of 10 min in Fig. 3(a). The wavelengths are 1553.86 (λ_1) and 1554.76 nm (λ_2), and the corresponding full-width at half-maximum (FWHM) bandwidths are 0.179 and 0.155 nm, respectively. The SMSRs are both about 32 dB. The wavelength separation is as narrow as 0.9 nm, indicating that the two wavelengths are selected from the same mode of the FPLD. The waveform of the output pulses is shown in Fig. 3(b), in which the pulses contain both wavelengths and have a pulsewidth of 137.65 ps. Figure 3(c) shows the pulses after traveling through a 13.0-km SMF, which has a dispersion parameter of 18 ps/(nm·km) at 1550 nm. The pulses are separated by 127 ps with the first pulse corresponding to the shorter wavelength. The widths of the pulses at λ_1 and λ_2 are 68.50 and 64.12 ps, respectively. Thus, the corresponding bandwidth-pulsewidth products are 1.53 and 1.24, indicating that the pulses are chirped.

By the same principle, two other groups of dual-wavelength pulses are generated when the temperature of the FPLD is adjusted to 19.3 and 24.4 °C. Figure 4 shows the spectral and temporal characteristics of the pulses generated when the temperature of the FPLD is adjusted to 19.3 °C. The laser output is also stable at room temperature, as shown by the repeated scans of the output spectrum over a period of 10 min in Fig. 4(a). The wavelengths are 1553.14 (λ_1) and 1555.46 nm (λ_2). The wavelength separation is 2.32 nm, indicating that the two wavelengths are selected from two different

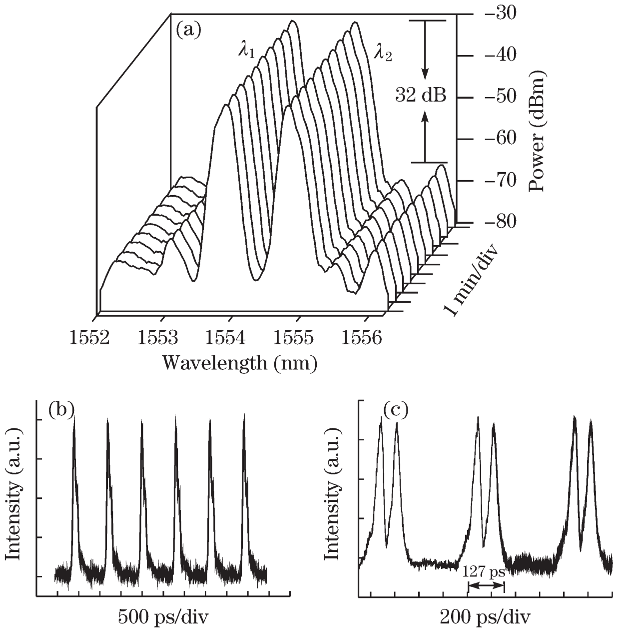

Fig. 3. Characteristics of the dual-wavelength pulses at λ_1=1553.86 nm and λ_2=1554.76 nm. (a) Repeated scans of the output spectrum. (b) Output pulses from the laser. (c) Output pulses after traveling through a 13.0-km SMF.

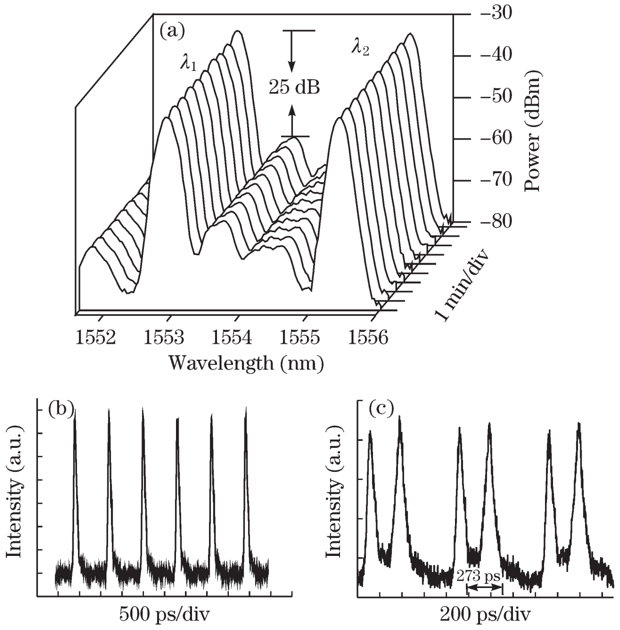

Fig. 4. Characteristics of the dual-wavelength pulses at λ_1=1553.14 nm and λ_2=1555.46 nm. (a) Repeated scans of the output spectrum. (b) Output pulses from the laser. (c) Output pulses after traveling through a 13.0-km SMF.

Table 1. Characteristics of Dual-wavelength Short Pulses

Temperature of the FPLD (°C)	Wavelength (nm)	SMSR (dB)	Pulsewidth (ps)	FWHM (nm)	Bandwidth Pulsewidth Product
23.7	1553.86 (λ_1)	32.62	68.50	0.179	1.53
	1554.76 (λ_2)	32.05	64.12	0.155	1.24
19.3	1553.14 (λ_1)	25.9	61.10	0.190	1.45
	1555.46 (λ_2)	24.83	73.36	0.177	1.62
24.4	1551.55 (λ_1)	29.03	132.05	0.163	2.69
	1553.95 (λ_2)	30.56	68.47	0.239	2.05

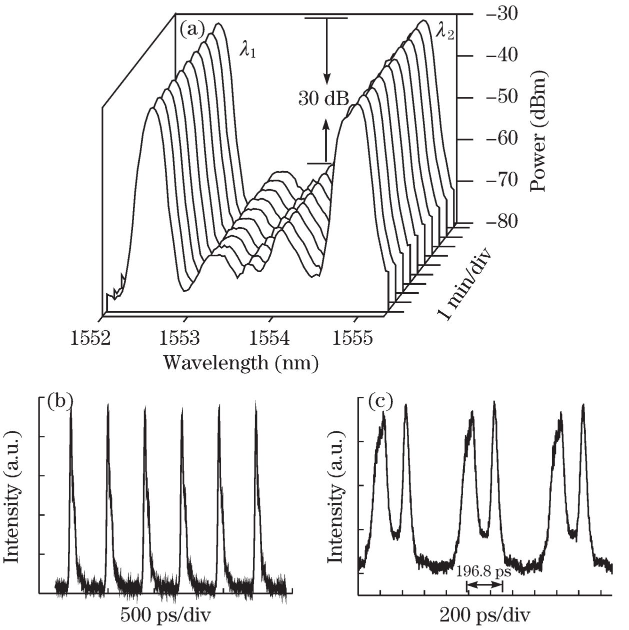

Fig. 5. Characteristics of the dual-wavelength pulses at λ_1=1551.55 nm and λ_2=1553.95 nm. (a) Repeated scans of the output spectrum. (b) Output pulses from the laser. (c) Output pulses after traveling through a 13.0-km SMF.

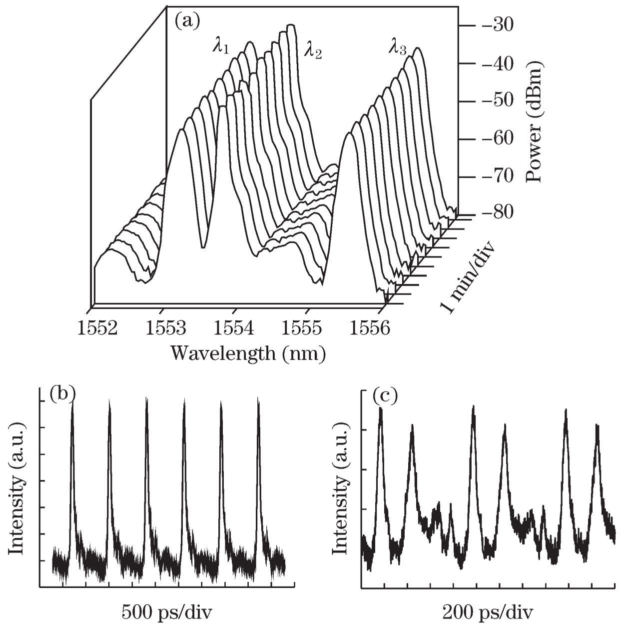

Fig. 6. Characteristics of the triple-wavelength pulses at λ_1=1553.19 nm, λ_2=1553.76 nm, and λ_3=1555.48 nm. (a) Repeated scans of the output spectrum. (b) Output pulses from the laser. (c) Output pulses after traveling through a 13.0-km SMF.

modes of the FPLD. The waveform of the output pulses is shown in Fig. 4(b), in which the pulses contain both wavelengths and have a pulsewidth of 77.98 ps. Figure 4(c) shows the pulses after traveling through a 13.0-km SMF; the pulses are separated by 273 ps with the first pulse corresponding to the shorter wavelength.

Figure 5 shows the spectral and temporal characteristics of the pulses generated when the temperature of the FPLD is adjusted to 24.4 °C. The laser output is again stable at room temperature, as shown by the repeated scans of the output spectrum over a period of 10 min in Fig. 5(a). The wavelengths are 1551.55 (λ_1) and 1553.95 nm (λ_2). Figure 5(b) shows that the pulses contain both wavelengths and have a pulsewidth of 97.88 ps. The pulses are separated by 196.8 ps after traveling through a 13.0-km SMF, as shown in Fig. 5(c). During wavelength tuning, the RF modulation frequency was kept unchanged; thus, the repetition rate of the pulses remained unchanged. The characteristics of all the dual-wavelength optical pulses obtained are shown in Table 1. The table shows that nearly all the SMSRs are above 25 dB and the pulsewidths are about 70 ps. The calculated bandwidth-pulsewidth products indicate that all the groups of pulses are chirped.

We can also obtain triple-wavelength pulses by carefully adjusting the PC when the temperature of the FPLD is adjusted to 28.9 °C. Figure 6 shows the spectral and temporal characteristics of the pulses generated under this condition. The laser output is relatively stable at room temperature, as shown by the repeated scans of the output spectrum over a period of 10 min in Fig. 6(a). The wavelengths are 1553.19 (λ_1), 1553.76 (λ_2), and 1555.48 nm (λ_3), and the corresponding FWHM bandwidths are 0.152, 0.124, and 0.152 nm, respectively. The wavelength separation between λ_1 and λ_2 is as narrow as 0.57 nm, but wavelength separation between λ_2 and λ_3 is 1.72 nm, indicating that the wavelengths λ_1 and λ_2 are selected from the same mode of the FPLD, but λ_3 is selected from another mode. The SMSRs are 29, 34, and 30 dB at λ_1, λ_2, and λ_3, respectively. The waveform of the output pulses is shown in Fig. 6(b), in which the pulses contain three wavelengths and have a pulsewidth of 71.16 ps. Figure 6(c) shows the pulses after traveling through a 13.0-km SMF; the pulses could not be completely separated because the wavelengths λ_1

and λ_2 are too close to be separated.

In conclusion, stable optical short pulses at different two or three wavelengths with pulsewidths of ~70 ps and SMSRs better than 25 dB were generated using a self-seeded FPLD with a tilted MMFBG as the wavelength-selection element. The wavelength separation could be as narrow as 0.57 nm in which the laser wavelengths are selected from the same mode of the FPLD. Wavelength tuning among different dual- and triple-wavelengths could be achieved by adjusting the temperature of the FPLD and the PC. Much flexibility can be offered by this laser for various applications.

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