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REVIEW ARTICLE

Recent progress on ultrafast/ultrashort/frequency-stabilized erbium-doped fiber lasers and their applications

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Abstract There are many kinds of fiber lasers in the 1.5 μm band using erbium-doped fiber amplifiers. Our group has been studying and developing advanced fiber lasers, such as 1) 10–40 GHz harmonically mode-locked fiber lasers, 2) femtosecond fiber lasers that use single-wall carbon nanotube (CNT)-doped polymers as a saturable absorber, and 3) frequency-stabilized fiber lasers that employ acetylene C_2H_2. We will describe recent progress on these fiber lasers and their applications in this article.

Keywords mode-locked erbium fiber laser, acetylene frequency-stabilized fiber laser, high-speed optical transmission, coherent optical transmission

1 Introduction

In recent years, rapid progress has been made on erbium-doped fiber lasers because of their simplicity and wide range of oscillation wavelengths. The oscillation wavelength in the 1.5 μm region corresponds to the minimum loss region of silica-based optical fibers, which makes these lasers attractive for applications in optical communication and optical metrology. In this paper, we review recent progress on erbium-doped fiber lasers and their applications.

First, we describe 10–40 GHz regeneratively mode-locked, subpicosecond fiber lasers, and refer to their application to a new type of Cs atomic clock and 160–640 Gbit/s ultrahigh-speed optical time division multiplexing (OTDM) transmission. Next, we describe 100–200 fs pulse generation at 50 MHz using a passively mode-locked fiber laser with a carbon nanotube (CNT) saturable absorber. Finally, we describe a frequency-stabilized fiber laser that has a frequency stability of greater than 10^{-11} and its application in coherent optical communication. We also refer to a frequency- and repetition-rate-stabilized mode-locked fiber laser using a new phase-locked-loop (PLL) scheme.

2 10–40 GHz regeneratively and harmonically mode-locked picosecond fiber laser

A stable optical short pulse source that operates in the GHz region is important to the development of ultrahigh-speed optical communication. Among many potential sources, a harmonic actively mode-locked fiber laser (MLFL) can easily produce pulses shorter than 10 ps in that region. Figure 1(a) shows the configuration of a 40 GHz PLL regeneratively and harmonically mode-locked fiber laser. All the fibers in the cavity are polarization maintaining to prevent any polarization fluctuation. The pumping source consists of 1.48 μm InGaAsP laser diodes and the filter bandwidth is 5 nm. The oscillation wavelength can be changed by tuning the center wavelength of the bandpass filter over 30 nm. The harmonic beat signal between the longitudinal modes was obtained with the clock extraction circuit in the feedback loop, which is composed of a high-speed photodetector, a 40 GHz high Q dielectric filter (Q~1400) and a high gain electrical amplifier. After adjusting the phase between the pulse and the modulation peak, this harmonic beat signal was amplified through the electric amplifier and fed back to the LN intensity modulator in the laser cavity, which results in regenerative mode-locking [1]. Once mode-locking is achieved, stable operation continues for a long time because the clock signal always follows the changes in the cavity length.

The repetition rate of a regeneratively MLFL under a free-running condition suffers from drift. We used a PLL technique to remove the frequency drift [2]. The PLL circuit was comprised of a synthesizer, a double balanced mixer (DBM), proportional and integral feedback circuits, and a high voltage controller, as shown in Fig. 1(a). Part of

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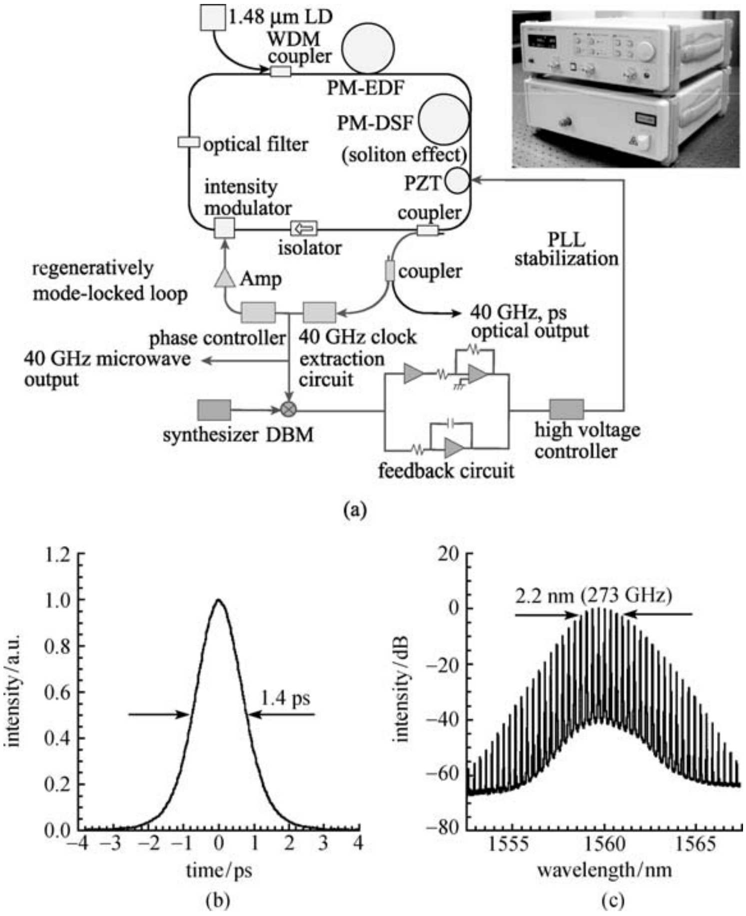

Fig. 1 40 GHz PLL regeneratively mode-locked fiber laser. (a) Configuration; (b) autocorrelation waveform; (c) optical spectrum

the dispersion-shifted fiber (DSF) was wound on a piezoelectric transducer (PZT) and the cavity length was changed by controlling the voltage supplied to the PZT. When an error signal, which was the output from the DBM, was fed back to the PZT, the repetition rate was stabilized by the PLL.

Figures 1(b) and 1(c) show the autocorrelation waveform and optical spectrum of the output pulse from the MLFL, respectively. The waveform has an almost sech shape, and the pulse width is 1.4 ps. The output power was approximately 10 mW at the pump power of 100 mW. The spectral width is 2.2 nm, and thus the time-bandwidth product is 0.36, which indicates that the output pulse is nearly a transform-limited sech pulse. From the single sideband (SSB) phase noise measurement, the timing jitter is estimated to be as little as 78 fs.

Another interesting way of stabilizing the repetition rate is to lock the frequency to an atomic microwave resonance such as Cs atoms [3]. Since regenerative mode-locking can simultaneously emit both a GHz optical pulse train and the corresponding microwave sinusoidal signal, the repetition rate can be stabilized to a Cs ground-state resonance between $F=3$ and $F=4$, which has a resonance frequency of 9.1926 GHz. This enables us to provide an ultrastable clock through an optical fiber network as the laser emits a stable pulse train with the same stability as a Cs clock. By adopting an optically pumped Cs gas cell with a double resonance method as a frequency standard, we have successfully demonstrated an ultrastable rack-mount type Cs optical atomic clock with excellent short-term stability. The obtained frequency stabilities reached as high as 1.2×10^{-12} for $\tau=1$ s and 8.8×10^{-14} for $\tau=100$ s for a 9.1926 GHz microwave output signal [4].

The MLFL has been used for various high-speed optical communication systems, such as 160–640 Gbit/s ultrahigh-speed OTDM transmission. Here we describe a 320 Gbit/s OTDM-DPSK (differential phase shift keying) transmission experiment over 525 km that we demonstrated recently [5]. Figure 2 shows the experimental setup and results. As an optical pulse source, we used a 40 GHz MLFL operated by FM mode-locking, which can directly emit a 0.8 ps pulse at 1550 nm. The pulse train was DPSK-modulated at 40 Gbit/s and optically multiplexed to 320 Gbit/s. In the DPSK receiver, the 320 Gbit/s signal

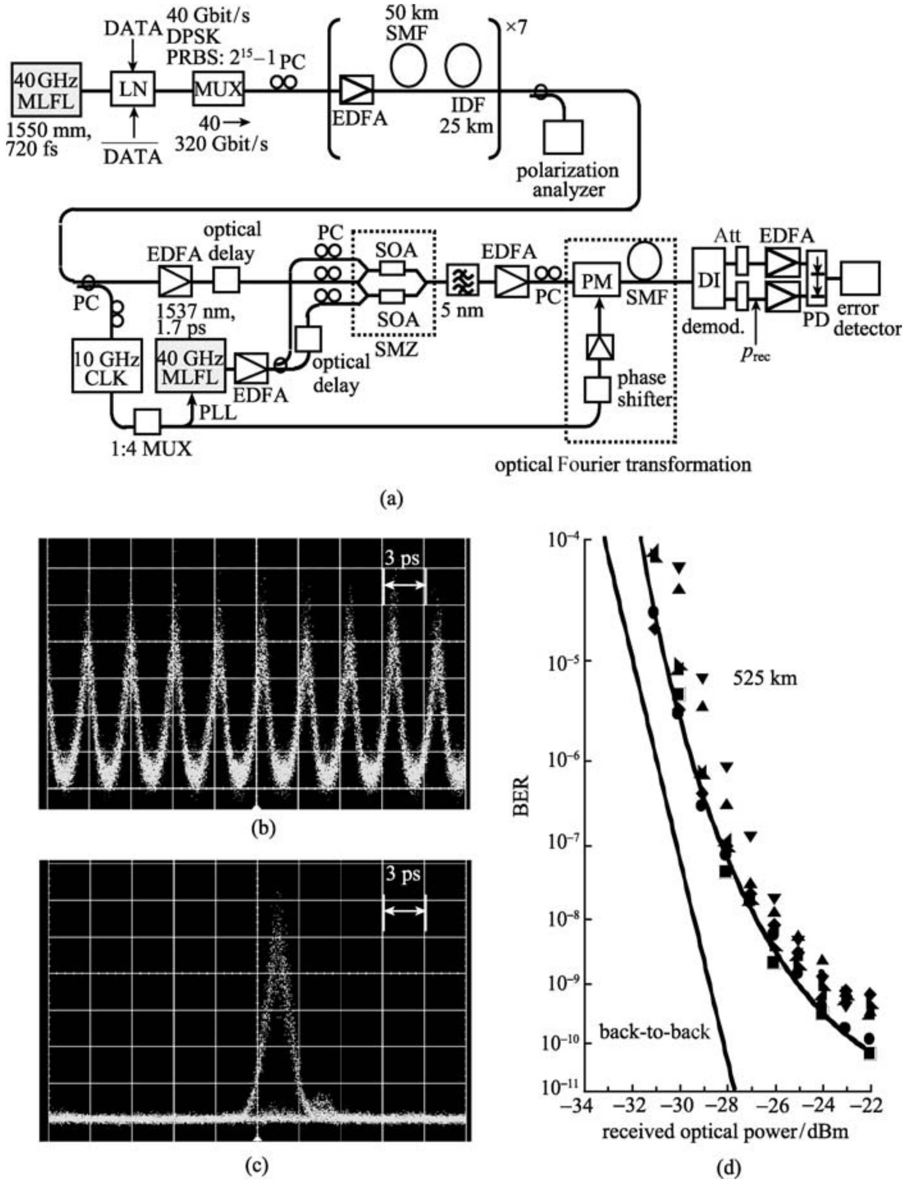

Fig. 2 320 Gbit/s-525 km OTDM-DPSK transmission experiment using 40 GHz MLFL. (a) Configuration; (b) 320 Gbit/s OTDM-DPSK signal after 525 km transmission; (c) demultiplexed 40 Gbit/s signal converted to OOK; (d) BER characteristics

shown in Fig. 2(b) was demultiplexed to 40 Gbit/s by using a symmetric Mach-Zehnder (SMZ) optical switch. The SMZ switch is an all-optical interferometric switch, in which semiconductor optical amplifiers (SOAs) are installed in each arm of a Mach-Zehnder interferometer [6]. As the optical source for the control pulse, we used another 40 GHz MLFL emitting a 1.8 ps pulse train at 1537 nm, which was PLL operated with the extracted 40 GHz clock. The demultiplexed 40 Gbit/s signal was then launched into an optical Fourier transform circuit, from which waveform distortions during transmission were eliminated [7]. Finally the Fourier-transformed DPSK signal was converted to on-off keying (OOK) with a one-bit delay interferometer (DI) as shown in Fig. 2(c). The bit error rate (BER) characteristics are shown in Fig. 2(d). A BER of less than 10^{-9} was obtained in all the measurements, indicating that the 320 Gbit/s signal was successfully transmitted over 525 km.

3 Passively mode-locked femtosecond fiber laser with CNT-doped polymer saturable absorber

Passively mode-locked fiber lasers operating in the 1.5 μm band enable an ultra-short pulse train to be emitted with a simple cavity structure. These lasers have many industrial applications such as all-optical switching and optical metrology. Recently, it has been found that single-wall carbon nanotubes (SWNTs) have an ultrahigh-speed saturable absorption effect whose recovery time is less than 1 ps [8]. This indicates the possibility of developing an ultrahigh-speed nonlinear optical device material in the 1.5 μm band that is both simple and inexpensive.

SWNT-based saturable absorbers have been realized in various ways. For example, incorporation of the SWNTs into polymers was proposed to disperse the SWNTs uniformly, which will enable us to realize a low-loss saturable absorber. To make this device easy to handle, it is very important to realize a thick SWNT-incorporated polymer material as this makes it easy for us to polish the polymer surface to optical grade. We previously reported an SWNT polymer material using polymethylmethacrylate (PMMA) and polystyrene (PS) with a thickness of 1 mm [9]. Here, we describe two new types of SWNT polymer saturable absorbers: SWNT-doped polycarbonate (PC), which has higher heat resistance than PMMA, and a fiber-connector-type saturable absorber in which SWNT/P3HT (poly-3-hexylthiophene) is coated on the end of a connector.

The SWNT/PMMA saturable absorbers that we used previously are vulnerable to optical damage because the heat resistance of PMMA is not very high. By contrast, PC has higher heat resistance than PMMA. We successfully dispersed SWNTs in PC by using dimethylformamide (DMF) as a dispersion solvent. We used an ultrasonic homogenizer to disperse them, and after drying the resulting solution in an oven and polishing the surface of the wafer into a mirror, we obtained an SWNT/PC saturable absorber. The wafer was 340 μm thick. We also demonstrated a fiber-connector-type SWNT saturable absorber designed to reduce both the cavity length and insertion loss. Here, the conductive polymer P3HT was used to achieve uniform SWNT dispersion. The SWNT/P3HT solvent was repeatedly coated on a fiber connector end and dried.

We constructed a 1.5 μm passively mode-locked femtosecond fiber laser incorporating the SWNT saturable absorber. Figure 3(a) shows the laser configuration. An erbium-doped fiber amplifier (EDFA) was used as the gain medium. The configurations of the SWNT/PC and fiber-connector-type SWNT/P3HT saturable absorber are shown in Figs. 3(b) and 3(c), respectively. The cavity length was 5.1 m, corresponding to a repetition rate of 39.1 MHz. The fiber cavity configuration was optimized to include the soliton effect in the cavity. Figure 4 shows the laser output characteristics. With SWNT/PC, 115 fs pulse was successfully generated with a pump power of 303 mW. The average power was 3.4 mW, and the time-bandwidth product was 0.35, indicating that the output pulse was a nearly transform-limited sech soliton pulse. With the fiber-type saturable absorber, a 145 fs, 51.0 MHz soliton pulse with an average power of 4.8 mW was generated with a pump power of 232 mW.

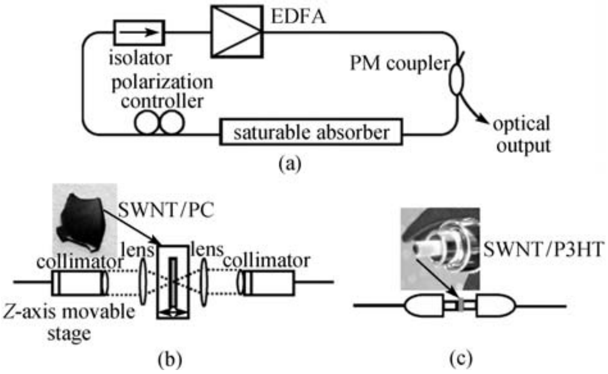

Fig. 3 Passively mode-locked soliton fiber laser with CNT-doped polymer saturable absorber. (a) Cavity configuration; (b) SWNT/PC saturable absorber; (c) connector-type SWNT/P3HT saturable absorber

4 C_2H_2 frequency-stabilized fiber lasers

A stable optical frequency in the 1.55 μm region has important uses in the fields of coherent optical

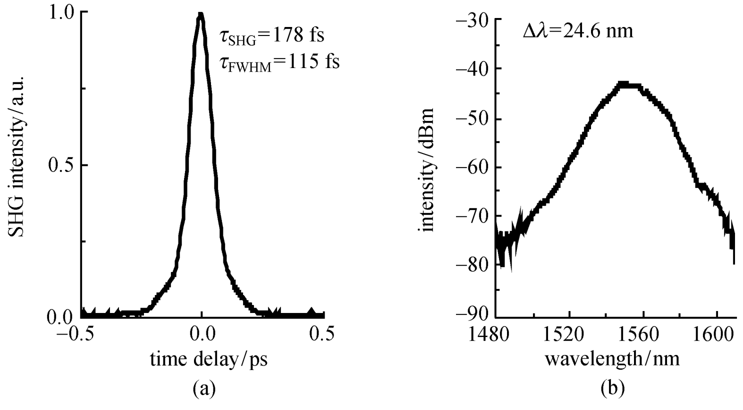

Fig. 4 Laser output characteristics with SWNT/PC. (a) Autocorrelation waveform; (b) optical spectrum

communication, metrology, and high-resolution spectroscopy. C_2H_2 molecules have been utilized for the frequency stabilization of semiconductor lasers and fiber lasers at 1.55 μm. Fiber lasers are particularly attractive candidates for such fields because of their narrow linewidth. Here we describe a frequency-stabilized, polarization-maintained erbium fiber ring laser that has no frequency modulation at the output beam.

Figure 5 shows the configuration of the $^{13}C_2H_2$ frequency-stabilized fiber ring laser. The laser has two main parts: a tunable, polarization-maintained single-frequency fiber ring laser and a laser frequency stabilization unit. The 1.5 GHz fiber Bragg grating (FBG) filter makes it possible to realize single-frequency operation by selecting only one longitudinal mode among many oscillation modes. The laser has two kinds of frequency controllers. One is a drum-type PZT with EDF wound around it. The other is a multi-layer PZT (MLP) on which an FBG is laid. When these controllers operate synchronously with a phase sensitive detection circuit, the laser frequency is continuously tuned over 2 GHz without mode hopping.

In the external frequency stabilization unit, we employed a phase sensitive detection circuit. With this configuration, we can detect the frequency deviation of a fiber laser from the center frequency of the P(10) linear absorption line, which has a center wavelength of 1538.8 nm and a spectral width of 500 MHz. The DBM generates a voltage error signal that is proportional to the frequency deviation. The error signal is fed back to the PZT to control the laser frequency. The linewidth of the frequency-stabilized fiber laser was 4 kHz, which is almost the same as that of the free running fiber laser. We also evaluated the frequency stability from the beat note signals of two lasers. For an integration time, τ, of 1 s, the square root of the Allan variance of the fiber laser is 1.3×10^{-11}, which corresponds to a frequency fluctuation of 2.6 kHz. For $\tau = 100$ s, the Allan variance is 2.0×10^{-11} corresponding to a frequency fluctuation of 4 kHz.

Frequency-stabilized lasers are indispensable for coherent optical transmission as a stable and fixed optical frequency difference between the transmitter, and the local oscillator (LO) is required if we are to obtain a stable intermediate frequency (IF) signal. We employed the C_2H_2 frequency-stabilized fiber laser as the transmitter and a high-speed free running fiber laser as the LO in a coherent quadrature amplitude modulation (QAM) transmission. Here we describe the result of 1 Gsymbol/s, 128 (2^7) QAM transmission, where each symbol represents 7 bits [10].

The experimental setup is shown in Fig. 6. By introducing polarization-multiplexing, a 14 Gbit/s data speed in a single channel is obtained. The laser output is split into two arms. One is coupled to two IQ modulators consisting of complex Mach-Zehnder modulators. The other frequency-stabilized beam, whose frequency is up-shifted by 2.5 GHz against the signal, is used as a pilot signal that tracks the optical phase of an LO (tunable tracking laser) under optical phase-locked-loop (OPLL) operation. The QAM signals and the pilot signal are coupled into a 160 km-long single-mode fiber (SMF). After the transmission, the two QAM signals are heterodyne-detected with an LO signal whose phase is locked to the pilot signal. Then the IF data signal is A/D converted, and the digital data are demodulated by software.

Figures 7–9 show the constellations and eye patterns for the back-to-back case and after 160 km transmissions with orthogonal and parallel polarizations, respectively. Clear constellations and eye patterns were obtained at the received power of −26.5 dBm for both polarization data. As a result, a 14 Gbit/s data was successfully transmitted over 160 km in an optical bandwidth of 1.4 GHz, indicating the possibility of spectral efficiency as high as 10 bit/s/Hz.

Frequency stabilization of MLFL, namely, simultaneous stabilization of the repetition rate and the absolute optical frequency, is also an important subject in terms of optical metrology and coherent pulse generation. We recently

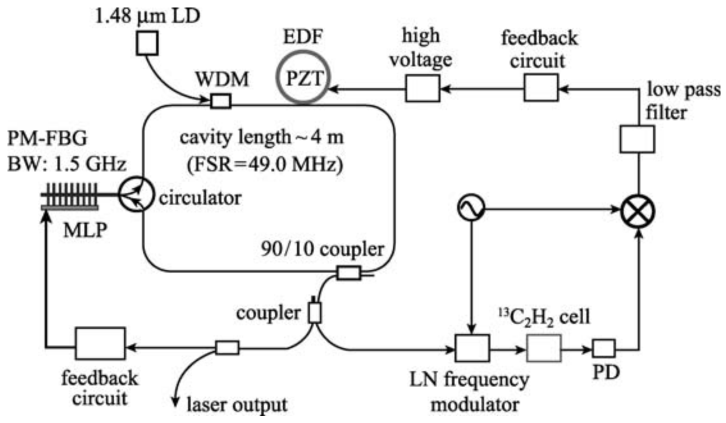

Fig. 5 Configuration of a $^{13}C_2H_2$ frequency-stabilized fiber laser

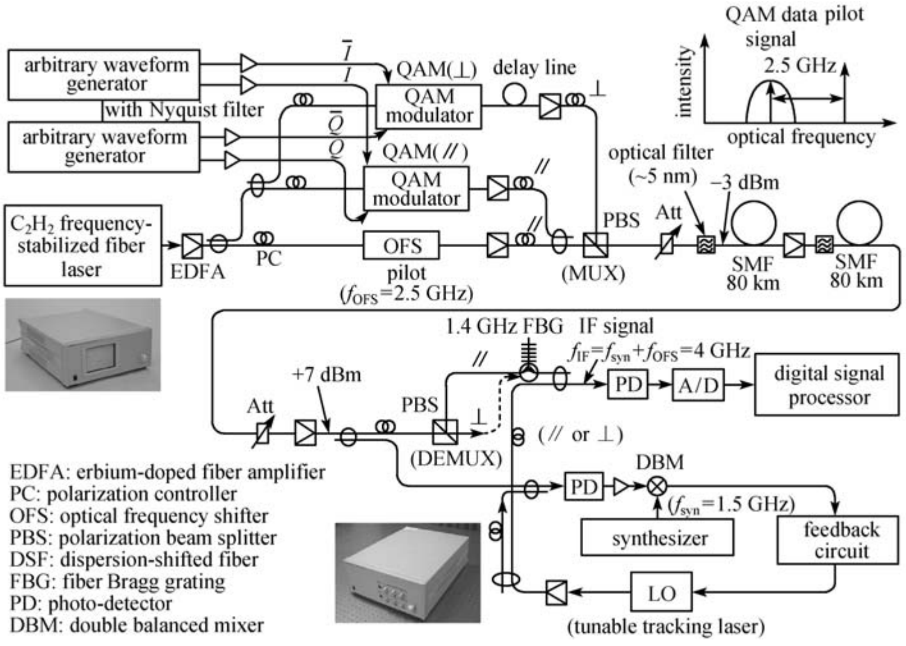

Fig. 6 Experimental setup for polarization-multiplexed 128 QAM coherent transmission over 160 km

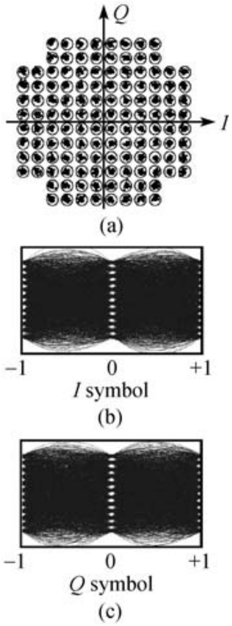

Fig. 7 Constellations and eye patterns for back-to-back case (received power: –29.5 dBm). (a) Constellations; (b) eye patterns of *I* symbol; (c) eye patterns of *Q* symbol

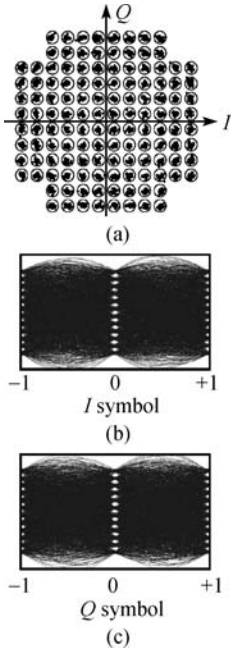

Fig. 8 Constellations after 160 km transmissions for orthogonal data (received power: –26.5 dBm). (a) Constellations; (b) eye patterns of *I* symbol; (c) eye patterns of *Q* symbol

proposed an independent frequency control technique that employs regenerative mode locking, in which the repetition rate can be controlled by changing the microwave phase in the electrical feedback loop [11]. This method is not accompanied by a direct optical frequency change, because we did not change the laser cavity length. Based on this control scheme, we successfully demonstrated the simultaneous stabilization of both the absolute optical frequency and the repetition rate of the pulse train by using a 40 GHz MLFL [12]. The optical frequency was locked to the linear absorption of C_2H_2 molecules at 1.53 μm while the repetition rate was locked to that of a 40 GHz synthesizer by using the PLL technique. The optical frequency stability of the MLFL in the present case is almost the same as that of the CW fiber laser and reached 2×10^{-11} for $\tau = 10-100$ s. Simultaneously, the stability of

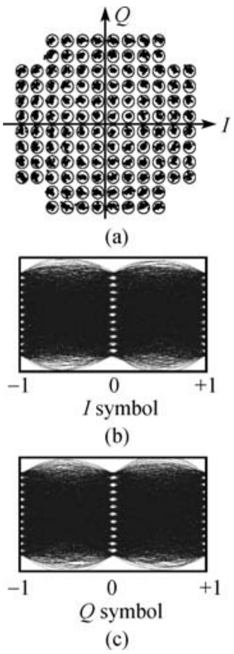

Fig. 9 Constellations after 160 km transmissions for parallel data (received power: –26.5 dBm). (a) Constellations; (b) eye patterns of *I* symbol; (c) eye patterns of *Q* symbol

the repetition rate is the same as that of the synthesizer, which is $1\times10^{-10}-1\times10^{-11}$.

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