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Using Dual-Mode Self-Locked Semiconductor Laser for Optical Millimeter-Wave Application[1]

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Abstract—In this study, an optical millimeter-wave (mm-wave) generator is proposed and experimentally demonstrated by using a self-injected Fabry–Perot laser diode (FP–LD), having mode spacing of 1.11 nm, for dual-mode beating in 140 GHz band (terahertz band). The created dual-wavelength also can be also modulated at 1.25, 2.5, and 10 Gb/s with on-off keying (OOK) modulation format by external optical modulator, respectively, in 20 km fiber transmission. Moreover, the dual-mode laser can be selected in difference wavelengths by tuning the optical filter inside cavity for the future WDM applications.

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1. INTRODUCTION

Millimeter-wave (mm-wave) access system was the promising technology on radio over fiber (RoF) link for the future distribution of high capacity and broadband services [1]. Here, the optical mm-wave generators in RoF system have the advantages of low phase-noise, tenability and tolerance against fiber dispersion. The mm-wave signal can also provide the huge bandwidth to overcome spectral congestion at the lower microwave frequency [1–5]. Millimeter-wave in RoF also could achieve the advantage of high-speed, high-capacity, high-quality and multiservice, for the broadband access applications [6]. In accordance with the heterodyne detection of two signals in a photodetector (PD) and mode-locked semiconductor lasers can not only achieve these advantages as above, but also reduce the dispersion effect and reference frequency for the carrier generation [7, 8]. Besides, based on the past study [9], using multi-mode Fabry–Perot laser diode (FP–LD) and erbium-doped fiber amplifier by ring loop scheme to generate dual-wavelength output was complex and expensive. And, the longer loop cavity was hard to control the polarization status and maintain stable lasing light output.

In this paper, we propose and experimentally investigate a 140 GHz mm-wave source using a self-locked dual-mode Fabry–Perot laser diode (FP–LD) serving as the optical mm-wave generator. The proposed laser scheme is not only simple and cheap, but also is easy to generate dual-mode. Moreover, the mm-wave signal could be modulated externally at 10 Gb/s on-off keying (OOK) with 1.6 dB power penalty at the bit error rate (BER) of 10^{-9} in 20 km single-mode fiber (SMF) transmission.

2. EXPERIMENTS AND RESULTS

Figure 1 presents the experimental setup of proposed optical mm-wave source by self-injection laser technology. The dual-wavelength laser (mm-wave) generator was consisted of two bandpass filters (BPFs), two polarization controllers (PCs), a 1 × 2 optical coupler (CP), a 2 × 2 CP, a fiber mirror (FM),

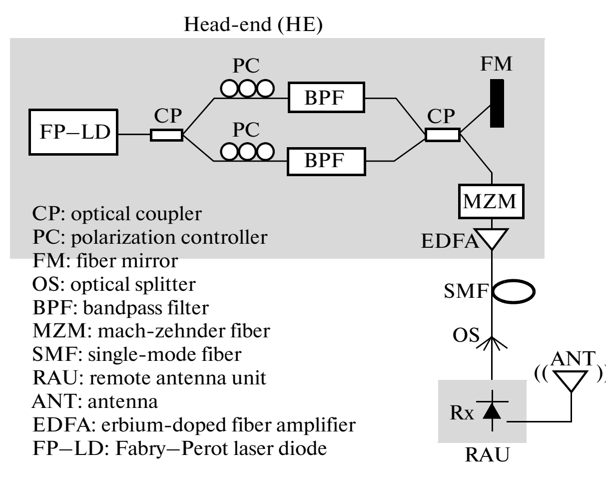

Fig. 1. Experimental setup for the proposed optical mm-wave laser scheme.

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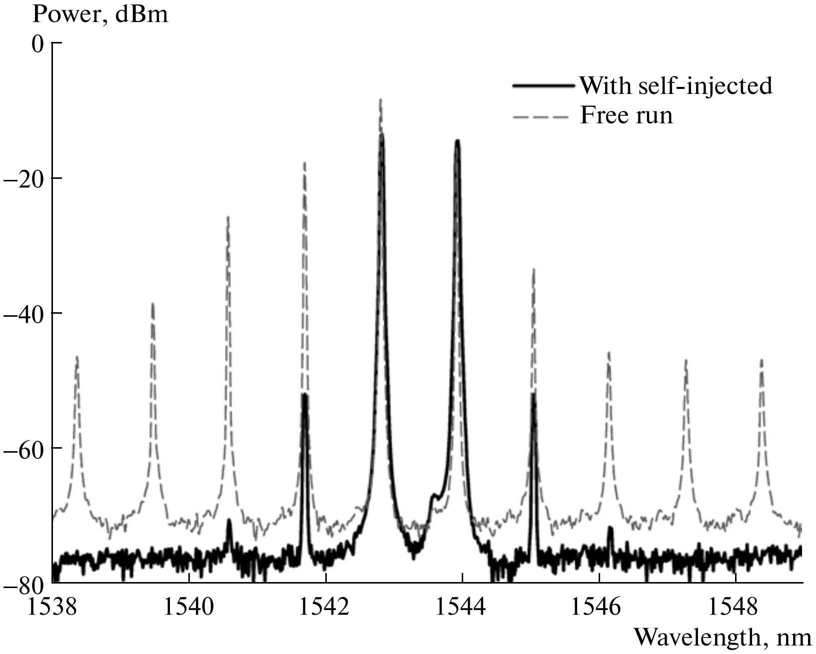

Fig. 2. Output spectra of FP–LD used in the proposed mm-wave generator before and after optical injection.

and a multi-longitudinal-mode (MLM) FP–LD. Besides, as illustrated in Fig. 1 the head-end (HE) can carry the dual-wavelength by the proposed laser via fiber to each remote antenna unit (RAU) to transmit mm-wave signal for end-users.

To obtain dual-wavelength output from MLM FP–LD, two BPFs having 3-dB bandwidth of 0.4 nm, were used to connect to FP–LD via 1 × 2 CP to match two corresponding modes of FP–LD. And, the selected dual-mode would be reflected via the FM with 99.5% reflectivity for self-injected mechanism. The two PCs were employed to adjust the properly polarization status and maintain the maximum output power for the mm-wave signal. In this experiment, the MLM FP-LD was operated at 30 mA at the temperature of 25°C.

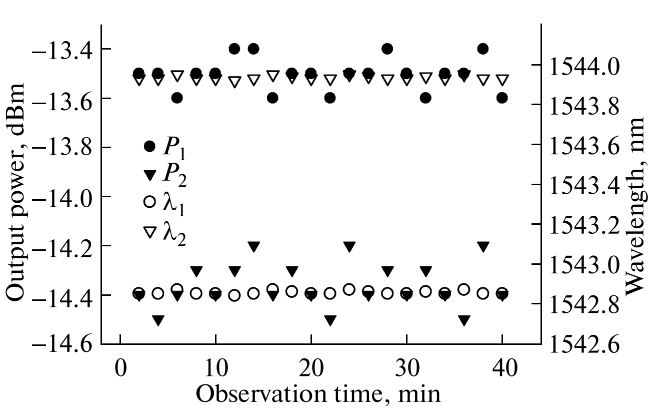

Fig. 3. The output stabilities of output power and wavelength over 40 min observing time.

Here, Fig. 2 illustrates the originally output spectrum of MLM FP–LD (dash line) used with the 1.11 nm mode spacing ($\Delta\lambda$) before optical self-injection. The central wavelength of MLM FP–LD was measured at 1542.82 nm. Therefore, the two central wavelengths of BPFs were selected at 1542.82 and 1543.93 nm to filter the dual-wavelength for self-injection. When the optical injection is done, the solid line of Fig. 2 presents the output dual beat-mode spectrum of the proposed mm-wave signal before applying on the modulated data by an optical spectrum analyzer (OSA) with a 0.01 nm resolution. The output spectrum of dual beat-mode is also measured at the wavelengths of 1542.82 and 1543.93 nm, as shown in Fig. 2. And the measured peak powers were –13.5 and –14.4 nm (power difference $\Delta P = 0.9$ dB) for the dual-wavelength. Besides, two side-modes of 1541.69 and 1545.04 nm are also induced due to the four wave-mixing (FWM) effect, as also illustrated in Fig. 2. Besides, the maximum side-mode suppression ratio (SMSR) of the proposed dualmode laser can achieve 37 dB. As seen the past studies [10–19], they used the Sagnac loop, high-birefringence fiber loop mirror or nonlinear soliton designs based on erbium-doped and ytterbium-doped fiber ring cavity utilizing optical filters inside cavity to achieve dual-wavelength output. However, due to the longer fiber ring cavity in these laser schemes, it would result in the unstable and multi-longitudinal-frequency output performances comparing with our proposed mm-wave laser configuration.

To investigate the output stabilization of the proposed dual-wavelength laser, a short-term observation of the output powers and wavelengths was measured,

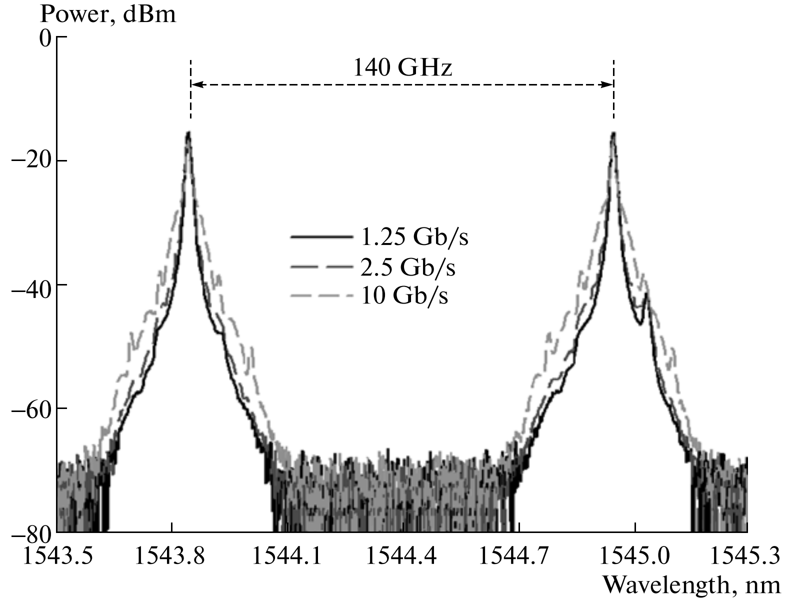

Fig. 4. Output spectra of the dual beat wavelength while the beating signal without and with externally modulation using NRZ format to generate OOK signal at the data rate of 1.25, 2.5, and 10 Gb/s, respectively.

as shown in Fig. 3. The lasing two wavelengths were at 1542.82 and 1543.93 nm (λ_1 and λ_2) with initially and the observation time was over 40 min. In Fig. 3, the wavelength variations of λ_1 and λ_2 for the proposed mm-wave laser can dramatically reduce to 0.03 and 0.04 nm. And the power fluctuations of P_1 and P_2 are 0.2 dB, as seen in Fig. 3. During two hours observing-time, the stabilized output of the proposed mm-wave laser is still maintained.

In the measurement, the dual-wavelength could be modulated by a Mach–Zehnder modulator (MZM). And the erbium-doped fiber amplifier (EDFA) was used to compensate the insertion loss of MZM, as seen in Fig. 1. This EDFA module has a saturation power of 15 dBm with the noise figure of 6 dB. Thus, Fig. 4 shows the output spectra of the dual beat wavelengths while the beating signal without and with externally modulation using a non-return to zero (NRZ) format to generate on-off keying (OOK) signal at the rates of 1.25, 2.5, and 10 Gb/s, respectively. Here, Fig. 5a shows its corresponding eye diagrams at the bit error rate (BER) of 10^{-9} before transmission. These eyes are clear and widely open. Besides, the self-injection dual-beating mode could be proved in coherence by the past study [20]. Furthermore, comparing with two CW lights from two distributed feedback: laser diodes (DFB–LDs) to act as dual-beating mode, modulating at 1.25, 2.5, and 10 Gb/s OOK format by MZM, respectively. Thus, Fig. 5b shows the corresponding eye diagrams at different modulation rates under the BER of 10^{-9} before transmission. The measured eyes are not better than that of proposed laser due to the incoherent characteristic.

In the experiment, the dual beat-mode signal was modulated at 1.25, 2.5, and 10 Gb/s by MZ modulator, respectively, using the NRZ pseudo random binary sequence (PRBS) with pattern length of 2^{31}–1. At the Rx end, a high speed PD could be used to convert the optical data to RF data at the carry frequency of 140 GHz (generated by the heterodyne beating at the PD), and then emitted by the antenna (ANT). In this

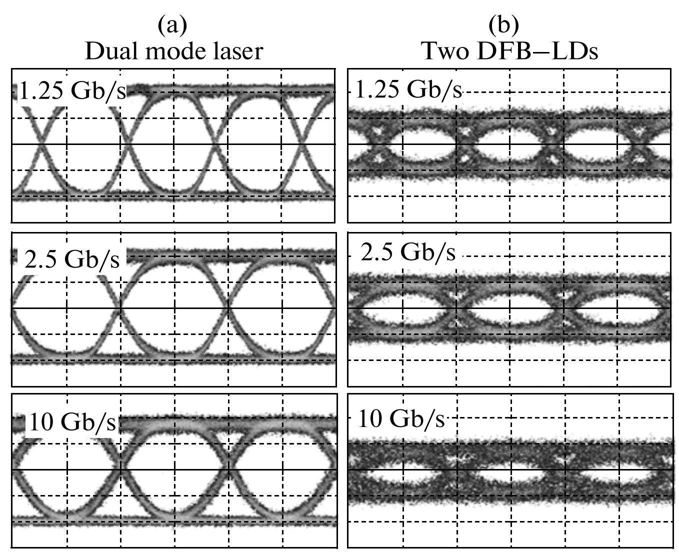

Fig. 5. The corresponding eye diagrams of (a) proposed dual-mode laser and (b) two DFB–LDs, modulating at 1.25, 2.5, and 10 Gb/s data rate by. a MZM at BER of 10–9, respectively.

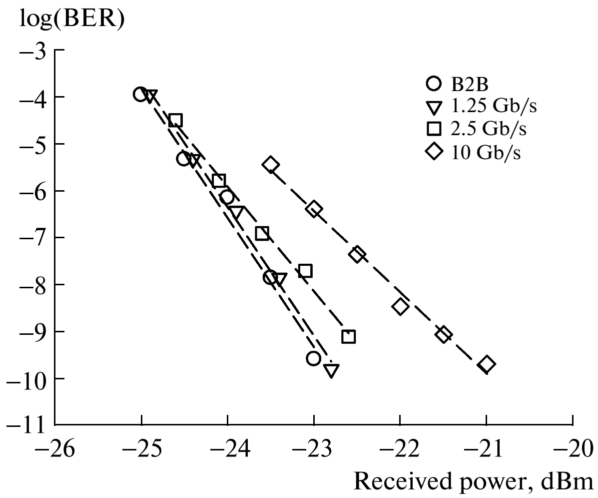

Fig. 6. BER curves at 1.25, 2.5, and 10 Gb/s NRZ direct modulations under B2B and 20 km long transmission distances, respectively.

proof-of-concept demonstration, due to the unavailable of a high speed PD at the laboratory, a PD with low-pass 2.5 GHz bandwidth (Bessel third order) was used to detect the signal. Besides, to investigate and realize the mm-wave over fiber performance, the BER measurements are also performed. Figure 6 presents the BER spectra at 1.25, 2.5, and 10 Gb/s NRZ modulations under B2B and 20 km long transmission distance, respectively. Here, the power penalties of 0.2, 0.6, and 1.6 dB at the BER of 10^{-9} are observed under 1.25, 2.5, and 10 Gb/s OOK rate after through 20 km fiber transmission, respectively, as seen in Fig. 6. Hence, it is noted that two optical carriers travels the fiber and would cause the differential propagation delay. The propagating effect would induce the power penalty due to the chromatic dispersion of fiber [21].

3. CONCLUSION

In summary, we have proposed and experimentally investigated a 140 GHz mm-wave source by using dual-mode self-locked FP–LD scheme for terahertz application. In the experiment, the mode spacing (Δλ) of MLM FP–LD used was ~1.11 nm. The created dual-wavelength also can be also modulated at 1.25, 2.5, and 10 Gb/s with OOK modulation format by external optical modulator, respectively, in 20 km fiber transmission. In addition, the dual-mode laser can be selected in difference wavelengths by tuning the optical filter inside cavity for the future WDM applications.

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