A 240-GHz active mode-locked laser diode for ultra-broadband fiber-radio transmission systems

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Abstract: A 240-GHz optical millimeter-wave signal with very narrow linewidth (<10Hz) is generated using an active mode-locked laser diode integrated with a high-mesa electroabsorption modulator. Fiber-radio transmission of 3-Gbit/s data at 240 GHz is also demonstrated.

OCIS codes: (140.5960) Semiconductor lasers; (140.4050) Mode-locked lasers; (320.7080) Ultrafast devices

1. Introduction

Wireless transmission of multi-channel non-compressed high-definition television signals is attracting great interests for various applications such as relaying broadcasts of live events and telemedicine. Since the data rate for transmitting such information amounts to multi-gigabits per second, its wireless transmission requires millimeter waves (MMWs) exceeding 100 GHz. Recently, 10-Gbit/s wireless data transmission over a 120-GHz carrier has been achieved using photonic techniques for the generation, modulation, and emission of MMW signals [1]. Further increasing the data rate requires the development of devices operating at higher frequency, such as at around 240 GHz, which is located in one of the atmospheric windows. The generation of optical MMW signal at frequencies higher than 100 GHz has been achieved by both a passive mode-locked laser diode (MLLD) [2, 3] and an active MLLD [4]. Since an active MLLD can synchronize its output signal frequency with electrical RF input, its frequency is quite accurate and stable, which is required for wireless transmission systems. In this paper, we report the generation and transmission of broadband wireless signal at around 240 GHz using a newly developed active MLLD. The use of a high-speed high-mesa electroabsorption (EA) modulator gate enables the active MLLD to generate a 240-GHz optical MMW signal with a 1/3-subharmonic-frequency (80-GHz) RF input.

2. Device structure

Fig. 1 is a schematic drawing of the fabricated MLLD. The device structure is basically similar to that of our 160-GHz active MLLD [4]. It consists of a gain section, a chirped distributed Bragg reflector (DBR), and an integrated high-mesa EA-modulator gate. The gain section consists of an InGaAsP multi quantum well (MQW) active layer buried with InP. At the left end of the gain section, the chirped DBR is formed on the MQW active layer by electron-beam lithography and chemical etching. The total cavity length was set to 175 µm for obtaining a 240-GHz repetition frequency. The DBR design was largely modified from that of the previous device [4]. To achieve lasing with at least two longitudinal modes 240-GHz apart, the reflection bandwidth was enlarged to about 10 nm by increasing the coupling coefficient to 230 cm^{-1}. The peak reflectivity was set to 50% to compensate for the large cavity loss. The EA modulator section is made of InGaAsP MQWs sandwiched by InP. These layers are processed into a 2.5-µm-wide and 4.0-µm-deep high-mesa waveguide by reactive ion etching and then buried with polyimide, on which a pad electrode is formed. With this structure, the EA modulator can be directly operated by 80-GHz electrical signal. The EA modulator section and the gain section are connected in the buried waveguide region using the butt-joint regrowth technique. On the right end of the EA modulator section, a rear mirror is formed using a cleaved facet coated with high-reflection films. The front facet is coated with anti-reflection films.

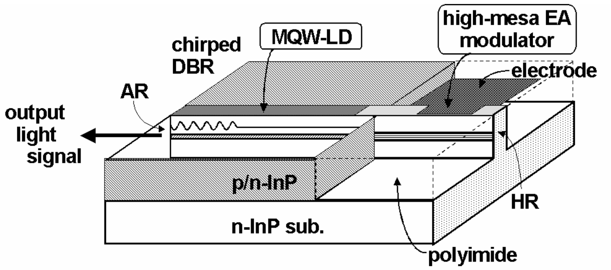


Fig. 1. Schematic drawing of the MLLD integrated with a high-mesa EA modulator.

3. Results and discussions

The light-output versus current characteristics of the MLLD were measured under continuous-wave operation conditions at 25 ^{0}C. The threshold current of this laser was 19 mA. By supplying a 79.78-GHz RF signal to the EA modulator together with a reverse bias of 0.76 V and a DC current of 34.4 mA to the gain region, a 239.34-GHz optical pulse train was generated. Here, the power of the applied RF signal was about 13 dBm. Fig. 2(a) shows the autocorrelation waveform of the obtained optical pulses, its fitting result, and the decomvoluted waveform. The optical modulation index obtained by fitting is about 94.9%. To the best of our knowledge, this is the highest repetition frequency ever achieved by an active MLLD. Fig. 2(b) shows the optical spectrum of the output of the MLLD together with the designed value for the DBR reflectivity. The operation conditions are the same as those for Fig. 2(a). A large spectral bandwidth was achieved by the newly designed DBR. The spacing of the two dominant modes is about 1.92 nm, which coincides with the pulse repetition frequency. Weak components located 0.64-nm away from the two dominant modes originate from the amplitude modulation caused by the EA modulation at 79.78 GHz. However, the amplitude modulation does not affect the MMW data transmission because its frequency is sufficiently far from the wireless transmission band.

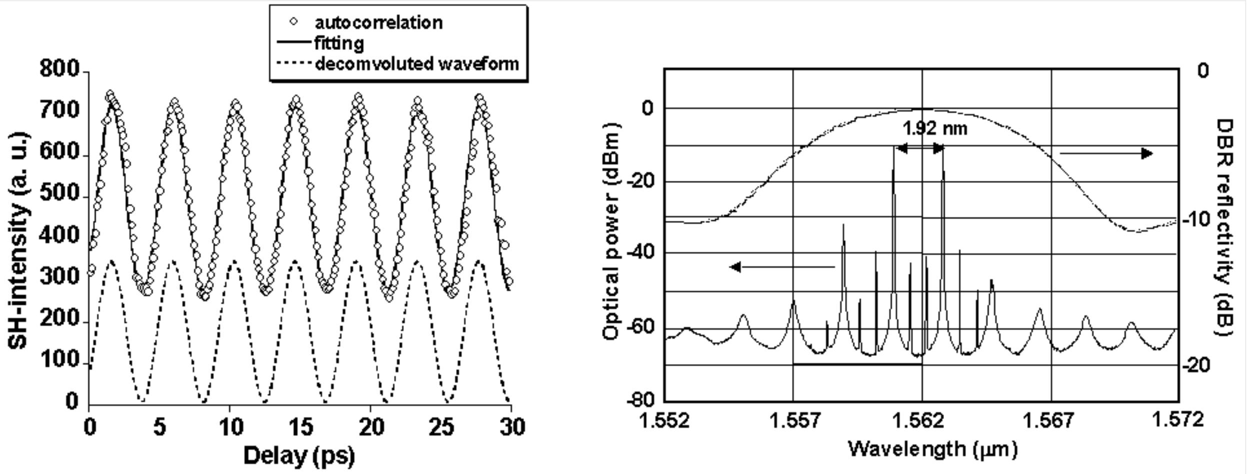
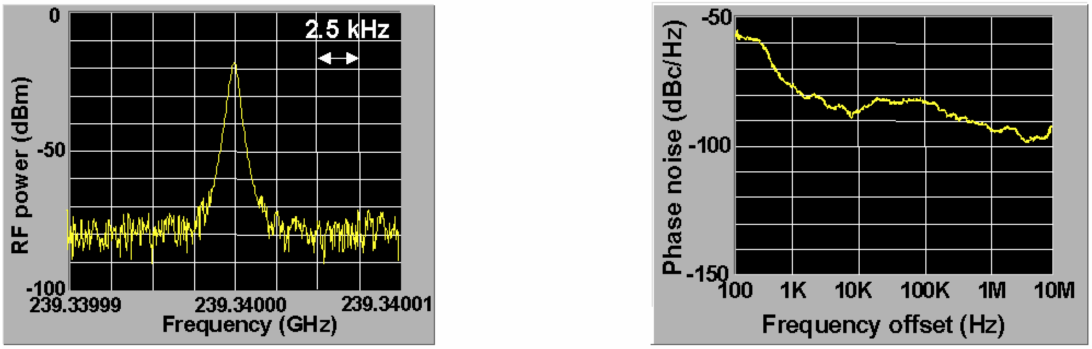


Fig. 2. (a) Autocorrelation waveform of the output of the 240-GHz MLLD. (b) Optical spectrum of the output of the 240-GHz MLLD.

To confirm the synchronization of the output signal with the external clock signal and evaluate the phase noise, the 240-GHz optical output signal was modulated by a 50-GHz signal with an external phase modulator. By using a beat signal between the second-order modulation sidebands of the original modes, the 240-GHz optical signal was down-converted to 40 GHz (240 - 2 x 2 x 50 = 40). Fig. 3(a) shows the RF spectrum of the down-converted signal after the O/E conversion. It was confirmed that the MLLD was operated at exactly triple the input frequency with very narrow linewidth of less than 10 Hertz. Fig. 3(b) shows the phase noise of the down-converted signal. The typical value for the phase noise at a 10-kHz offset and the timing jitter obtained from this measurement were -86 dBc/Hz and 0.38 ps, respectively. Although the value of the timing jitter is still higher than that of the input electrical signal (0.05 ps), we believe that we can reduce it by raising the modulation efficiency of the EA gate by further improving the high-frequency performance of the EAM.



(a)

(b)

Fig. 3 (a) RF spectrum of the down-converted 240-GHz signal. (b) Single sideband phase noise of the down-converted signal.

Finally, we tried to transmit a wireless data signal using a 240-GHz carrier generated using the MLLD. Fig. 4(a) shows the experimental setup. The amplitude of the optical MMW signal was modulated by a 3-Gbit/s pseudo-random binary sequence (2^7-1) using a $LiNbO_3$ Mach-Zehnder modulator (MZM). The optical signal was then amplified with an erbium-doped fiber amplifier (EDFA), passed through an optical band-pass filter, and transmitted through a 1-km-long standard single-mode fiber to a remote antenna site.

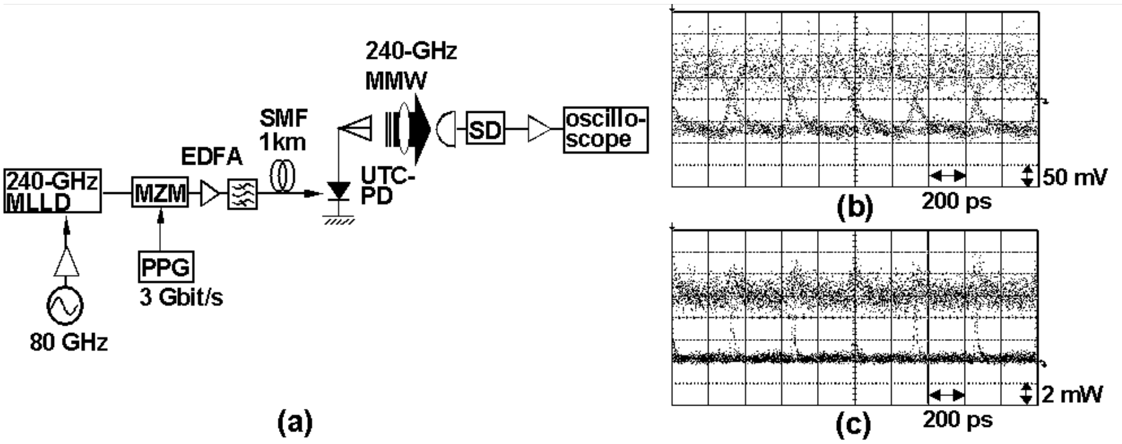


Fig. 4. (a) Experimental setup for wireless data transmission. (b) Eye pattern of demodulated PRBS data after transmission. (c) Eye pattern of the optical output of the MZM.

At the remote antenna site, a uni-traveling-carrier photodiode (UTC-PD) module with a WR-6 waveguide output port [5] converted the transmitted optical subcarrier into an MMW signal. Although this UTC-PD module was not optimized for operation at 240 GHz, it can output about -11-dBm MMW for 12.5-dBm optical input. The UTC-PD module was connected to a horn antenna, by which the MMW signal was radiated. The transmitted wireless signal was collimated by a dielectric lens and received by a Shottoky diode (SD) module integrated with a log-periodic toothed planar antenna and a Si hyper-hemispherical lens. The distance between the UTC-PD module and the SD module was about 10 cm. The SD module demodulated the MMW signal into the baseband signal. The output signal was amplified and observed with a sampling oscilloscope.

Fig. 4(b) shows the eye pattern of demodulated PRBS data at 3 Gbit/s after transmission in free space. Clear eye openings are observed. To the best of our knowledge, 240 GHz is the highest carrier frequency ever used for wireless data transmission. We think the signal to noise ratio of the transmitted data can be further improved by employing RF amplifiers operating in the G band [6] and a photodetector properly designed for 240-GHz operation. For comparison, we also observed the eye pattern of the optical output of the MZM on a sampling oscilloscope with an optical plug-in module. A rise and fall time as short as 25 ps indicate that the MZM used has a potential for operation at 20 Gbit/s. Thus, the smaller phase margin for the wireless transmitted data mainly comes from the inadequate electrical packaging of the SD module. These results demonstrated that the quality of the output signal of the 240-GHz MLLD is suitable for broadband wireless data transmission at 20 Gbit/s or higher.

4. Conclusion

We successfully generated a 240-GHz optical MMW signal with very narrow linewidth (< 10 Hz) using an active MLLD integrated with a high-mesa EA-modulator. We also demonstrated a wireless transmission of 3-Gbit/s data at 240 GHz and observed clear eye openings. These results clearly indicate that the fabricated MLLD is promising for use in future 240-GHz broadband wireless transmission systems at data rates of over 20 Gbit/s.

5. References

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