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A monolithically integrated dual-mode laser for photonic microwave generation and all-optical clock recovery

Liqiang Yu, Daibing Zhou and Lingjuan Zhao

Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Science, Beijing 100086, People's Republic of China

E-mail: yuliqiang10@semi.ac.cn

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Abstract

We demonstrate a monolithically integrated dual-mode laser (DML) with narrow-beat-linewidth and wide-beat-tunability. Using a monolithic DFB laser subjected to amplified feedback, photonic microwave generation of up to 45 GHz is obtained with higher than 15 GHz beat frequency tunability. Thanks to the high phase correlation of the two modes and the narrow mode linewidth, a RF linewidth of lower than 50 kHz is measured. Simulations are also carried out to illustrate the dual-mode beat characteristic. Furthermore, using the DML, an all-optical clock recovery for 40 Gbaud NRZ-QPSK signals is demonstrated. Timing jitter of lower than 363 fs (integrated within a frequency range from 100 Hz to 1 GHz) is obtained.

Keywords: photonic microwave generation, semiconductor laser, dual-mode laser diode, all-optical clock recovery

(Some figures may appear in colour only in the online journal)

1. Introduction

Microwave photonics has been defined as the study of photonic devices operating at microwave frequencies. Its applications include radio-over-fiber (RoF) networks, sensor networks, radar, satellite communications and warfare systems [1–3]. Unlike traditional schemes of generating microwave signals within electric circuits and transmitting through coaxial cables, photonic generation of microwave signals offers a simple method to generate optical carrier signals and transmit them through cost-reduced and low-attenuation optical fibers over long distances. A number of photonic microwave generation techniques have been investigated. One approach is to use mode-locked lasers for monolithic photonic microwave generation, but the microwave frequency is usually restricted by the fixed cavity length [4]. Another option is to use an optical phase lock loop to obtain high-quality frequency-tunable microwaves. However, it requires a microwave reference source for phase stabilization, which increases the complexity and cost of the system [5]. Alternatively, an optoelectronic oscillator (OEO) can generate photonic microwave signals with excellent frequency stability through attaining a high-quality factor using a very long fiber loop [6]. But, the construction of an OEO often requires other high-frequency components, such as microwave filters, microwave amplifiers, photodetectors (PD) and optical modulators. The electronic bandwidths of these components limit the frequency tunability of the microwave signals [7].

Recently, dual-wavelength single-longitudinal-mode (DW-SLM) lasers have offered much promise for tunable photonic microwave or mm-wave generation [8–13]. By using two optical waves detuned at a desired frequency beating directly at a photodetector (PD), this optical heterodyning scheme can be used to generate tunable microwave signals at low cost and free of external microwave sources. Yet, the current challenge of using an optical heterodyning scheme as a microwave generator is to reduce the linewidth of the beating signal, since very-narrow-spectral-linewidth signals are required in microwave systems [2]. For example, Kim *et al* have reported a widely tunable mm-wave generator consisting of a distributed feedback (DFB) laser and a distributed Bragg reflector (DBR) laser within a single resonator [12]. However, the heterodyned signal had a spectral linewidth of a few megahertz. Price *et al* demonstrated a microwave source based on

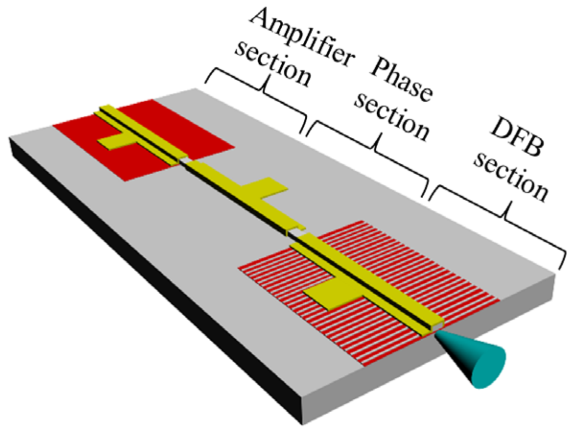

Figure 1. Schematic diagram of the dual-mode laser diode.

two surface-etched DBR lasers with outputs combined by a y-branch coupler, where, however, the spectral linewidth was also around 1 MHz [13].

In this letter, we present a monolithically integrated dual-mode laser (DML) using a DFB laser combined with a feedback cavity. By tuning the feedback strength, continuously tunable dual-mode lasing is realized. Thanks to the high phase correlation and efficient mode beat of the two modes, photonic microwave generation with narrow-beat-linewidth is obtained. The frequency stability of the beat signal is also demonstrated. Furthermore, using the DML, we realize an all-optical clock recovery and the recovered optical clock has a root-mean-square (RMS) timing jitter of 363 fs (integrated in the 100 Hz to 1 GHz range).

2. Device fabrication and performances

Figure 1 shows a schematic diagram of the monolithic dual-mode laser diode, which consists of a DFB section, a phase section and an amplifier section. A number of the laser diodes with various section lengths are measured and show similar dual-mode outputs. Typical results presented here are obtained from a device with a 220 μm DFB section, a 240 μm phase control section, and a 320 μm amplifier section, where the short (< 600 μm) feedback cavity enables us to obtain a beat frequency of up to 45 GHz. While the DFB section works in a single mode by itself, the optical feedback to the DFB section can give comparable threshold gains to two compound-cavity modes, the beat of which gives rise to a microwave output in a PD. In the laser diode, the phase and the amplifier sections act as a feedback cavity and allow the feedback strength and phase to be controlled via tuning the injection currents, and accordingly, the beat frequency can be tuned. A theoretical analysis has been previously carried out in [14].

The device structure is grown by metal organic chemical vapor deposition (MOCVD) on n-InP substrates. This structure has a symmetrical cladding and the active region is composed of six undoped InGaAsP quantum wells with a 1.55 μm photoluminescence (PL) peak. A band-gap wavelength shift of 120 nm between the gain sections and the passive region is achieved by quantum well intermixing (QWI). After that,

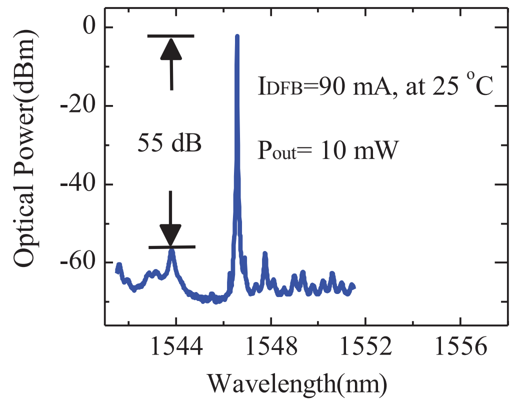

Figure 2. Optical spectrum of the laser diode when operating in single mode. Here, I_{DFB} = 90 mA, $I_{amplifier}$ = I_{phase} = 0 mA.

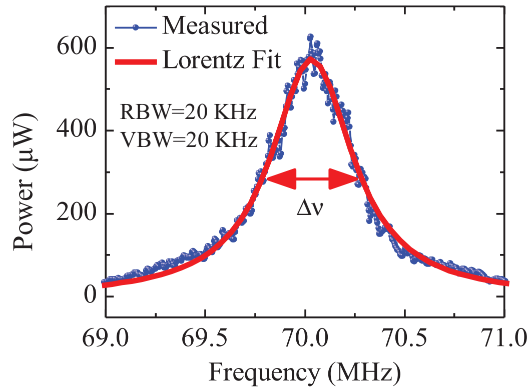

Figure 3. Self-heterodyned spectrum of the laser operating in single mode.

a grating is formed in the cladding layer of the DFB section through holographic lithography and dry etching. Then, the growth of p-doped top cladding is done still by MOCVD. A 3 μm ridge-waveguide is formed to minimize the thermal saturation while preserving lateral single-mode operation. 30 μm isolation sections between each section are accomplished by etching the p-InGaAs layer off and He+ implantation. A Ti-Au metal layer is sputtered on the p-InGaAs contact layer to form a p-contact. After the substrate is thinned, Au-Ge-Ni metal is evaporated on the backside. Finally, chips composed of a 220 μm DFB section, a 240 μm phase control section, and a 320 μm amplifier section are cleaved with both sides uncoated.

The laser from the uncoated facet of the DFB section is coupled into a tapered single mode fiber and tested by an optical spectrum analyzer (OSA, Advantest Q8384). The threshold current of DFB is 24 mA. When the DFB current is 90 mA and other sections are unbiased, the laser diode operates in a single-mode with an output power of 10 mW. The optical spectrum is shown in figure 2, in which a 55 dB side mode suppression ratio (SMSR) is obtained. Then, the spectral linewidth of the laser is measured using a delayed self-heterodyning method with a 70 MHz acoustooptic modulator and a 25 km single mode fiber (SMF). An example of the self-heterodyned spectrum observed on the electrical spectrum analyzer (ESA, Agilent N9030A) is shown in figure 3. The measured FWHM linewidth is 498 kHz at a DFB current of 90 mA, resulting in

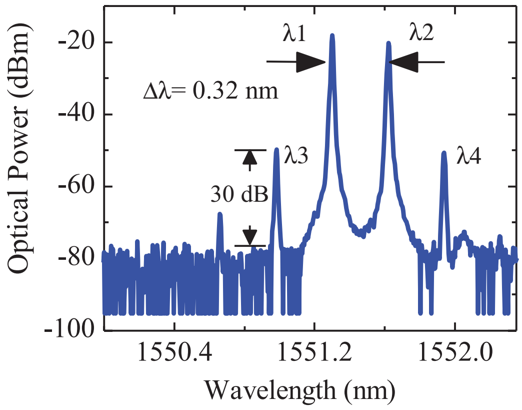

Figure 4. Dual-mode-lasing optical spectrum of the laser diode when the amplifier current increases to 58 mA.

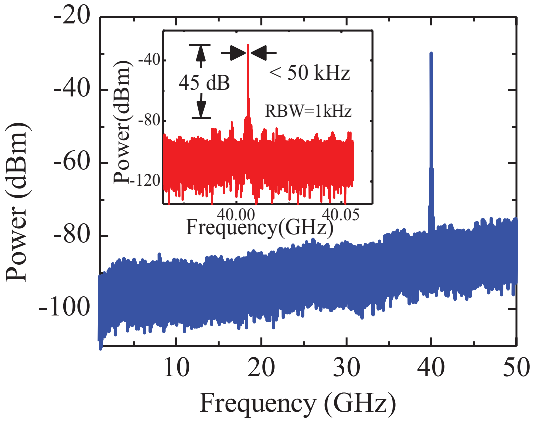

Figure 5. RF spectrum of the 40 GHz beat signal. The inset shows the detailed spectrum with a RBW of 1 kHz.

a linewidth value of 249 kHz. This narrow spectral linewidth will be beneficial to reduce the beat linewidth.

Then a dual-mode operation is obtained when the amplifier section is biased. An example of dual-mode output is shown in figure 4, where the DFB, amplifier, and phase currents are 90 mA, 58 mA and 0 mA, respectively. The mode spacing ($\Delta\lambda$) is 0.32 nm, which corresponds to a beat frequency of around 40 GHz. The satellites (λ_3 and λ_4), separated from the main peaks by the same spacing, are due to four-wave mixing (FWM) of the two coexisting modes (λ_1 and λ_2 [14]). The power level of the FWM signal is over 30 dB from the spontaneous emission level. The presence of such intense mixing products signifies a high phase correlation and efficient mode beat of the two modes within the device [12]. Figure 5 shows the RF spectrum of the 40 GHz beat signal, where a microwave linewidth of less than 50 kHz with a carrier-to-noise ratio of 45 dB is obtained. The measured narrow-beat linewidth may be derived from the high phase correlation of the two modes. Besides, the narrow spectral linewidth of the laser diode could also be helpful to reduce the beat linewidth. The frequency stability is also measured, where the beat frequency is stable to within ~ 50 MHz.

Furthermore, the frequency tunability of the beat signal is also investigated by tuning the amplifier current. As an example, a dual-mode spacing increase from 0.24 nm to 0.34 nm is measured when increasing the amplifier current from 34 to

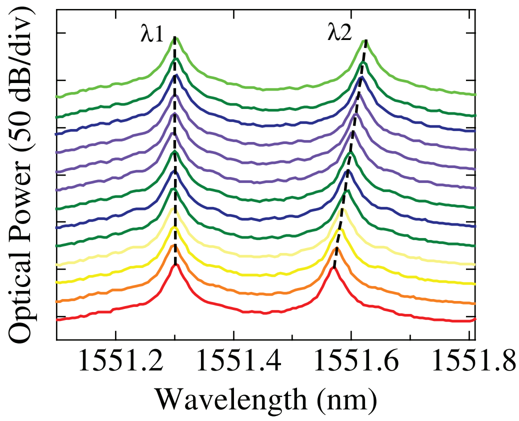

Figure 6. Wavelength tuning characteristics of the laser diode operating in dual mode when increasing the amplifier current from 34 to 58 mA.

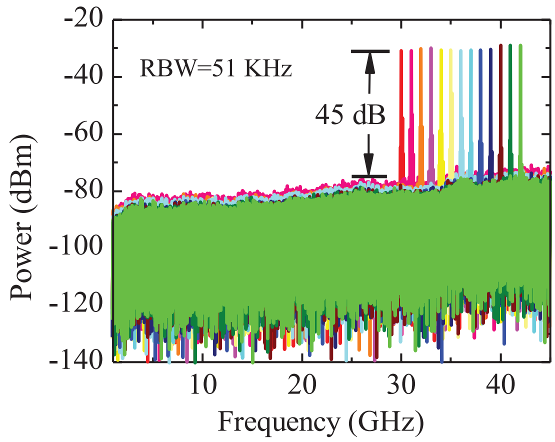

Figure 7. RF tuning characteristics of the laser diode for different amplifier currents. Here, RBW is 51 kHz.

58 mA, as shown in figure 6. Accordingly, figure 7 shows the RF spectra of the continuously increased beat frequencies from 30 GHz to 42 GHz, in which all beat signals show 45 dB carrier-to-noise ratios. Beat signals of higher than 45 GHz are obtained, when we further increase the amplifier current to 65 mA. The measured beat signals with the narrow-beat-linewidth, wide-beat-tunability and good frequency-stability indicate that the laser diode is well qualified as a photonic microwave generator.

In order to illustrate the dual-mode beat characteristic clearly, simulations are carried out using a commercial package VPItransmissionMaker^{TM}. Simulation results are shown in figure 8, where both single-mode and dual-mode operations are depicted through the frequency domain and time domain characteristics. For a single-mode lasing, the RF spectrum just resembles a noise floor, while for a dual-mode lasing, a fundamental frequency of around 40 GHz emerges. As shown in figure 8(*b*3), a uniform microwave signal is simulated, which indicates an efficient dual-mode beat.

3. Clock recovery and results

All-optical clock recovery (CR) using a dual-mode laser is a simple and low-cost method. Nevertheless, the quality of the

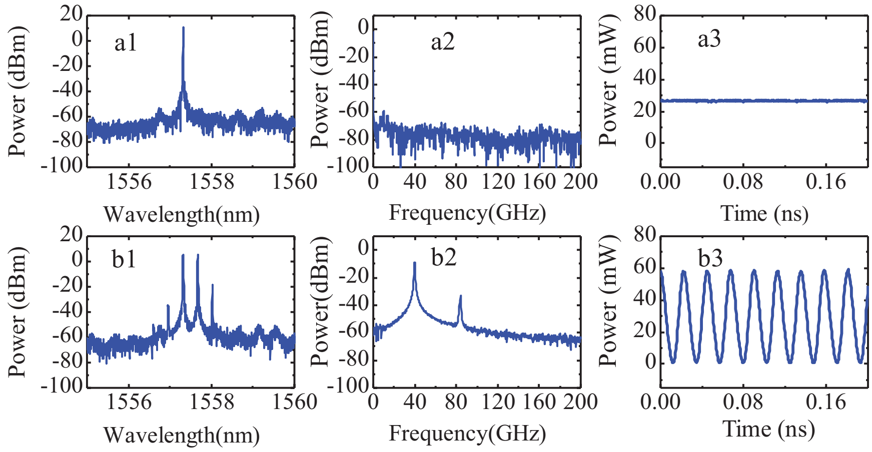

Figure 8. (*a*1)–(*a*3) Simulated optical spectrum, RF spectrum, and temporal waveform of the laser diode operating in single mode; (*b*1)–(*b*3) Simulated optical spectrum, RF spectrum, and temporal waveform of the laser diode operating in dual mode.

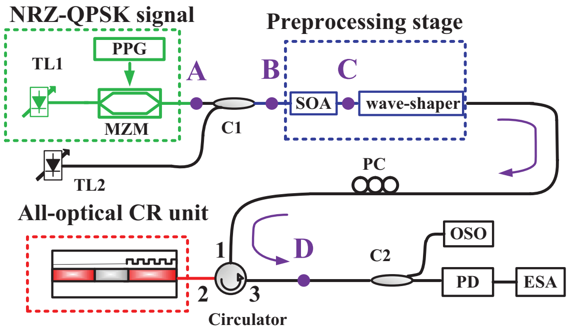

Figure 9. Experimental setup for the all-optical clock recovery. TL: tunable laser. PPG: pulse pattern generator. MZM: Mach–Zehnder modulator. SOA: semiconductor optical amplifier. PC: polarization controller.

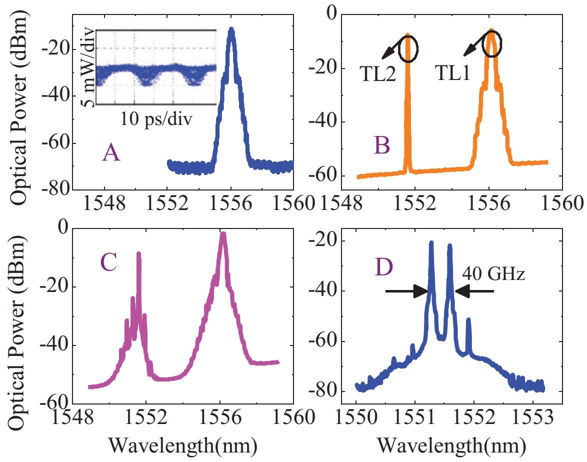

Figure 10. Optical spectra in the clock recovery setup. (*a*) After the MZM; (*b*) after the couple 1; (*c*) after the SOA; (*d*) after injection-lock.

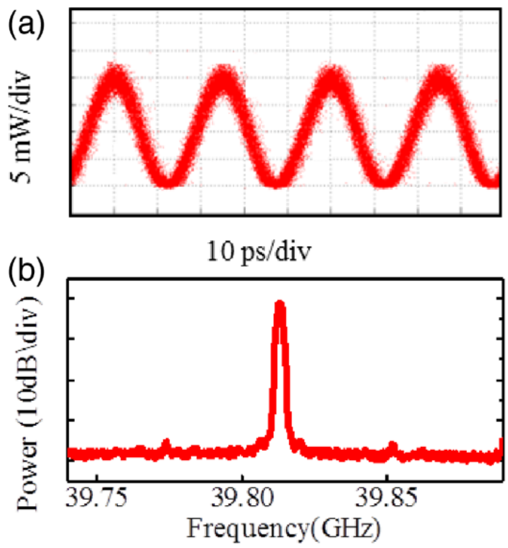

Figure 11. (*a*) Temporal trace of the recovered clock signal. (*b*) RF spectrum of the recovered clock signal.

recovered optical clock greatly relies on the RF linewidth of the free-running DML [15]. Here, in order to obtain a low-timing-jitter clock, we use the narrow-beat-linewidth laser diode to recovery the clock of the 40 Gbaud NRZ-QPSK signals. For MZM-generated NRZ-QPSK signals, the optical power will experience a temporary quick change as a bit changes its phase from one to another. This change in power will yield a weak clock tone in its modulation spectrum, which can be used to extract the optical clock.

Figure 9 shows the experimental setup of the proposed clock recovery with a preprocessing stage. A transmitter based on a Mach–Zehnder modulator driven by a pulse stream was used to generate NRZ-QPSK signals with a carrier wavelength of 1556 nm. The length of the pseudo random bit sequence (PRBS) pattern was 2^7–1. The coded signal was injected into the DML through an optical circulator and a lensed fiber. The recovered clock signal was then analyzed by an optical sampling oscilloscope (OSO) and ESA through a 50 GHz PD.

Figure 10(*a*) shows the measured optical spectrum and eye diagram of the input NRZ-QPSK signal. The wavelength of the tunable laser 2 is tuned to 1551.6 nm. The measured optical spectrum of the signal output from the couple 1 (C1) is shown in figure 10(*b*). Then, a SOA is used to eliminate the phase information in the incoming QPSK signal through cross gain modulation (XGM) effects, so as to 'purify' the clock

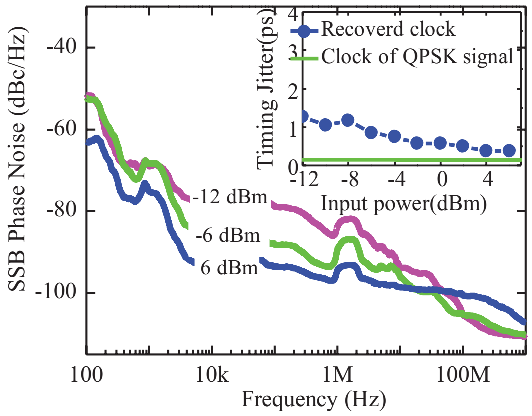

Figure 12. SSB phase noise spectral of the recovered clock under various input power values. Inset: dependence of the RMS timing jitter on the power of the injected signals.

tone in the incoming signal. After passing through a SOA, the phase information of the NRZ-QPSK signal is eliminated and the intensity variation is modulated on the CW light from TL2 through XGM. As shown in figure 10(*c*), some sidebands arise in the intensity-modulated light from TL2, which gives a clean clock tone. Following the SOA, a wave shaper is used to select the wavelength-converted signal. Then, the signal is set to the same wavelengths as that of the free-running DML so that one of the sidebands is aligned to one mode of the DML while the signal carrier is aligned to the other mode of the DML. After the injection of the clock-tone-enhanced signal into the DML, the lasing optical spectrum exhibits an injection-locked state due to the phase synchronization in the DML diode, as shown in figure 10(*d*). Finally, a synchronized clock is obtained from the beat of the two injection-locked modes.

Figures 11(*a*) and (*b*) show the typical temporal trace and RF spectrum of the recovered 40 GHz clock, respectively, in which the resolution bandwidth (RBW) is 510 kHz. Figure 12 shows the single sideband (SSB) phase noise of the recovered clock signal where the optical power values are varied from −12 dBm to 6 dBm, in which a significant suppression of the phase noise is obtained by increasing the input power. The input signal power value refers to the power of the optical signal out of port 2 of the circulator. The inset in figure 12 shows the dependence of the root-mean-square (RMS) timing jitter of the recovered clock on the power of the injected signal. When the injected power is 6 dBm, the lowest timing jitter of 362.8 fs is obtained in our experiment, where the timing jitter may be primarily from the input signal. It is worth noting that the timing jitter of 161 fs for the clock of the original QPSK signal is measured, which corresponds to the jitter noise floor, as shown by the blue solid line.

4. Conclusion

We have fabricated and demonstrated a monolithically integrated dual-mode laser (DML). Using a monolithic DFB laser subjected to amplified feedback, photonic microwave generation with narrow RF linewidth (<50 kHz) is obtained due to the high phase correlation of the two modes. Beat frequency of up to 45 GHz is obtained with larger than 15 GHz beat frequency tunability. It has been observed that the beat frequency can be stable to within ~ 50 MHz. Simulations are also carried out to illustrate the dual-mode beat characteristic. The results indicate that the DML is well qualified as a photonic microwave generator. Furthermore, using the DML, an all-optical clock recovery for 40 Gbaud NRZ-QPSK signals is demonstrated. Thanks to the narrow RF linewidth of the DML, a low timing jitter (~363 fs) is realized.

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