Dynamical Characteristics for Semiconductor Microdisk Laser Subject to Optical Injection

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Abstract— In this paper, the dynamic characteristics of four-wave mixing, period-one and period-two oscillations, and optical injection locking state are demonstrated for a 8-μm-radius directional-emission microdisk laser subject to optical injection. For the microdisk laser biased at 7 mA, the 3 dB bandwidth of the small signal modulation response is increased from 3.4 to 137 GHz due to the optical injection locking with an injected optical power of 0.5 mW.

The rapid development of computing systems, data centers, and other short reach datacom networks has driven the demand for optical output devices with higher bandwidth. One potential candidate to meet this requirement is the directly modulated semiconductor microlaser due to its compactness and low cost However, the 3 dB modulation bandwidth is ultimately limited by its relaxation resonance frequency for a typical semiconductor laser. Optical injection-locking is an effective technique to enhance the modulation bandwidth.

In this paper, dynamical characteristics are investigated for an 8-μm-radius microdisk laser connected with a 2-μm-width output waveguide subject to optical injection. Dynamic states under optical injection including four-wave mixing, period double and optical injection locking are observed at different detuning wavelengths, and the enhancement of the 3 dB bandwidth due to optical injection are demonstrated.

Microdisk lasers are fabricated using an AlGaInAs/InP laser wafer grown by metal-organic chemical vapor deposition, with the technique process similar as in [1, 2].

The scanning electron microscope (SEM) cross-sectional-view for a cleaved waveguide which is directly connected to a microdisk resonator is shown in Fig. 1(a), while the microscopic picture of a fabricated microlaser laser is shown in Fig. 1(b). The microdisk cavity is laterally confined by BCB cladding layer, on which a pad patterned P-electrode is formed using lifting off technology.

After cleaving over the output waveguide, the microdisk laser is bonded p-side up on an AlN submount and mounted on a thermoelectric cooler (TEC).

The output powers coupled into a tapered multi-mode fiber (MMF) are measured as functions of the continuous-wave (CW) injection current and plotted in Fig. 2(a) together with the corresponding applied voltage. The maximum output powers obtained at 296, 290 and 288 K are 115.5, 163.3 and 176.2 μW, respectively. A series resistance of 28 Ω is estimated from the VI curve, and the threshold current is about 5.5 mA at 288 K. The laser spectra are measured by an optical spectrum analyzer (OSA) at the resolution of 0.1 nm. The spectrum measured at 288 K for the microdisk laser is plotted in Fig. 2(b) at an injection current of 10 mA, which shows single mode operation at 1540.1 nm with the side mode suppression ratio (SMSR) of 35.4 dB.

The optical injection locking provides an effective and promising method for generating microwave signals as well as enhancement of modulation bandwidth Setting the output power of the tunable laser to 500 μW with the wavelength detuning $\Delta\lambda = \lambda_I - \lambda_C$ with λ_I and λ_C injection

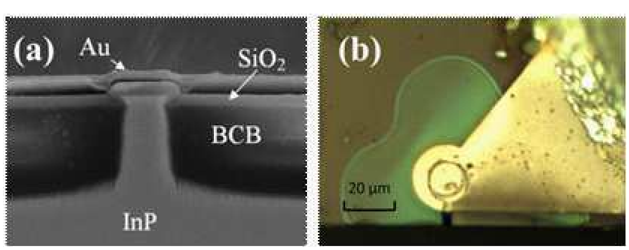

Figure 1: (a) SEM cross-sectional-view for a cleaved waveguide which is directly connected to a microdisk resonator, (b) the microscopic picture of a microdisk laser connected with an output waveguide.

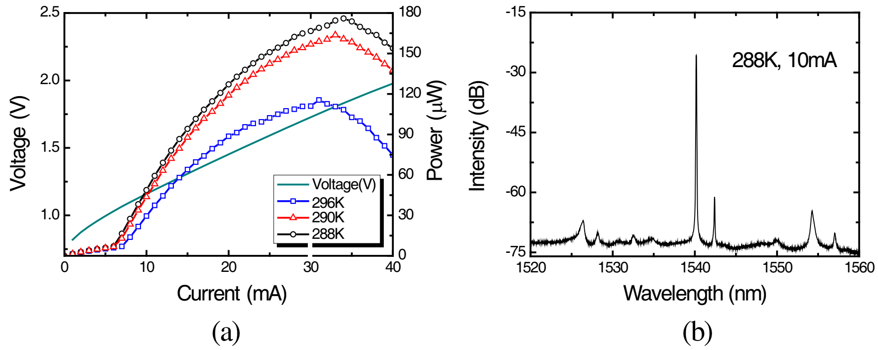

Figure 2: (a) MMF coupled power and the applied voltage versus CW injection current at 296, 290 and 288 K, and (b) laser spectra at the CW injection current of 10 mA for a 8-μm-radius microdisk laser at the temperature of 288 K.

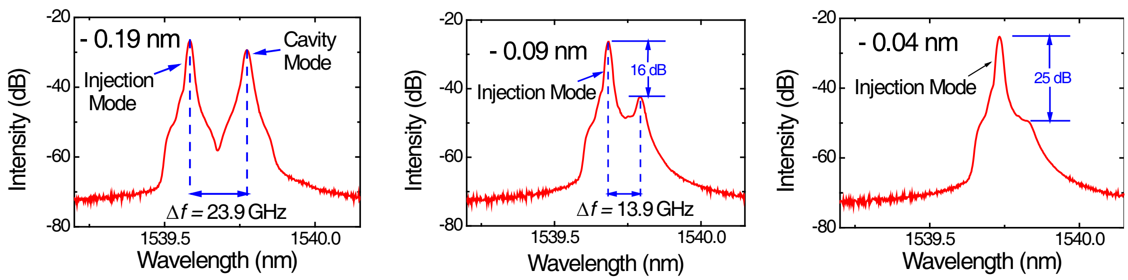

Figure 3: The measured lasing spectra at the wavelengths detuning $\Delta\lambda = -0.19$, -0.09 and -0.04 nm and injection power of 500 μW for the microdisk laser at the injection current of 7 mA.

light wavelength and the lasing mode wavelength, we firstly measure the impact of optical injection locking on the lasing spectra and dynamic performance for the microdisk laser biased slightly above threshold at 7 mA. The lasing spectra are plotted in Fig. 3 for the microdisk laser subject to optical injection at $\Delta\lambda = -0.19$, -0.09 and -0.04 nm. At $\Delta\lambda = -0.19$ nm, two clear peaks appear with the intensity difference of 2.7 dB, corresponding to the injecting mode and the lasing mode at the wavelengths of 1539.585 and 1539.775 nm, respectively. With the wavelength of the injection mode approaching the lasing mode, the intensity difference becomes 16 and 25 dB, respectively, at $\Delta\lambda = -0.09$ and -0.04 nm, and the optical injection locking is clearly observed at $\Delta\lambda = -0.04$ nm.

The small signal modulation response of the microlaser are measured by a 20-GHz-bandwidth network analyzer, at the free running state and subjection to optical injection. Using a high-frequency bias-T, the bias current together with the modulation is fed to the microdisk laser through a radio-frequency probe. The emitting light is coupled into a tapered single-mode fiber (SMF) and pass through an erbium-doped fiber amplifier (EDFA) followed by an optical band-pass filter, to suppress the amplified spontaneous emission noise. Afterwards, the output light is split into two waves by an optical fiber coupler. 1% of the output light is launched into an OSA, while 99% of the output is feeded into a high speed detector and then the converted high-frequency electrical signal is received by the network analyzer. Setting the TEC temperature of 288 K, small-signal modulation responses of the microdisk laser at biasing current of 7 mA are measured and plotted in Fig. 4 at the free running state and under optical injection locking at $\Delta\lambda = -0.04$ nm. At the free-running state, the microlaser has a 3 dB bandwidth of 3.4 GHz and a resonance frequency of 1.85 GHz. Under the optical injection locking with the optical power of 0.5 mW and $\Delta\lambda = -0.04$ nm, the 3 dB bandwidth is greatly enhanced by four times to 13.7 GHz for the microlaser under the injection locking.

The detail lasing spectra versus the detuning wavelength are measured and plotted in Figs. 5(a) and 5(b) at the injection optical power of 0.5 and 3 mW, respectively, for the microdisk laser at the injection current of 25 mA. As shown in Fig. 5(a), the optical injection locking is realized at the region I as $-0.04\,\mathrm{nm} < \Delta\lambda < 0.04\,\mathrm{nm}$, and multiple peaks of four-wave mixing are observed in the region II corresponding to a $\Delta\lambda$ ranged from -0.11 to -0.04 nm and 0.04 to 0.12 nm, respectively. In the region III, only one addition peak of four-wave mixing is observed. As the the injection optical power is 3 mW, the injection locking range is corresponding to the wavelength detuning

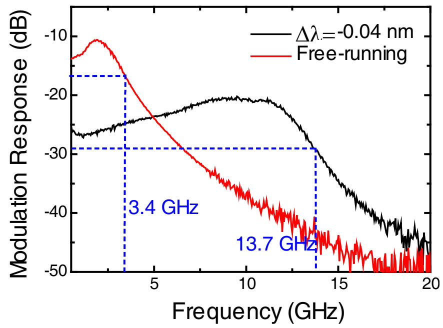

Figure 4: Small signal modulation response curves for the microdisk laser with the injection current of 7 mA at the free running state and subject to optical injection with $\Delta\lambda = -0.04$ nm and injection power of 0.5 mW.

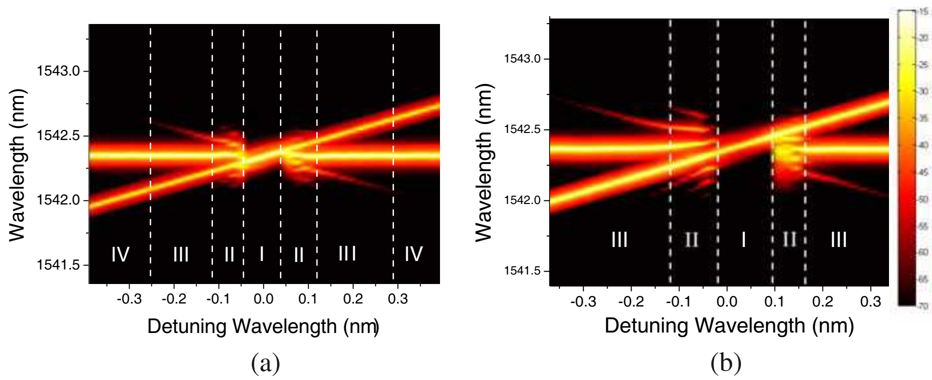

Figure 5: Lasing spectra versus wavelength detuning for the microdisk laser biased at 25 mA with the lasing wavelength of 1542.35 nm at the injection optical power of (a) 0.5 mW and (b) 3 mW, respectively.

from -0.02 to 0.09 nm, and clear four-wave mixing operation is observed for $\Delta\lambda$ ranged from -0.13 to -0.03 nm. Furthermore, period double states appear in the region II under the wavelength detuning from 0.09 to 0.16 nm.

In conclusion, optical injection locking, period double state, and the improvement of small signal modulation response have been demonstrated for an 8-μm-radius microdisk laser connected with a 2-μm-width output waveguide subject to optical injection. At the injection current of 7 mA, the optical injection locking enhances the 3 dB bandwidth from 3.4 to 13.7 GHz. The dynamic states under optical injection including four-wave mixing, period double and optical injection locking are demonstrated at different detuning wavelengths, and additional peaks appears at the halfway between the injection peak and the cavity peak similar to the period-doubling state is observed with the well-proportioned peak intensity in the central area.

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