Temperature stability of small-signal modulation response of WGM microlasers with InGaAs/GaAs quantum well-dots in the active region

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Abstract. In this paper, results are presented on III-V quantum well dot microring diode lasers tested at elevated temperatures. To the best of our knowledge, the first uncooled microdisk lasers with diameter of 40 µm with 3-dB bandwidth above 2 GHz at 55°C are demonstrated.

1. Introduction
Small-footprint lasers with narrow linewidth and low power consumption are a promising way of developing optical data transmission technology [1, 2]. Such lasers can be based on semiconductor resonators supporting whispering gallery modes (WGM), such as microdisks and microrings. Besides low power consumption and high Q-factor, these microlasers allow direct high-frequency signal modulation. Recently, we have proposed microlasers with active region based on quantum well-dots (QWDs) [3]. High output optical power was demonstrated for a 30 µm in diameter microdisk laser [4] tested at room temperature. High operation temperature and (or) self-heating leads to a decrease in the differential efficiency due to a decrease in the inverted population and an increase in the threshold pumping power due to additional optical losses on the free carriers. An increase in the internal temperature of the laser leads to saturation not only of the output optical power, but also of the resonance frequency. For example, in [5] the WGM microlasers were tested only at 287 K. In [6] microring operation at 20°C was studied. In [7] the 3-dB bandwidth decreases from 12.1 to 10.9 GHz as the temperature rises from 290 to 298 K.

Meanwhile, the reports on the dynamic characteristics of QWD-based microdisk/microring lasers at different temperatures are practically absent. In this work, we studied temperature dependence of small-signal modulation response of the microlasers with InGaAs/GaAs quantum well-dots in the active region.

2. Experiment
A laser heterostructure was grown by low pressure MOVPE on an n⁺-GaAs substrate with a surface off-axis oriented by 6° from the (100) plane. An active region represents 5 planes of quantum well-dots formed by the deposition of 8 monolayers of In₉₀Ga₅₀As and separated with 40 nm-thick GaAs.
spacers. The active region was placed in the middle of a 0.8 μm-thick GaAs waveguide. GaAs waveguide was inserted between n- and p- doped Al$_{0.39}$Ga$_{0.61}$As cladding layers. Microdisk and microring lasers with outer diameters $D_{\text{out}}$ varied from 10 to 50 μm were formed by photolithography and dry etching. Mesa height was chosen about 5 μm to ensure sufficient optical confinement of the whispering gallery modes. Sidewall verticality was controlled with the precision of 5 degrees. AgMn/NiAu and AuGe/Ni/Au metallization was used for formation of ohmic contacts to the p$^+$-GaAs cap layer and the n-doped GaAs substrate, respectively.

Microlasers were then planarized using SU-8 epoxy resist and contact pads were made over the epoxy planarization. A chip comprising a group of MDs of different diameters was soldered on a high-frequency submount suitable for connection using a ground-signal-ground (GSG) radio frequency probe. The top contact of the individual microlaser was connected to a signal line of the submount using a 50 μm-thick gold wire. High-frequency submount were soldered on a copper heat sink with indium and mounted on a heater to be tested at various temperatures. The emission from the investigated microdisk was collected by an Olympus LMPlan IR 100x objective lens, transmitted via an optical fiber, and detected by a Yokogawa AQ6370C optical spectrum analyzer. Dynamic characteristics were measured in the range from 50 MHz to 20 GHz with a New Focus 1434 25 GHz photodetector and an Agilent E8364B network analyzer (schematic layout is shown in figure 1).

![Figure 1. Schematic representation of setup for high-frequency measurement](image)

3. Results and discussion

3.1. Light-current and current-voltage characteristics

Figure 2 presents the light-current and current-voltage (I-V) characteristics of a microring laser with 20μm outer diameter obtained at room temperature. All the lasers demonstrated the diode behaviour with I-V characteristics fitted by equation $U=IR_s+U_0$, where $R_s$ – is series resistance and $U_0$ – is the turn-on voltage. A turn-on voltage values $U_0$ approximately correspond to the emission wavelength of the lasers near the threshold ($\sim$1.09 μm). The series resistance $R_s \approx 50 \ \Omega$. At the light-current characteristics the lasing behavior is observed with the threshold current of $\sim$7 mA.

The electroluminescence spectra were measured at injection currents below and above the threshold (spectra obtained at 5 and 21 mA are presented at Figure 3). At the spectra below the threshold one can observe broad line in 950-1150 nm spectral range, corresponding to spontaneous emission of InGaAs/GaAs QWDs. At the spectra above the threshold a dominant WGM lasing line is observed near 1100 nm.
3.2. Small-signal modulation response at different temperatures

Small-signal modulation response of the microlasers was measured in temperature range from 13°C to 55°C. Modulation response for a microring laser with 40μm outer diameter is presented in Figure 4. At the injection current of 16 mA the 3-dB bandwidth ($f_{3\text{dB}}$) drops from 3.7 GHz to 2.2 GHz when the sample is heated up on 42°C.

The most direct way to increase the modulation frequency is associated with an increase in the photon density in the cavity by increasing the injection current. However, self-heating of the laser with increasing the current leads to a decrease in the active area gain. As a result, the maximum achievable modulation frequency is limited by thermal effects. The 3-dB bandwidth as a function of injection current is presented in Figure 5. Increasing the current the maximal 3-dB bandwidth value of 3.7 GHz for 20-μm in diameter microlaser and 3.1 GHz for 40-μm in diameter microlaser is achieved. Near the
threshold, the experimental data can be described well as \( f_{3dB} = \text{MCEF} \cdot (I - I_{th})^{1/2} \) using the modulation current efficiency factor value (MCEF) as fitting parameter (solid lines in Figure 5). The value of MCEF drops from 1.5 GHz/mA\(^{1/2}\) at 13°C to only 1 GHz/mA\(^{1/2}\) at 55°C for the 40-\(\mu\)m in diameter microring. It can be seen that a change in temperature does not lead to a dramatic deterioration in the characteristics of the laser, although, of course, an improvement in heat dissipation would allow, in general, to increase the frequency characteristics.

![Figure 5](image)

**Figure 5.** The 3-dB bandwidth for the microring with outer diameter 40 \(\mu\)m at temperatures 13°C, 40°C and 55°C.

MCEFs for microrings with outer diameter 40 \(\mu\)m and 20 \(\mu\)m are presented in Figure 6 as functions of temperature. The dependencies show that a decrease of the laser diameter improves the MCEF parameter due to reduced mode volume. The decrease in MCEF with temperature is caused by a decrease in the differential gain and the obtained results may be used to find dependence of the differential gain on the carrier concentration \(\frac{dg}{dn(T)}\) for a given type of active region, as this information is extremely useful for optimization laser design.

![Figure 6](image)

**Figure 6.** Dependency of MCEF vs temperature for the microring lasers with 40 \(\mu\)m and 20 \(\mu\)m outer diameter.
4. Conclusion
In summary, we examine uncooled QWD-based microdisk lasers at elevated temperatures. We demonstrate, for the first time, small-signal modulation response of the microring lasers at 55°C. Under these operation conditions the 3-dB bandwidth value of 3.1 GHz for 40-μm in diameter microlaser and 3.7 GHz for 20-μm in diameter microlaser is achieved. An increase in temperature leads to a decrease in the modulation current efficiency factor. Obviously, for increasing the modulation frequency of the laser further, it is necessary to reduce the thermal resistance and dissipation level. The results obtained can be useful for the development of components for future photonic circuits for data transmission over short distances.

Acknowledgments
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