# A Thermally Tunable Microdisk Laser Built on a III-V/Silicon-on-Insulator Heterogeneous Integration Platform

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***Abstract*—A thermally tunable microdisk laser integrated on a silicon-on-insulator waveguide circuit is demonstrated. A local heater is fabricated surrounding the microdisk cavity for tuning/trimming the lasing wavelength through the thermo-optical effect. The proposed device can be easily implemented without adding extra fabrication steps. A tuning efficiency of 0.35nm/mW is obtained. 2-nm smooth tuning with 20-µW constant lasing power is also demonstrated.**

***Index Terms*—heterogeneous integration, microdisk laser, silicon-on-insulator, thermo-optical tuning**

## I. Introduction

HETEROGENEOUS integration based on III-V/silicon-on-insulator (SOI) die-to-wafer or wafer-to-wafer bonding has been demonstrated as a versatile platform for integrated active devices on a silicon chip [1-9]. Among them, the laser devices built are the most relevant since it is very difficult to obtain gain from monolithic crystalline silicon at communication wavelengths. III-V microdisk or microring lasers integrated on an SOI waveguide circuit have been demonstrated with promising performance [5-7]. Single-mode lasing with 120-µW output power in the SOI waveguide was achieved recently using a 7.5-µm-diameter disk [7]. This kind of compact laser may have many applications in future photonic integrated circuits, e.g., as a multiwavelength laser source [8], or an all-optical flip-flop memory element [9]. In these applications, the lasing wavelengths from multiple microdisks have to be aligned to each other or to a pre-defined channel grid. The wavelengths can be controlled, to some extent, by using high accuracy patterning tools, e.g., deep ultraviolet [10] or electron-beam lithography [5, 8]. However, deviations in the final lasing wavelengths of different devices are always expected. Wavelength variations of ±0.5nm have been observed for 7.5-µm-diameter (nominal value) microdisk lasers across the same die [8].

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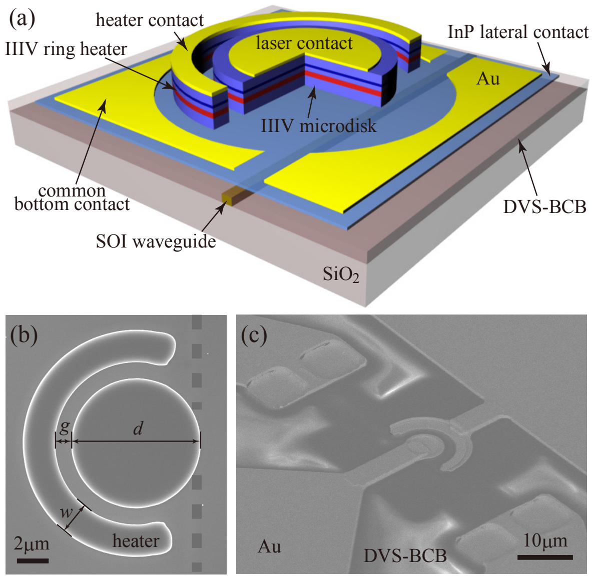


Fig. 1. (a) Schematic drawing of the proposed tunable microdisk laser integrated on an SOI waveguide. (b) Top-view of a fabricated device after the III-V etching. The gray dashed line indicates the SOI waveguide beneath the III-V layer. (c) Bird's-eye view of a finished device.

In this paper, we demonstrate a tunable microdisk laser built on the III-V/SOI heterogeneous integration platform. A local heater in the form of a III-V ring surrounding the microdisk cavity is designed for tuning/trimming the lasing wavelength of the devices through the thermo-optical effect. The best obtained tuning efficiency is 0.35nm/mW. 2-nm tuning with 20-µW constant output lasing power is also demonstrated with the proposed device.

## II. Device Design and Fabrication

Figure 1(a) shows a schematic structure of the proposed tunable microdisk laser, which is composed of a III-V microdisk laser cavity, and a concentric ring made of the same III-V layer. The III-V layer, which consists of three compressively strained InAsP quantum wells for providing transverse electric mode

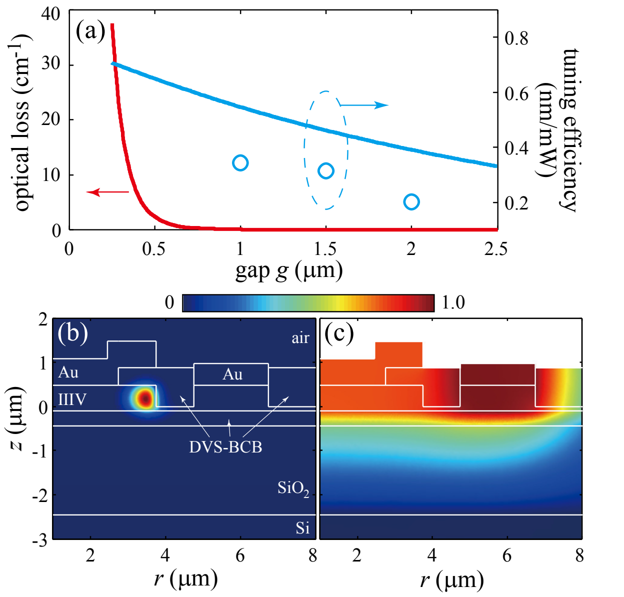


Fig. 2. (a) Simulated optical loss of the WGM and tuning efficiency with different values of *g* for a 7.5-μm-diameter disk cavity. Open circles are the experimental data of the tuning efficiency. (b) Optical mode and (c) temperature profiles for the structure of *g*=1μm.

gain and a tunnel junction for a low-loss p-contact, is integrated on top of an SOI wire waveguide (dimension: 500nm×220nm) through adhesive bonding technology using the divinylsiloxane-benzocyclobutene (DVS-BCB) polymer [3]. The heater and the laser cavity share the same bottom metal contact, but have two isolated top contacts, so that they can be driven separately. Figure 1(b) shows a picture of the fabricated microdisk and the ring heater after the III-V etching. Instead of a full ring, the heater here is designed to be an arc shape, so that the heater section would not lie on top of the underlying SOI waveguide. This avoids extra losses to the light propagating in the waveguide [8]. Fig. 1(c) also shows a finished device, in which the whole III-V structure is embedded in a DVS-BCB isolation layer and only the metal wires and vias to the different contacts are visible. The SOI waveguide is terminated with grating couplers for characterization purposes [5]. We refer to [7] for further details on the epitaxial layer and the fabrication.

The gap *g* (see Fig. 1(b)) between the microdisk cavity and the ring heater is a critical parameter. If the gap is too wide, the tuning efficiency (defined as the ratio of the lasing wavelength shift to the amount of heating power applied on the heater) would be low due to an increased thermal resistance between the heater and the disk. On the other hand, a small gap may cause leakage of the laser mode, i.e., the whispering gallery mode (WGM) around the edge of the disk cavity, to the heater, and thus give rise to extra optical losses. This would decrease the laser performance, e.g., a higher threshold current. The optical and thermal properties of the proposed devices were first numerically analyzed as shown in Fig. 2. Here, the diameter *d* of the microdisk cavity is 7.5μm, and the thickness of the III-V layer, the InP lateral contact layer, the DVS-BCB bonding layer and the buried oxide layer is 583nm, 100nm, 350nm and 2μm, respectively. The above figures are measured directly from the fabricated devices. The structure is considered axially symmetric for simplicity, and the underlying SOI waveguide is not included in the simulation. The width *w* of the ring heater is fixed at 2μm, considering the resolution of the patterning tool used in the fabrication, i.e., ultraviolet contact lithography. The values for the thermal properties of different materials were taken from [11]. Figure 2(a) shows the optical loss of the WGM and the tuning efficiency with different values of *g*. Figure 2(b) and 2(c) show the optical-mode and temperature profiles when *g*=1μm,. We obtain the tuning efficiency by calculating the temperature rise at the edge of the disk cavity and assuming a temperature sensitivity of the lasing wavelength of 86pm/K [11]. Both optical loss and tuning efficiency increase as the gap *g* decreases. Especially, the optical losses induced by the ring heater increase dramatically when *g* decreases below 0.5μm. It will dominate over other losses of the cavity, which are estimated to be about 10cm$^{-1}$ for a standalone disk [4]. Therefore, devices with *g*=1μm, 1.5μm, and 2μm were fabricated, for which the heater-induced losses are negligible.

## III. Measurement and Discussion

The power-current (PI) curve of one fabricated device (*d*=7.5μm, *g*=1.5μm) measured from one end of the SOI waveguide is presented in Fig. 3(a). The peak power reaches 36μW in the waveguide. From the spectrum shown in the inset one can find that the lasing wavelength is around 1580nm and it works in a single mode with a >20dB side-mode suppression ratio. No unidirectional operation or switching between the lasing directions were found here due to a relatively large feedback (originated from reflections of the grating couplers) to the WGM as the coupling strength between the disk and the SOI waveguide is designed higher in this chip [9]. The clear periodic oscillation in the PI curve is also an indication of the feedback through reflections [8]. The threshold current is 0.3mA which is very similar to that of standalone disks in the same chip. The voltage-current (VI) curves for driving the disk cavity and the ring heater are also presented in Fig. 3(a), where both of them show the typical response of a forward biased diode. The tuning of the lasing wavelength is demonstrated in Fig. 2(b) by fixing the laser driving current $I_L$ at 1.25mA and varying the heater driving current $I_H$. The laser peak shifts to longer wavelengths as $I_H$ increases. The tuning rate is fitted to be 0.32nm/mW as shown in the inset. The heating power is counted as multiple of the current and voltage applied on the heater. Note that the electrical power applied on the heater will be dissipated as both heat and spontaneous emission. However, the latter one is inefficient in this structure, and therefore neglected. This result, together with those from two other fabricated structures with *g*=1μm and 2μm, is also plotted in Fig. 2(a). As expected, the highest tuning rate of 0.35nm/mW is achieved when *g*=1μm. No obvious variation of the threshold currents is observed for the three structures, meaning that the inclusion of the III-V ring heater does not influence the lasing characteristics, as was predicted by simulations. However, as shown in Fig. 2(a) the experimental tuning rates are about 40-50% lower than those

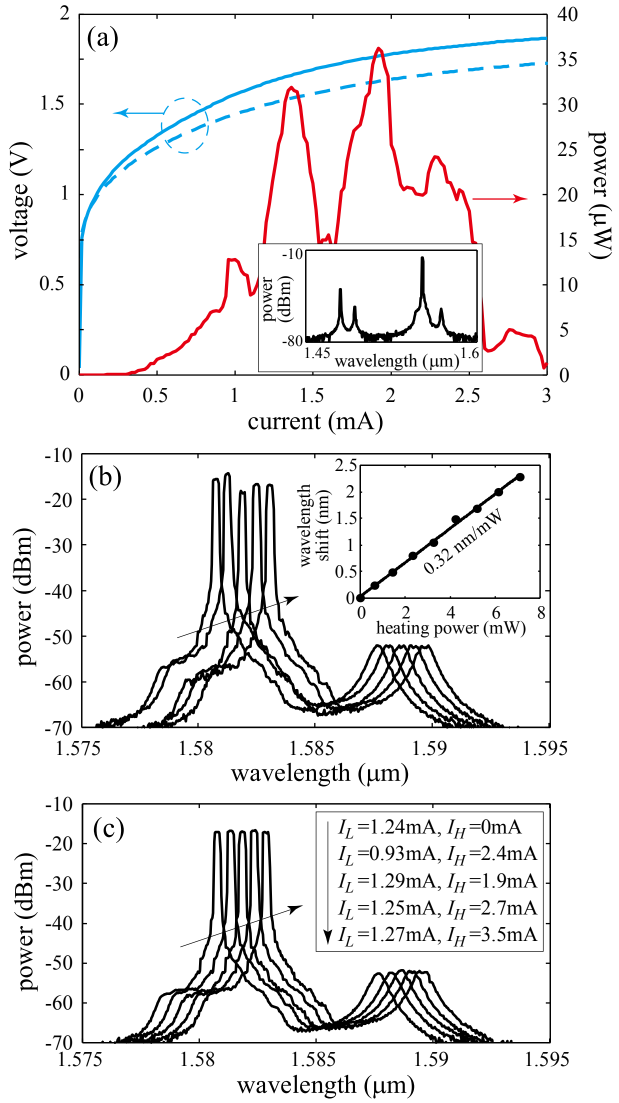


Fig. 3. (a) PI and VI curves (solid lines) of a laser with $d$=7.5μm, $g$=1.5μm, and VI curve (dashed line) of the heater. Inset shows the laser spectrum with $I_L$=1.25mA, $I_H$=0mA. (b) Wavelength tuning by varying $I_H$ (0–4mA with a step of 1mA along the arrow direction). $I_L$=1.25mA. Inset shows the linear fit (line) of the measured wavelength shift (dots) to the heating power. (c) Wavelength tuning with a step of 0.5nm and with a constant power (20μW). The driving conditions are marked in the legend along the arrow direction.

obtained from the theoretical model. This is most likely due to the fact that an arc shaped heater is adopted in the fabrication instead of a full ring in the simulations. It is also worthwhile to note that the lasing power varies for about 3dB (15μW–35μW) during the tuning process in Fig. 3(b). The reason is two-fold. First, the wavelength change affects the phase of the feedback to the WGM, and thus the lasing power, which also causes the oscillations in the PI curve in Fig. 3(a). Another reason lies in the degradation of the lasing performance at higher temperature. The former one can be avoided in some applications, e.g., on-chip interconnect, where no grating couplers are needed. The latter one is intrinsic, and is the limiting factor in further extending the tuning range of the device. Nevertheless, we can use the proposed structure for compensating the wavelength drift resulted from fabrication uncertainties. By fine-tuning $I_L$ and $I_H$ separately, we demonstrate in Fig. 3(c) smooth tuning over a 2nm range with a constant lasing power. However, the power here is somewhat compromised, and limited to 20μW.

## IV. Conclusion

We have demonstrated a thermally tunable microdisk laser integrated on an SOI waveguide. The tuning of the lasing wavelength is achieved by electrically heating a III-V ring/arc located closely to the microdisk cavity. The device is compact and requires no additional fabrication steps. A maximal tuning efficiency of 0.35nm/mW has been achieved. 2nm tuning with 20μW constant output power has also been demonstrated. The proposed device can be used for compensating wavelength variations resulted from the fabrication.

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