Application Note 53

Characterization of an Optical Microresonator Using a TLB-6700 *Velocity™* Widely Tunable Diode Laser

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Introduction

The demand for micro-scale, integratable photonic devices continues to motivate many researchers. The optical microresonator, which can be used to confine and store light for up to hundreds of nanoseconds, is one photonic device that continues to show promise. Optical microresonators can be fabricated on Si (i.e., on-chip) from glasses, polymers, and III-V binary semiconductors. Figure 1 shows scanning electron micrographs of four microresonators of different geometries. One type of microresonator is the toroid, shown in fig. 1(a). Due to its sensitivity to its immediate environment, it has found applications in biodetection[1] and chemical sensing[1,2]. The toroid had also been used as a microlaser because of the large light intensity that can be built up in its ring.[3] In addition, the toroid has been used to generate a frequency comb[4] which spanned hundreds of nanometers. Although the focus of this Note is the toroid, microresonators are as varied in geometry as in their application, with rings, disks, and spheres also having been reported in the literature, see fig. 1(b)-(d), respectively.

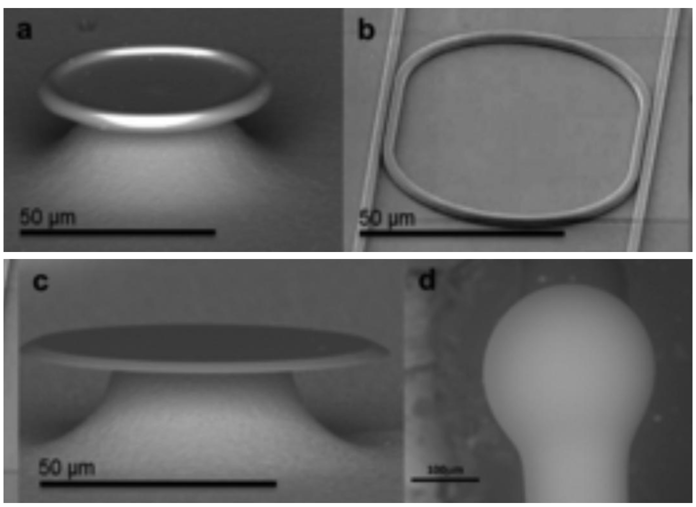


Figure 1. SEM *micrographs of different geometry microresonators. Photo courtesy of* Maria Chistiakova, *Armani lab*, USC.

One way to couple laser light into a microresonator is through the use of a tapered optical fiber waveguide, see fig. 2. Light traveling through a fiber waveguide will undergo total internal reflection along its length; however, every solution to Maxwell's equations for a dielectric waveguide allows for a localized, time-dependent evanescent field to exist *outside* the waveguide. This field will decay with distance from the core of the fiber. By aligning a toroid closely enough to the tapered region of the fiber waveguide, some of this field can be coupled into it, initiating a second longitudinally propagating wave within its ring, shown in fig. 2. However, confinement and storage of light within the ring will only occur at certain wavelengths, called the resonance wavelengths of the toroid, λ_r. Resonance occurs when the wavelength is an integral multiple of the circumference of the toroid ring. Thus, the toroid ring constitutes an optical resonator and the modes it supports are the so-called "whispering gallery modes" (WGMs), named after the legendary whispering gallery under the dome of St. Paul`s cathedral in London. In the whispering gallery, a whisper at one point along the circular wall of the dome can be heard at the opposite side of the gallery along the wall.

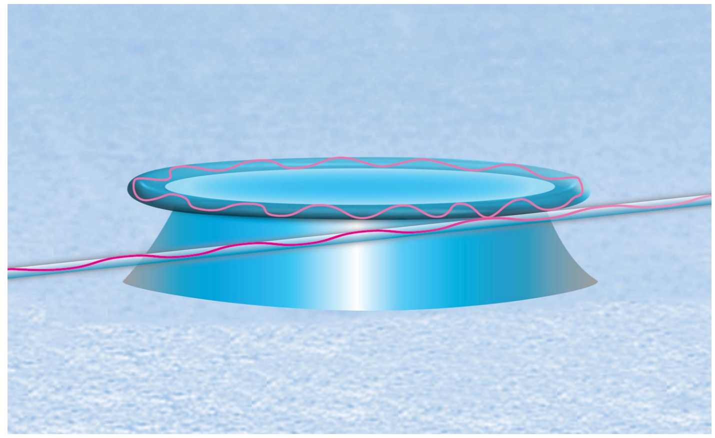


Figure 2. *Rendition of toroid microresonator resonantly excited by light propagating through tapered optical fiber.*

In the absence of losses, an optical microresonator would confine light for an infinite period of time. In reality, the resonator will confine light for a finite period of time known as the photon lifetime, τ. The quality factor, Q, is a dimensionless number that quantitatively describes the microresonator's ability to confine light at λ_r and is given by eq. 1,

$$Q = \frac{\lambda_r}{\Delta\lambda} = 2\pi\nu\tau \qquad (1)$$

where $\Delta\lambda_r$ is the full-width-at-half-max (FWHM) of the resonance peak and ν is the resonance frequency.[5] Therefore, a device with a longer photon lifetime will have a higher Q. Note that these alternative expressions for Q in terms of linewidth and photon lifetime are equivalent, and related through a Fourier transform. In some of the the highest-Q toroids reported to date (with $Q \sim 10^8$), a photon will have a lifetime of hundreds of nanoseconds. Experimentally, there are two ways of finding the Q of a toroid: (1) by performing a cavity ring-down measurement to obtain τ, or (2) by finding $\Delta\lambda$ by recording the resonance spectrum of the cavity in the vicinity of λ_r. In the second method, light from a tunable source (usually an ECDL) is passed through the tapered fiber and its transmission is recorded with wavelength. On resonance, a large fraction of the power through the tapered fiber will couple into the toroid resulting in a drop in the transmitted power. Therefore, a plot of absorbance versus wavelength will reveal a peak centered at λ_r with a linedwidth $\Delta\lambda_r$. However, this method is only effective if the laser linewidth used to perform the measurement is narrower than the linedwidth of the cavity (typically in the sub-MHz range).

Furthermore, a toroid microresonator can have many resonant wavelengths. The free spectral range (FSR) of a Fabry-Perot cavity is the spacing between two sequential longitudinal modes. By analogy to the Fabry-Perot cavity, for a toroid microresonator the FSR can be expressed as

$$\mathrm{FSR} = \frac{\lambda_r^2}{2\pi \mathrm{R} \cdot n_{\mathrm{eff}}} \tag{2}$$

where R is the radius of the toroid and n_{eff} is its effective index of refraction. For example, a SiO_2 microtoroid with $R = 50$ µm, $n_{\mathrm{eff}} = 1.5$, at $\lambda_r = 1550$ nm will have a FSR on the order of 5 nm. This underscores the need for a widely tunable laser in microresonator measurements.

Although applications of the toroid are varied, most begin with a measurement of the resonant wavelengths of the toroid. This allows the quality factor Q intrinsic to the device to be obtained in addition to its FSR. The TLB-6700 Velocity Widely Tunable Diode Laser is ideally suited for these measurements owing to its single-mode, mode-hop-free output. In addition, the TLB-6700 Velocity's extremely narrow linewidth (< 200 kHz) and wide tunability allow for the fine frequency sweeping capabilities that are required by toroid microresonator experiments. Therefore, it is the aim of this Note to describe the use of the TLB-6700 Velocity Widely Tunable Diode Laser in the characterization and study of a SiO_2 toroid microresonator. (For a brief description of the New Focus Tunable Diode Lasers, the reader is referred to Ref.6.) Although the focus will be on the microtoroid, the methods described herein are also applicable to the study of microresonators of different geometries.

Fabrication of Silica (SiO_2) Toroid Microtresonators

Microresonators made of SiO_2 can be patterned onto Si wafers through techniques standard in the integrated circuit industry. A schematic which shows the main steps in the fabrication process is shown in fig. 3 for the toroid microresonator. Briefly, (a) SiO_2 is lithographically defined and etched to give disks of controllable size, (b) XeF_2 gas is used to isotropically etch the Si underneath the disks, and finally (c) the SiO_2 disks are reflowed with a CO_2 laser to form the toroids. For a more detailed description of the fabrication process, the reader is referred to Ref.7.

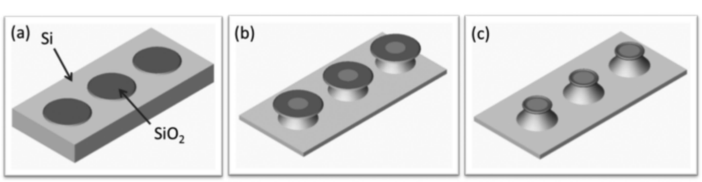


Figure 3. *Main steps in silica toroid microresonator fabrication.*

Experimental Setup

Toroid microresonators were characterized on a setup similar to that shown in fig. 4. As shown in the figure, the free space output of a (a) TLB-6700 Velocity laser is launched into a single-mode optical fiber spool through the use of a (b) fiber coupling kit. Note, that integrated permanent fiber coupling is also available. The tapered portion of the fiber is held in place by two (c) single-arm bare fiber holders attached to a homemade mount which integrates two (d) micrometer heads that are used to increase the tension in the taper. A bare fiber adaptor is used to connect the end of the fiber to a (e) 10 MHz photoreceiver coupled to a high speed digitizer/oscilloscope

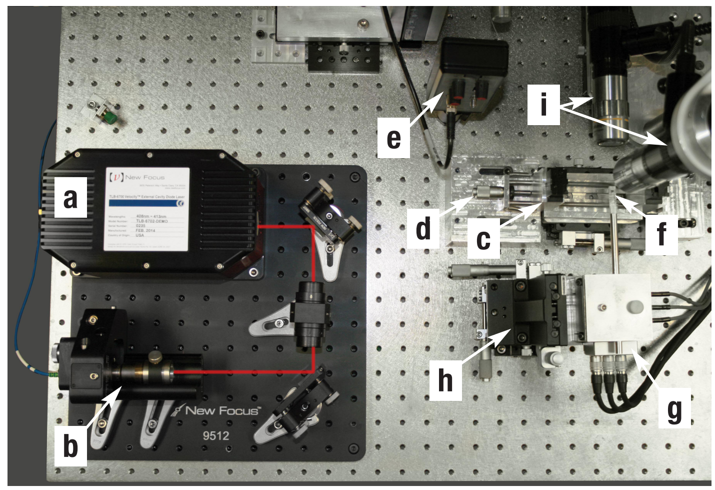


Figure 4. *Toroid microresonator testing station, Andrea Armani lab, University of Southern California.* ***(a)*** *TLB-6700 Velocity laser, see fig. A1 in Appendix* ***(b)*** *fiber coupling kit, fig. A3* ***(c)*** *single-arm bare fiber holders, fig. A4* ***(d)*** *micrometer heads, fig. A5* ***(e)*** *photoreceiver, fig. A7* ***(f)*** *sample holder,* ***(g)*** *motorized nanopositioning stage, fig. A9* ***(h)*** *ball bearing XYZ stage, fig A11* ***(i)*** *optical microscopes/cameras.*

which is used to measure the transmission through the fiber.

Also shown in fig. 4 is the toroid alignment hardware. The (f) sample holder, which holds the toroid array, is mounted onto a (g) motorized nanopositioning stage which is nested in a second (h) ball bearing XYZ stage. Two (i) optical microscopes oriented perpendicular to the fiber are used to visualize the alignment. The toroid position is optimized using the nested XYZ stages until coupling of light into the toroid is observed on the oscilloscope as a minimum in the transmitted power. Coupling can also be observed through the microscopes; fig. 5 shows an image of light at 410 nm being coupled into a toroid, which was taken using the side-view microscope. On resonance, the power circulating, P_{circ}, in the toroid is given by

$$P_{circ} = \frac{\lambda_r Q P_{in}}{\pi^2 n_{eff} \mathrm{R}} \tag{3}$$

where P_{in} is the input power through the tapered fiber. For instance, by coupling 1 mW into the toroid shown in fig. 1, a couple hundred watts can be made to circulate. Such high circulating power is what enables the toroid to achieve low lasing thresholds in microlaser applications.

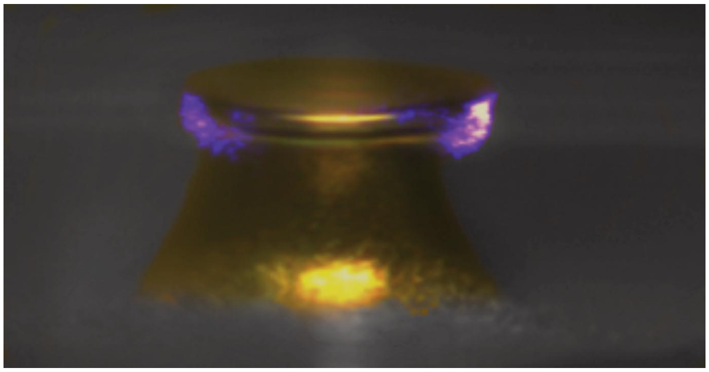


Figure 5. *Side view of toroid microresonator aligned with tapered fiber (seen as horizontal blur). Light at 410 nm is being coupled into the toroid. Photo courtesy of Ashley Maker, Armani lab, USC.*

Obtaining the Quality Factor *Q* of a Toroid Microresonator

After the alignment is optimized and coupling is observed, the resonant wavelengths of the toroid microresonator are found. This is accomplished by performing a broad scan of the TLB-6700 Velocity laser typically over a couple of the microresonator's FSRs (i.e., on the order of 5 nm). The broad scan can be controlled through the front panel of the controller or by using the NI LabVIEW™ device driver software provided with each TLB-6700 Velocity laser. Alternatively, each TLB-6700 Velocity controller comes equipped with a 'Wavelength Input' BNC connector (rear panel) which accepts a signal from 0 to 10 VDC that is used to linearly specify the laser output wavelength.

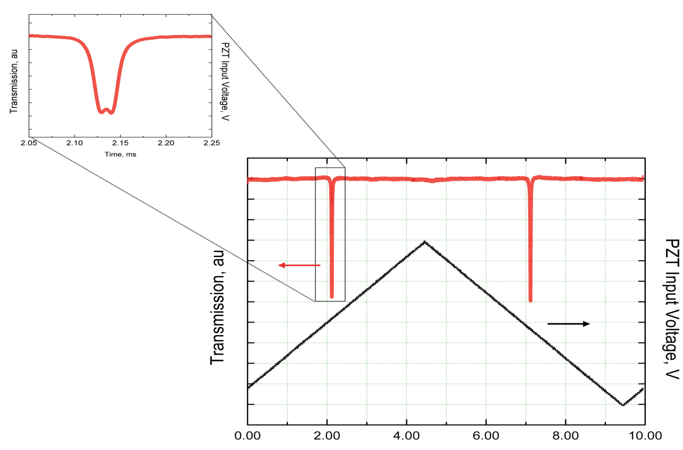


Figure 6. *Oscilloscope screenshot shows triangular waveform used to modulate PZT voltage (white) and measured transmission spectrum measured for a SiO_2 toroid (red). Photo courtesy of Sahar Elyahoodayan, Armani lab, USC.*

To measure the quality factor Q of a high-Q toroid, the wavelength of the TLB-6700 Velocity laser is piezo-dithered about the resonance wavelength while the transmission through the taper waveguide is recorded. This method of fine-scanning allows for sub-angstrom resolution. Piezo dithering is accomplished by sending the output of an arbitrary waveform generator to the 'Frequency Modulation' input on the rear panel of the TLB-6700 Velocity 's controller. The input will accept a ±3 V input tringular voltage, as shown in fig. 6. The voltage allows external analog control of the wavelength through the voltage applied to the PZT on the tuning arm. Also shown in fig. 6 is a representative transmission spectrum for a SiO_2 toroid (R ~ 25 nm) recorded while the PZT was dithered. A Lorentzian fit to the peak yields $Q = 10^3$ for this device. Note that this is loaded quality factor, and not the quality factor intrinsic to the cavity in the absence of coupling. Note that toroid microresonators with much higher Qs (well over 100 million) have been studied with the TLB-6700 Velocity laser and reported. [8]

Conclusions

We have briefly described the use of the TLB-6700 Velocity laser in characterizing and testing a toroid microresonator device. As we have seen, many of the key performance features of the TLB-6700 Velocity (i.e., narrow linewidth, wide tunability, single-mode, mode-hop-free) make it ideally suited for interrogation of these devices. It should be noted that this experimental approach is also amenable to testing microresonators of various geometries. It is no wonder why research groups across the globe have come to regard the TLB-6700 Velocity Widely Tunable Diode Laser as the workhorse laser in the exciting field of optical microresonators.

Appendix 1: Parts List

Fig. A1 TLB-6700 Velocity™ and controller Model TLB-6700

Fig. A2 Single-mode fiber, various cut-off wavelengths available.

Fig. A3 Post-Mount Singlemode Fiber Aligner Model 9091

Fig. A4 Bare Fiber Holder, 250 um Magnetic, Single Arm, Model 466A-711

Fig. A5 Mitutoyo Micrometer Heads Model 9354

Fig. A6 Bare Fiber Adaptor, Multi-mode, FC Connector Model F-AM-FC

Fig. A7 10 MHz adjustable photoreceiver, Model 2051-FC

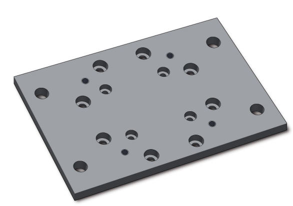
Fig. A8 Lab Power Supply, ±15 VDC, Model 0901

Fig. A9 Nanopositioning XYZ Stage, 100 μm, Strain-guage Model NPXYZ100SG

Fig. A10 3-channel piezo amplifier, strain-gauge position control, Model NPC3SG

Fig. A11 Triple Divide XYZ Axis Translation Stage, 1.1 in., 8-32 and 1/4-20 Model 9064-XYZ

Fig. A12 Base Plate, NanoPositioning Translation Stages Model NPX-BP



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