Tuning for Resonances

Widely tunable diode lasers advance microresonator research

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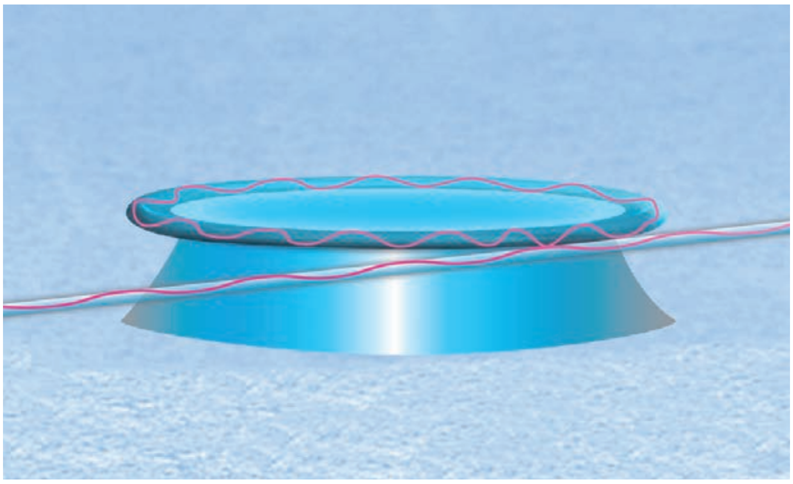
Due to a very distinct spectrum of resonant frequencies, the characterization of optical microcavities calls for widely tunable sources of continuous wave laser light, offering suitably narrow linewidths and single-mode operation over the entire tuning range. This is why external cavity diode lasers, which allow for mode-hop free wavelength tuning, often over more than a hundred nanometers, have matured to a fundamental tool of the optical microresonator research apparatus.



Rendition of a toroid microresonator being resonantly excited by light propagating through an optical fiber.

Diode lasers are ubiquitous in their use as cost-effective sources of laser light in a broad variety of commercial and industrial applications. However, low cost "off-the-shelf" semiconductor laser diodes typically operate with several longitudinal modes lasing simultaneously, leading to low coherence and large linewidths. Owing to their relatively poor optical output characteristics, such devices are typically not suitable when more demanding linewidth specifications and single-mode operation are required. Furthermore, a variety of applications, such as the characterization of optical microresonators that is touched on in an illustrative manner in the present article, demand that the laser wavelength be continuously tunable over as large a range as possible.

The development of tunable single frequency diode lasers has been driven by the evolution of coherent optical telecommunication systems. Nowadays, so-called "monolithic" semiconductor lasers can be roughly categorized into three configuration designs [1]. Most of the tunable telecom lasers are based on distributed feedback (DFB) technology (i. e., on a resonator medium with a periodic structure) and wavelength tuning that is accomplished by varying the temperature and/or the operating current. Distributed Bragg reflector (DBR) lasers, in turn, use a gain medium sandwiched between Bragg grating sections. Vertical-cavity surface-emitting lasers (VCSELs) with micro-electro-mechanical system (MEMS) based tuning elements are a relatively recent development.

All three of these configurations, however, are plagued by limitations on the available wavelength range, tunability, and/or achievable linewidth. Also, these types of single-mode tunable laser diodes may exhibit a phenomenon called "mode-hopping", in which the laser output frequency discontinuously hops from one value to another during tuning of the laser wavelength.

External Cavity Diode Lasers

As an alternative to monolithic designs, external cavity diode lasers (ECDLs) are another practical approach to achieve wavelength tunability of semiconductor diode lasers. Basically, an ECDL can be defined as a device that consists of a diode with an anti-reflection coating on (at least) one side, a collimator, and an external mode selection filter [1]. Though commercial ECDLs are based on off-the-shelf laser diodes, the output characteristics of the diode can be greatly enhanced by integration into the external cavity. By doing so, the diode acts purely as a gain element while the wavelength selective optics helps to ensure that only a single mode lases at any given time. While a variety of particular cavity designs has been demonstrated [2], the so-called Littrow and the Littman-Metcalf configurations are the two most prevalent, both of which employ gratings to select single-mode operation (**Fig. 1**).

In the Littrow design (**Fig. 1, left**) the grating is positioned at the Littrow angle (where the angle of incidence equals the angle of diffraction). Simply speaking, the lasing wavelength of the cavity is determined by a combination of the standing-wave condition (cavity-length) and the center wavelength of the grating feedback. For mode-

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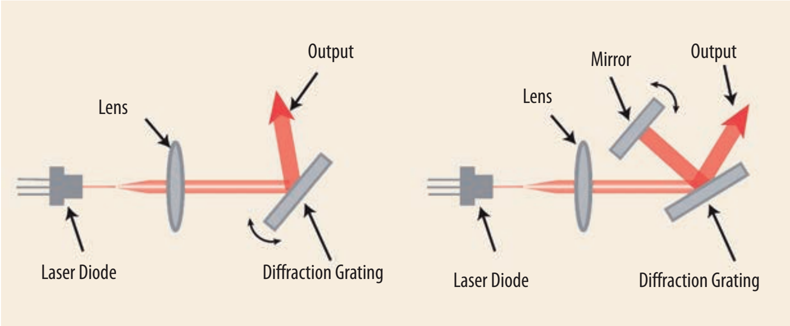

Fig. 1 Comparison of the Littrow (left) and the Littman-Metcalf (right) configuration in tunable external cavity diode lasers (ECDLs). While the Littrow design typically offers less than a tenth of a nanometer mode-hop free tuning range, the Littman-Metcalf design achieves mode-hop free tuning in the range of tens to hundreds of nanometers.

Fig. 2 Commercial turn-key widely tunable diode laser system from New Focus, consisting of a laser head and a single easy-to-use control electronics unit. The laser platform permits access to wavelength ranges from 400 nm to 2175 nm.

hop free tuning, the cavity length has to be continually readjusted to match the grating retro-reflection condition. This can be accomplished by rotating the grating about a carefully chosen pivot point, however, the tolerance of the pivot point location error is very restrictive, which imposes limitations on practical tunability.

The tunability limitations of the Littrow geometry are overcome in the Littman-Metcalf configuration (**Fig. 1, right**), which uses a double-pass through the grating under a steep angle of incidence (typically ≈ 85° versus ≈ 30°). Since at grazing-incidence the grating dispersion is very high (due to a large number of grooves encountered by the incident beam), the Littman-Metcalf design intrinsically offers very high mode selectivity, frequency stability, and narrow linewidth.

The principal advantage of the Littman-Metcalf design, however, is a distinctly wider mode-hop free wavelength tuning range, which can be achieved without any beam-walk of the laser output beam, through rotation of the retro-reflecting cavity end-mirror. This rotation can be accomplished with a variety of actuators, ranging from micrometer screws, piezoelectric actuators, servo motors, or voice-coil type designs, depending on the tuning range and the tuning speed required by the specific application. For example, the commercial platform shown in **Fig. 2**, employing a combination of a servo motor and a piezoelectric transducer, offers mode-hop free tuning ranges of up to more than 100 nm, while maintaining a linewidth of < 200 kHz.

Optical Microresonators

Broadly speaking, microresonators are micro-scale photonic devices that confine and store light within small volumes and with very small losses, by resonant recirculation [3]. **Fig. 3** illustrates size and geometry of just a couple of microresonator geometry variants that have been developed for various applications. While microresonators can be fabricated “on-chip” from glasses, polymers, or III-V binary semiconductors, it is worth noting that SiO_2 based devices, in particular, can be patterned onto silicon wafers through techniques standard in the integrated circuit industry [4].

Coupling of light into a microresonator of toroid type (**Fig. 4**) can be accomplished by carefully aligning the device closely enough to the tapered region of a tapered optical fiber waveguide. By doing so, some of the light carried through the fiber is evanescently coupled into the toroid, initiating a second longitudinally propagating wave within its ring. Confinement and storage of light within the toroid ring, however, occurs only at certain wavelengths (respectively resonance frequencies). Notably, these resonances or modes are called “whispering gallery modes”, named after the legendary whispering gallery under the dome of St. Paul’s cathedral in London, UK, in which 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.

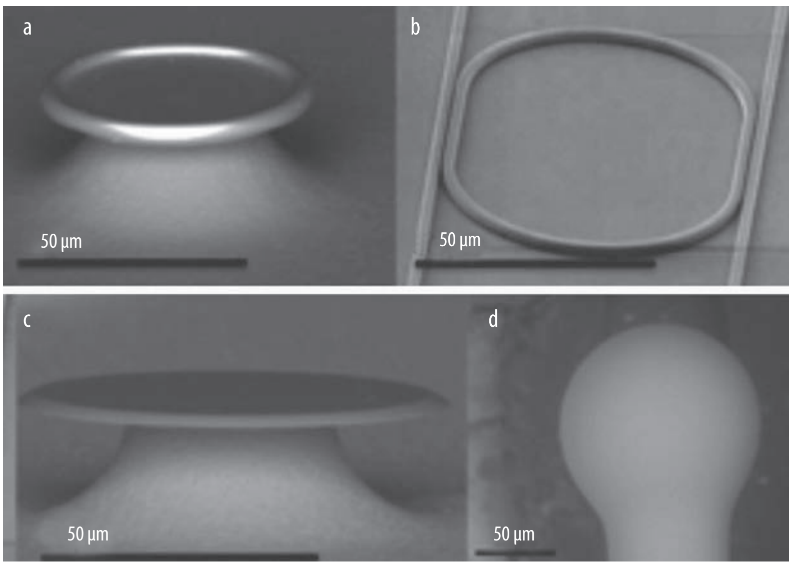

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Fig. 3 Scannning electron microscope images of different geometry microresonators: a) toroid, b) ring, c) disk, and d) sphere. Black bars indicate size comparison.

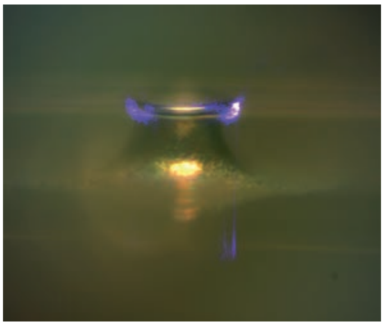

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Fig. 4 Side view of a toroid microresonator aligned with an optical fiber (perceptible as horizontal blur). Light at 410 nm is being coupled into the toroid.

Measuring Essential Characteristics of a Toroid Microresonator

In the absence of any losses, an optical microresonator would confine light for an infinite period of time. Real world resonators can confine light for only a finite period of time, known as the photon lifetime. The photon lifetime, in turn, is intimately linked to the so-called quality factor (Q-factor), defined as the ratio between the center frequency (of a resonance) to the width of the resonance peak. Since devices with a higher quality factor will have a longer photon lifetime, the Q-factor is an essential value characterizing the quality of microresonators, and of high interest for most applications (in some of the highest-Q toroids reported to date photon lifetimes can reach hundreds of nanoseconds).

Experimentally, the characterization of toroid microresonators is typically accomplished by passing light from a tunable source (such as an ECDL) through a tapered optical fiber waveguide (as described above), while recording the amount of light that is transmitted through the fiber. When scanning the laser frequency through a resonance, a large fraction of the power through the tapered fiber will couple into the toroid, resulting in a drop in the transmitted power. The spacing between successive resonances, commonly referred to as the free spectral range (FSR), is typically on the order of nanometers, which underscores the need for wide tunability and makes Littman-Metcalf ECDLs particularly well-suited for the experiment.

After surveying the resonances by performing a broad scan of the wavelength (typically over a couple of the microresonator's FSRs), a high-resolution scan is carried out to eventually determine the Q-factor. This can be accomplished by piezo-dithering the wavelength about a resonance peak, which allows for fine-scanning the laser wavelength with sub-angstrom resolution. Obviously, this procedure will only be effective if the laser linewidth is by far narrower than the width of the resonance peak (the latter typically in the MHz range). To close, representative data from a transmission spectrum measurement of a SiO_2 toroid is shown in **Fig. 5**.

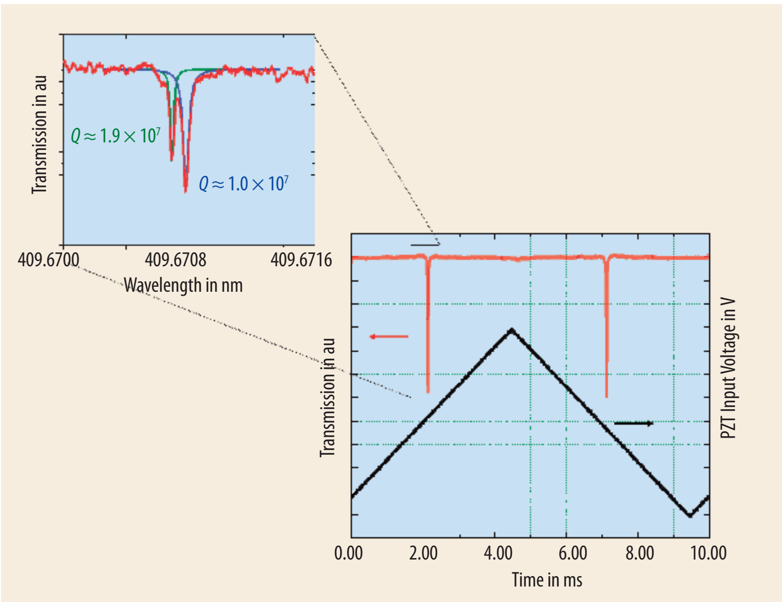

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Fig. 5 Representative data from a transmission spectrum measurement of a SiO_2 toroid. The oscilloscope screenshot shows a triangular waveform voltage used to tune the laser wavelength (black line) along with the recorded transmission intensity (red line). Lorentzian fits (zoom) yield quality factors of $Q \approx 10^7$ for the device.

Outlook

With the toroid being just one of numerous examples, optical microresonators are an emerging opportunity of scientific research, driven towards commercialization by the high interest in versatile microscale photonic devices. Intrinsically linked to the fundamental optical properties of microresonators, their experimental characterization requires widely tunable sources of continuous wave laser light with sufficiently narrow linewidth. Suitably designed External Cavity Diode Lasers are proven to be an indispensable tool in this context.

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[1] *C. Ye,* Tunable External Cavity Diode Lasers, World Scientific Publishing (2004)

[2] *B. Mroziewicz,* Opto-Electronics Review **16**, 347 (2008)

[3] *K. J. Vahala,* Nature **424**, 839 (2003)

[4] *A. J. Maker* and *A. M. Armani,* Journal of Visualized Experiment **65**, e4164 (2012)

