Preventing Raman Lasing in High-Q WGM Resonators

Raman-lasing threshold power is increased through suitable choice of dimensions.

NASA's Jet Propulsion Laboratory, Pasadena, California

A generic design has been conceived to suppress the Raman effect in whispering-gallery-mode (WGM) optical resonators that have high values of the resonance quality factor (Q). Although it is possible to exploit the Raman effect (even striving to maximize the Raman gain to obtain Raman lasing), the present innovation is intended to satisfy a need that arises in applications in which the Raman effect inhibits the realization of the full potential of WGM resonators as frequency-selection components. Heretofore, in such applications, it has been necessary to operate high-Q WGM resonators at unattractively low power levels to prevent Raman lasing. (The Raman-lasing thresholds of WGM optical resonators are very low and are approximately proportional to Q^{-2}.)

Heretofore, two ways of preventing Raman lasing at high power levels have been known, but both entail significant disadvantages:

- A resonator can be designed so that the optical field is spread over a relatively large mode volume to bring the power density below the threshold. For any given combination of Q and power level, there is certain mode volume wherein Raman lasing does not start. Unfortunately, a resonator that has a large mode volume also has a high spectral density, which is undesirable in a typical photonic application.
- A resonator can be cooled to the temperature of liquid helium, where the Raman spectrum is narrower and, therefore, the Raman gain is lower. However, liquid-helium cooling is inconvenient.

The present design overcomes these disadvantages, making it possible to operate a low-spectral-density (even a single-mode) WGM resonator at a relatively high power level at room temperature, without risk of Raman lasing.

The present design exploits the following two physical principles:

- There is a wavelength interval between the optical pump signal (in this case, the optical signal at the desired resonance frequency) and the Raman signal emitted by the resonator material in response to the pump signal. For a CaF_2 resonator, this wavelength interval is ≈80 nm; for a diamond resonator, this wavelength interval is ≈400 nm.
- In a single-mode resonator, there is a cutoff frequency — a minimum frequency at which the optical mode is still confined and has high material-limited value of Q. At lower frequency, Q is limited by leakage of the partially confined mode to the environment.

The essence of the present design is to choose the dimensions of a single-mode WGM resonator to place the cutoff frequency between the pump and Raman frequencies. For example, if the resonator is to be made of diamond and to have a resonance wavelength of 1,550 nm, then its dimensions should be chosen to place the cutoff wavelength between 1,550 nm and the Raman wavelength of 1,550 + 400 = 1,950 nm. Preferably, the cutoff wavelength should be set at or near 1,750 nm. The basic inequality that expresses the required relationship among the wavelengths and dimensions for a WGM resonator like the one in the figure is

$$\lambda_p < 2L(2\varepsilon h/R)1/2 < \lambda_R,$$

where λ_p is the pump wavelength, L is the axial length of the resonator, ε is the relative permittivity of the resonator material, h is the radial depth of the groove that separates the resonator from the rest of the rod of resonator material, R is the radius of the rod, and λ_R is the Raman wavelength.

In a resonator designed in this way, the value of Q at the Raman lasing wavelength is a fraction, $1/\rho$, of the value of Q in an otherwise identical WGM resonator that has not been designed to place the cutoff wavelength between the pump and Raman wavelengths. Consequently, the Raman-lasing threshold power is about ρ^2 times as high as it is in the absence of this innovation.

This work was done by Anatoliy Savchenkov, Andrey Matsko, Dmitry Strekalov, and Lute Maleki of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-43334

Procedures for Tuning a Multiresonator Photonic Filter

A desired high-order filter function can be established and maintained.

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Two procedures have been devised for tuning a photonic filter that comprises multiple whispering-gallery-mode (WGM) disk resonators. As used here, "tuning" signifies locking the filter to a specific laser frequency and configuring the filter to obtain a desired high-order transfer function.

The main problem in tuning such a filter is how to select the correct relative loading of the resonators to realize a prescribed filter function. The first of the two procedures solves this problem.

As temperature gradients develop during operation, the spectra of individual resonators tend to drift, primarily because of the thermorefractive effect. Thus, there arises the additional problem of how to adjust the tuning during operation to maintain the desired transfer function. The second of the two procedures solves this problem.

To implement the procedures, it is necessary to incorporate the resonators into an apparatus like that of Figure 1. In this apparatus, the spectrum of each resonator can be adjusted individually, via the electro-optical effect, by adjusting a bias voltage applied to that resonator. In addition, the positions of the coupling prisms and resonators can be adjusted to increase or reduce the gaps between them, thereby reducing or increasing, respectively, the optical coupling between them. The optical power (P_i) in resonator i is monitored by use of a tracking photodiode. Another tracking diode monitors the power reflected from the input terminal (P_r),

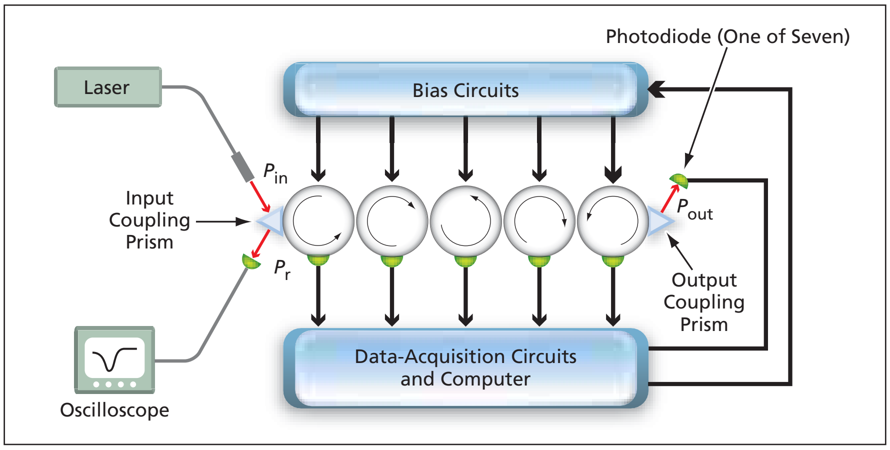

Figure 1. **Five WGM Resonators** are arranged to form a filter chain. Through adjustment of gaps and voltages, guided by monitoring of optical power levels, desired transfer function (P_{out}/P_{in} versus frequency detuning) can be obtained. The underlying principles of design and operation are also applicable to a chain of more or fewer than five WGM resonators.

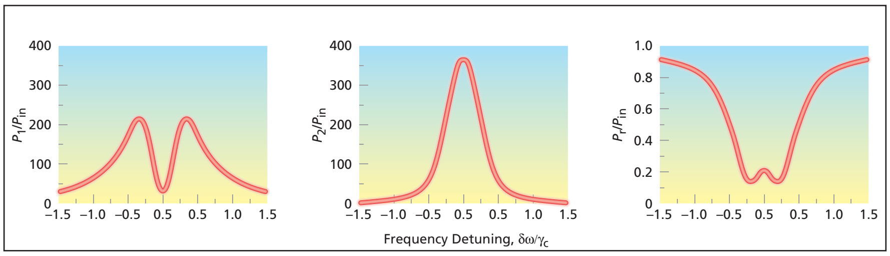

Figure 2. **These Curves Represent Optimal Coupling** of the first two resonators in an intermediate step toward realizing a fifth-order Butterworth filter. On the abscissa, $\delta\omega$ denotes the frequency detuning and γ_c denotes the full frequency width of the resonance spectral peak at half maximum in the fully loaded condition.

and still others monitor the input power (P_{in}) and output power (P_o). The readings of these photodiodes are used to guide the tuning adjustments described below.

The steps of the first procedure are the following:

1. Uncouple all the resonators and prisms by increasing all the gaps.
2. Overload resonator 1 with the input coupling prism, then measure the input power (P_{in}), reflected power (P_r), and the power in resonator 1 (P_1) as functions of frequency detuning from resonance, and use the measurement data to determine the resonance quality factor (Q).
3. Couple resonator 2 to resonator 1, then measure P_{in}, P_r, P_1, and P_2 as functions of frequency detuning from resonance. Adjust the gap between resonators 1 and 2 until P_r/P_{in}, P_1/P_{in}, and P_2/P_{in} as functions of frequency detuning match a set of theoretical template functions (see Figure 2) calculated to contribute to the desired high-order transfer function.
4. Couple resonator 3 to resonator 2, then measure P_{in}, P_r, P_1, P_2, and P_3 as functions of frequency detuning from resonance. Adjust the gap between resonators 2 and 3 until P_r/P_{in}, P_1/P_{in}, and P_2/P_{in} as functions of frequency detuning match a different set of theoretical template functions calculated to contribute to the desired high-order transfer function.
5. Repeat step 4, each time adding the next resonator (and then adding the output coupling prism after the last resonator has been added) and adjusting the gaps to obtain the desired responses.

The steps of the second procedure are the following:

1. Measure and tabulate the dependence of each resonance frequency of each resonator on the bias voltage applied to that resonator.
2. Introduce, into the filter operation, "dark" periods, during which the laser and the resonators are scanned over some finite frequency band.
3. During a dark period, apply a specified voltage to resonator 1 to shift its resonance frequency by some amount. Measure the shift, then compensate it by applying another voltage to shift the resonance to the middle of the scan of the laser frequency.
4. Repeat step 3 for resonator 2 and subsequent resonators except the last one.
5. Adjust the voltage on the last resonator to scan its frequency until the filter exhibits maximum transmission, at which point the desired high-order transfer function has been restored.

This work was done by Andrey Matsko, Anatoliy Savchenkov, Dmitry Strekalov, and Lute Maleki of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).

The software used in this innovation is available for commercial licensing. Please contact Karina Edmonds of the California Institute of Technology at (626) 395-2322. Refer to NPO-43872.

Robust Mapping of Incoherent Fiber-Optic Bundles

Images scrambled by the bundles can be unscrambled.

Marshall Space Flight Center, Alabama

A method and apparatus for mapping between the positions of fibers at opposite ends of incoherent fiber-optic bundles have been invented to enable the use of such bundles to transmit images in visible or infrared light. The method is robust in the sense that it provides useful mapping even for a bundle that contains thousands of narrow, irregularly packed fibers, some of which may be defective.

In a coherent fiber-optic bundle, the input and output ends of each fiber lie at identical positions in the input and output planes; therefore, the bundle can be used to transmit images without further modification. Unfortunately, the fabrication of coherent fiber-optic bundles is too labor-intensive and expensive for many applications. An incoherent fiber-optic bundle can be fabricated more easily and at lower cost, but it produces a scrambled image because the position of the end of each fiber in the input plane is generally different from