Loss characterization in microcavities using the thermal bistability effect

H. Rokhsari, a) S. M. Spillane, and K. J. Vahala
Department of Applied Physics, California Institute of Technology, Pasadena, California 91125

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We demonstrate a powerful method based on the thermal bistability effect to characterize distinct loss mechanisms limiting the quality factor of microresonators. The relative importance of absorption and scattering losses are investigated in toroidal microcavities using this technique. Empirical results on thermal nonlinearity of these structures have been used to study the interaction of microtoroids with their ambient environment. © 2004 American Institute of Physics.

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At sufficiently high quality factors \( Q \), whispering gallery mode microresonators can enter a regime where minute injected optical powers can result in large thermal nonlinearities.\(^1\)\(^2\) The circulating intensity in these cavities, greatly enhanced due to their high quality factors and small mode volumes, is partially absorbed and the generated heat can produce thermal bistability.\(^3\) In this work, we exploit this phenomenon as a tool for characterizing distinct optical loss mechanisms responsible for limiting the quality factor of high-\( Q \) toroidal microcavities.\(^4\) The results, applicable to any other type of microresonator, provide insight into the relative importance of surface scattering and absorption centers in these cavities as well as the role of surface contaminants in altering the quality factor and thermal nonlinearities of these structures.

Thermal broadening/compression of the resonance line shape is frequently encountered in ultra-high-\( Q \) (UHQ) microcavities (\( Q > 10^9 \)).\(^5\) As the laser frequency is swept across the cavity resonance, optical power coupled into the resonator is partially absorbed and converted to heat, hence altering the optical properties of the bulk medium and shifting the resonant frequency either along or opposite to the direction of laser scanning. In silica, the dominant effect is due to the temperature-dependent refractive index of the cavity material which results in a negative frequency shift of the resonance with increased temperature:

\[
\nu - \nu_0 = -\frac{dn}{dT} \Delta T, \tag{1}
\]

where \( \nu - \nu_0 \) is the resonant frequency shift due to temperature change of \( \Delta T \). \( \nu_0 \) is the initial resonant frequency and \( \frac{dn}{dT} \) is the thermo-optic coefficient of the cavity bulk material (i.e., the rate of refractive index change as a function of temperature). As a result, the resonance line-shape is distorted from its original Lorentzian profile, becoming broader when scanned toward lower frequencies and narrower when scanned in the opposite direction.

The characteristic power for the optical power transmission spectrum in the presence of nonlinearity is given by

\[
1 - T = \frac{C}{1 + 4 \left[ x + \frac{P_{in}}{P_{th}} (1 - T) \right]^2}, \tag{2}
\]

where \( T \) is the transmission beyond the resonator-waveguide coupling region and \( C \) is the criticality factor which determines the degree to which the resonator is coupled to the waveguide (\( 0 \leq C \leq 1 \)).\(^6\)\(^7\) \( C \) starts at zero when the resonator is far from the waveguide (no coupling), reaches unity at the critical coupling point \( (T=0) \), and then declines toward zero as the resonator-waveguide coupling increases further and transmission recovers in the overcoupled regime. \( x \) is the normalized frequency defined as the deviation from the initial resonant frequency in units of resonator linewidth, i.e., \( x = (\nu - \nu_0) / (\Delta \nu) \). The characteristic power in this equation, referred to as threshold power \( (P_{th}) \), is the required input power to shift a resonance by its linewidth.

Figure 1(a) shows how the resonant line-shape is modified from its original Lorentzian profile (achievable at \( P_{in} \ll P_{th} \)). The transmission spectrum appears as the ABC curve when the input laser is tuned toward lower frequencies and as the CDE curve when scanned in the opposite direction. The minimum transmission \( (T=1-C) \) occurs at \( x = -CP_{in} / P_{th} \) which shows that monitoring the thermal broadening as a function of launched power provides a tool for accurate measurement of threshold power for thermal bistability.

For the thermal nonlinearity, threshold power is related to the resonator properties in the following form:

\[
P_{th} \approx \frac{nv_0C_p}{Q \alpha n_{thermal} \frac{dn}{dT}}, \tag{3}
\]

\( C_p = \rho V_{eff} c_p \) is the heat capacity of the effective volume (\( V_{eff} \)) in the bulk medium where the heating occurs, \( \rho \) and \( c_p \) are the density and special heat capacity of the medium, respectively, and \( \alpha \) is the absorption fraction of lost power (i.e., power lost to absorption relative to total power lost through all mechanisms contributing to intrinsic \( Q \)). From Eq. (3) \( P_{th} \) is inversely proportional to the quality factor \( (Q) \) and the thermal response time \( (\tau_{thermal}) \), which determines how fast the temperature of the optical mode volume rises.

In order to excite the whispering gallery modes of microtoroids, fiber tapers were used to couple light into and out of the resonators.\(^8\) Single-mode, tunable external-cavity lasers emitting in the 1550, 1300, and 980 nm bands were used as light sources. Transmission power through the fiber taper...
was monitored using fast photodiode detectors as the laser frequency was slowly (≤10 Hz) scanned over 10 GHz using a function generator.

Figure 1(b) shows the measured thermal shift of the resonant frequency versus input power for a high-Q ($Q = 0.9 \times 10^6$) whispering gallery mode in a toroidal microresonator at two different wavelengths. Although $Q$ values at these wavelengths are about the same, the threshold power at 970 nm is a factor of 20 higher than that at 1545 nm. From Eq. (3), the above difference suggests a higher absorption loss (higher $\alpha$ value) at 1545 nm compared to 970 nm. Such a difference in absorption cannot be explained in terms of silica absorption as fused silica is about four times more absorptive at 970 nm. Absorption losses at 1550 nm however, can be higher if there is a monolayer of water molecules on the resonator surface.\(^{10,11}\) Figure 2 contains the calculated quality factor versus wavelength of a 60-μm-diameter sphere (comparable to the microtoroids used for study of large toroidal minor diameters) that is limited by the combination of absorption due to a monolayer of surface water and the intrinsic absorption of fused silica. From this plot, a difference in threshold power of about 25 can be predicted using the calculated $Q$ values alone (inversely related to absorption losses) at the measured wavelengths indicated in the figure. The close agreement between the predicted and measured ratio of threshold powers at these wavelengths is thus consistent with the assumption of a water monolayer on the surface and suggests a highly efficient heat transfer mechanism from the surface water layer to the bulk glass where the optical mode is mainly located.

From Eq. (3), threshold power is inversely proportional to the quality factor and to the absorption fraction of lost power $\alpha$. In cases of exceptionally smooth whispering-gallery surfaces (i.e., low scattering loss) and large diameter resonators (not whispering gallery loss limited) the absorption fraction can approach unity (i.e., all the injected power converts to heat) and a $Q^{-1}$ behavior of threshold power is expected. On the other hand, if nonthermal losses (scattering or WGM losses) are the dominant loss mechanism, they determine the quality factor and therefore the absorption fraction (here the ratio of thermal to nonthermal losses) would be proportional to $Q$. In such cases a $Q^{-2}$ dependence in threshold power should be observable in modes belonging to the same resonator, but having different quality factors. In a regime where both losses are relatively important an intermediate behavior is expected.

Figure 3(a) shows the threshold powers measured for different modes of a scattering limited resonator. These WGM modes have $Q$’s ranging from $10^5$ to $10^8$ and they all lie within one free spectral range (9 nm) of the cavity. The data show a clear polynomial behavior with a slope of about −1.8 (close to inverse quadratic) in the 1550 nm band (circles). The data also show an exceptionally low threshold power ($\sim10$ nW) at 1550 nm. The same measurement on this resonator repeated in the 980 and 1300 nm bands reveals a similar behavior indicating that the quality factors in these cases are dominated by either surface roughness or scattering centers in the bulk material. The deviation from inverse quadratic behavior in these data can be due to the fact that distinct optical modes of the microtoroid have different extensions outside the cavity surface and hence experience differing water absorption losses. This would in turn alter the assumption of a $Q^{-1}$ dependence of absorption fraction on quality factor in scattering limited resonators. Figure 3(b) illustrates a resonator of similar size and quality factor but which exhibits absorption limited behavior in the 1550 nm band (slope −1.1), scattering limited behavior in the 980 nm band (slope −1.9), and an intermediate behavior at 1300 nm (slope −1.6). By examination of Fig. 2, this can be under-
measurements presented, information was obtained about the 
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nonlinear thermal effects in microresonators is an effective 
face of the cavity.

rectly related to the number of water molecules on the sur-
change in absorption fraction parameter which can be di-
change in threshold power therefore arises entirely from the 
input frequencies move to more transparent part of the water absorption spectrum.

stood as resulting from variation in water absorption losses at 
these wavelengths.

As further evidence that surface water layers play a ma-
jor role in absorption losses of the microtoroids under con-
sideration, we investigated the thermal bistability effect in 
humid environments. Figure 4 shows how the bistability 
threshold power at 1550 nm wavelength decreases as the en-
vIRONMENT becomes more humid. Significantly, the quality 
factor of the resonator in this measurement does not change 
noticeably as humidity is varied, which indicates that scatter-
ing limited case obtained in resonator 1; (b) illustrates the data from a 
similar experiment on resonator 2. In this case, a monotonic increase in the 
slope of graphs from 1500 nm (circles) to 1300 nm (triangles) and 980 nm 
(stars) wavelengths shows the transition from absorption limited to scatter-
ing limited regime. Also the threshold powers increase as the input frequen-
cies move to more transparent part of the water absorption spectrum.

The presented work demonstrates that measurement of 
nonlinear thermal effects in microresonators is an effective 
method to characterize different loss mechanisms in these 
structures. In particular, the degree to which resonators are 
absorption limited or scattering limited can be inferred from 
measurement of threshold power versus $Q$. In cases where 
there is a strong spectral dependence of absorption centers 
(such as the case of water adsorbed onto silica), it is also 
possible to make this determination through a combination 
of spectral measurements of threshold power and $Q$. In the 
measurements presented, information was obtained about the 
surface chemistry of the cavity, which revealed the presence 
of monolayers of water on the surface. Generalization of this 
method to other surface contaminants which could adver-
tently be deposited on the surface of these structures can be 
potentially useful in sensing applications and surface chem-
istry studies. Furthermore, real time monitoring of thermal 
properties and quality factor can be beneficial in studying the 
dynamics of interaction between the resonator surface and its 
environment.

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