

Vibration-insensitive disk-resonators for metrological applications

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Inhibition of vibration- and acceleration-induced frequency fluctuations would pave the way to metrological applications for whispering gallery mode disk-resonators.

Ultra-high Q whispering gallery modes (WGM) disk-resonators are expected to play an ever increasing role in metrological applications. In these cavities, photons are trapped by total internal reflection into the torus-like eigenmodes (the WGMs). These millimeter-size optical resonators are characterized by significantly long photon lifetimes (> 1 microsecond), and correspondingly, ultra-narrow modal linewidths. Such features are indeed highly desirable in a wide spectrum of applications, ranging from time-frequency metrology, navigation systems, spectroscopy, sensing, or ultralow phase noise microwave and terahertz generation.

In all these applications, the stability of the resonance frequency is critical. Any fluctuation in the refraction index and/or the cavity radius is automatically transferred to the resonance frequencies. Both the internal and the environment induced fluctuations are setting the ultimate floor in terms of frequency stability. In particular, mechanical vibrations and acceleration contribute to deform the cavity and shift the eigenmode frequency, which is ideally expected to remain constant when the WGM resonator is used as a reference cavity.

Just to give an order of magnitude, if we consider the mere action of gravity on a WGM calcium fluoride disk-resonator with 5 mm diameter and 1 mm thickness, it can be shown that the cavity undergoes a radius increase of only few tenths of pm (this is one hundred times smaller than the size of the hydrogen atom), but the related resonance frequency shift is already as huge as ~ 10 kHz around 200 THz (frequency corresponding to an infrared laser probe around 1550 nm). Ensuring a frequency precision of the order of 1 Hz requires stabilizing the cavity radius down to ~ 1 fm, which is the size of the proton.

Table-top laboratory experiments already enable the frequency stabilization of lasers locked to passive optical cavities at $\sim 10^{-15}$ [1,2]. Performances so far with WGM disk resonators are typically of the order of $\sim 10^{-12}$ [3,4], but the thermal limit at $\sim 10^{-14}$ indeed be reached [5]. However, the perspective of achieving such performances in embarked systems is so far unrealistic, since navigating systems (planes, spacecrafts, satellites, etc.) are unavoidably subjected to strong accelerations and vibrations at some point.

A key challenge is therefore to design clever mounting architectures able to inhibit environmental fluctuations of mechanical nature in WGM disk-resonators. An interesting solution relies on the concept of “*neutral mounting*”, where the mounting forces are distributed in a way such that the deformation of the optical cavity is null in a given direction, regardless on their intensity [6]. The null force-to-displacement conversion guarantees that any mechanical fluctuation should not be transferred to the displacement field, that is, to the reference resonance frequency.

Designing such a neutral mounting is not straightforward in WGM disk-resonators, as mounting such disks obey a certain number of stringent constraints. The most important one is that the rim of the disk (lateral surface) has to be free. Effectively, any mechanical contact with the rim would at the same time degrade the Q-factor and possibly affect the circular the optical path of the modes through the circumference deformation. In this latter case, any fluctuation in the mounting force would automatically induce a fluctuation of the optical path, and then, of the resonance frequency.

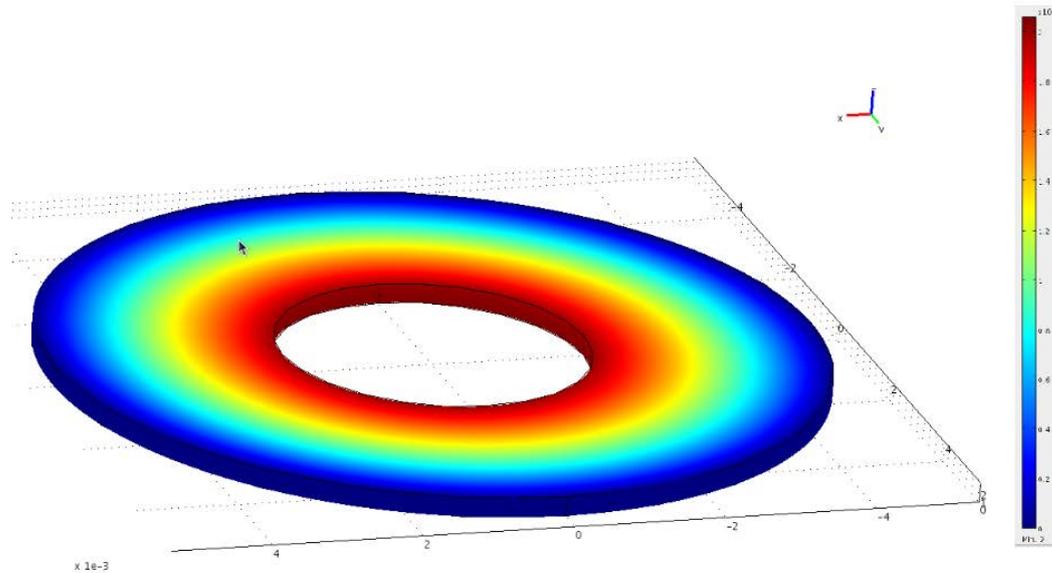


Figure 1: Color-coded radial displacement field of a clamped WGM disk-resonator. The displacement field is null at the edge, thereby ensuring the stability of the radius, and accordingly, of the resonant frequency reference.

However, it can be shown that clamping the disk between two cylinders with different radii can in optimal conditions induce a radial displacement field that is null at the rim of the disk, regardless of the mounting force intensity. This possibility can in fact be foreshadowed from the Euler-Bernoulli beam theory, which tells that when a beam is loaded (let's say bended downwards), the top-half is stretched while the bottom-half is symmetrically compressed. Therefore, the plane of symmetry does not undergo any longitudinal deformation at the first order.

As it can be seen in Fig. 1, the same phenomenology occurs when a resonator is bend. The figure displays the finite-elements numerical simulation of the displacement field corresponding to a clamped WGM disk-resonator. This color-coded representation clearly shows that the radius displacement is null in the plane of symmetry (the neutral plane), where the torus-like WGMs are physically located. Theoretical analysis also indicates that the stress and strain fields are also null in this neutral plane. Hence, from an elastostatic point of view, the WGMs are indeed under the physical condition of a load-free resonator regardless of the mounting force.

This interesting theoretical result, which is still to be confirmed experimentally, indicates that the inhibition of vibration- and acceleration-induced frequency fluctuations in WGM disk-resonators could be achieved with a fairly simple strategy, and enable the reliable use of these reference cavities in a non-laboratory environment.

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References

1. A. D. Ludlow, X. Huang, M. Notcutt, T. Zanon-Willette, S. M. Foreman, M. M. Boyd, S. Blatt and J. Ye, Compact, thermal-noise limited optical cavity for diode laser stabilization at 1×10^{-15} , *Opt. Lett.* 32, pp. 641-643, 2007.
2. S. A. Webster, M. Oxborrow, S. Pugla, J. Millo and P. Gill, Thermal-noise-limited optical cavity, *Phys. Rev. A* 77, 033847, 2008.
3. W. Liang, V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, D. Seidel, and L. Maleki, Whispering-gallery-mode-resonator-based ultranarrow linewidth external-cavity semiconductor laser, *Opt. Lett.* 35, pp. 2822-2824, 2010.
4. D. V. Strekalov, R. J. Thompson, L. M. Baumgartel, I. S. Grudinin and N. Yu, Temperature measurement and stabilization in a birefringent whispering gallery resonator, *Optics Express* 19, pp. 14449-14501, 2011.
5. J. Alnis, A. Schliesser, C. Y. Wang, J. Hofer, T. J. Kippenberg and T. W. Hansch, Thermal-noise limited laser stabilization to a crystalline whispering-gallery-mode resonator, arXiv:1102.4227v1, 2011.
6. D. R. Leibrandt, M. J. Thorpe, M. Notcutt, R. E. Drullinger, T. Rosenband and J. C. Bergquist, Spherical reference cavities for frequency stabilization of lasers in non-laboratory environments, *Optics Express* 19, pp. 3471-3482, 2011.

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