Crystalline Mirrors in Optical Reference Cavities

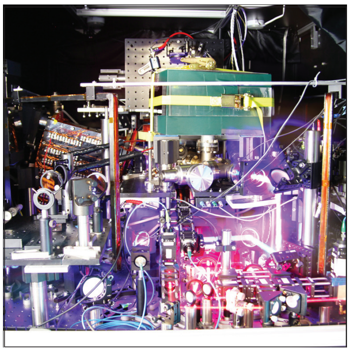
THORLABS APPLICATION NOTE

APPLICATION

Optical reference cavities are resonators for light and provide a way to precisely define an optical frequency. These tools are used analogously to tuning forks for musical instruments, which define a reference acoustic frequency; the ability to define an extremely precise optical "note" is a fundamental need in precision metrology. Whether implemented for the measurement of length displacements at the 10^{-18} m level, which can be induced by transiting gravitational waves at facilities such as LIGO, Virgo, or KAGRA; the production of optical frequencies to a precision better than a single hertz for atomic clocks; or the detection of trace gases; optical reference cavities have become ubiquitous and indispensable tools for high-precision laser-based metrology and sensing.

QUICK FACTS

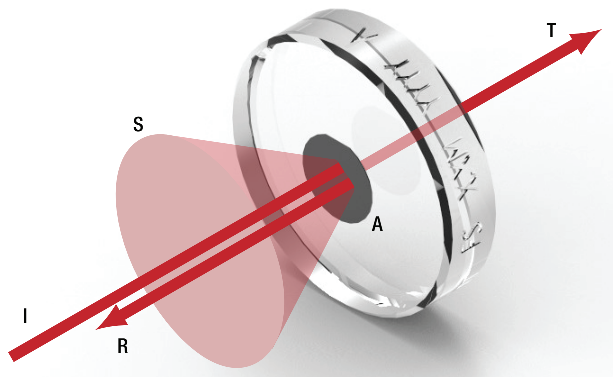
- Optical reference cavities consist of two parallel, highly reflective mirrors facing one another.[1]
- Resonant enhancement of the optical field, or constructive interference, occurs when the cavity length is an integer multiple of $\lambda/2$, where λ is the wavelength of the incident light.
- The cavity ringdown technique allows for accurate and precise measurement of a cavity end mirror's optical losses: transmission, scatter, and absorption.
- Thorlabs' crystalline supermirrors are ideal for the construction of optical reference cavities, optical atomic clocks, stabilized lasers, and even the next generation of gravitational wave detectors.



Left: Photograph of a Strontium Optical Clock Constructed by Researchers at the University of Colorado and the National Institute of Standards and Technology. Photo Credit: Ye Group and Baxley/JILA.

Right: Aerial View of the Virgo Gravitational Wave Observatory. Photo Credit: The Virgo Collaboration.

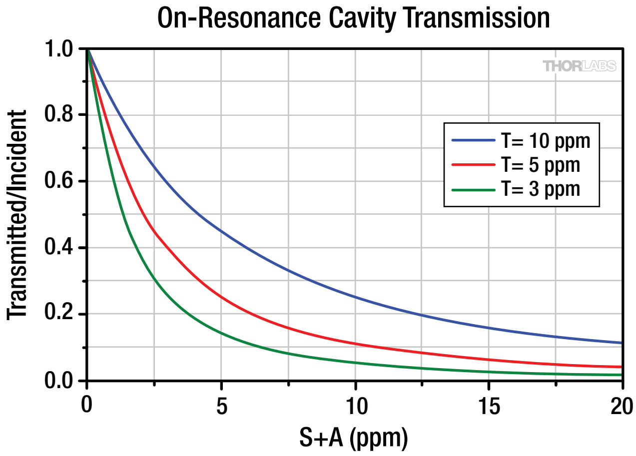
OPTICAL AND MECHANICAL LOSSES



Schematic Showing Optical Loss Mechanisms Caused by an Optical Coating

Coating optical loss mechanisms consist of transmission (*T*), scatter (*S*), and absorption (*A*). Scatter and absorption are known as excess optical losses and are critical parameters for supermirrors. While transmission is typically a design parameter controlled by the layer structure of interference coatings, excess losses are generally harder to control beyond a minimum level driven by manufacturing and material imperfections. In the case of an optical cavity, the partition of losses between transmission and excess loss determines the usability of the cavity. The power transmitted through the cavity is given by $P_t/P_i = T^2/(T+S+A)^2$, where P_t and P_i are the optical powers transmitted and incident on the cavity, respectively.

In applications where the reference cavity length noise arising from the thermal atomic motion in the coating matters (e.g. in the construction of narrow-linewidth lasers with active locking to an optical cavity, or precision displacement sensing as with gravitational wave detectors), the mechanical material properties also become important.[2] Monocrystalline semiconductor materials such as GaAs and AlGaAs exhibit quasi-bulk properties and lower mechanical noise than amorphous, dielectric coatings created from sputtering.[3]

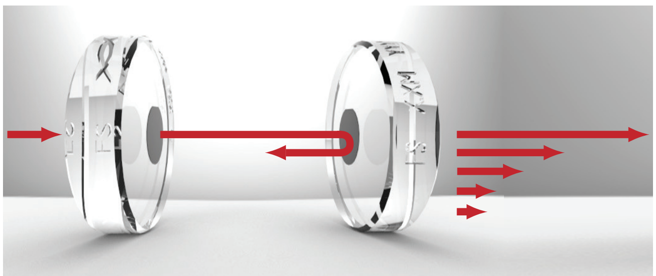


Plot of On-Resonance Cavity Transmission Assuming Perfect Spatial Mode Matching and Identical Input and Output Mirrors

CAVITY RINGDOWN FOR OPTICAL LOSS CHARACTERIZATION

Precise and accurate determination of the transmission and the excess losses, scatter and absorption, presents a difficult measurement challenge due to the small values and dynamic range involved. Typically, $5 < T < 10$ ppm and $S + A < 5$ ppm for Thorlabs' coatings. Commercial spectrophotometry systems typically provide accuracies at a 3000 ppm level up to reflectivities of about 99.9%. Similarly, ratiometric laser power measurements providing 100 ppm accuracies for reflectivities up to 99.99% fall short of characterization requirements for these supermirrors.

In 1984, Anderson, *et al.*[4] described a reflectometer based on a resonant optical cavity comprising high-reflectivity end mirrors in order to convert an amplitude measurement into a pure time-delay measurement by exploiting the finite speed of light. When a pulse of incident light reaches the output mirror, a fraction equal to the transmission T is outcoupled and a fraction R is reflected back into the cavity. On the second round-trip, the same fraction T of this now-reduced incident power is again out-coupled. This ratiometric progression of loss per round trip of the cavity leads to an exponential decay of the transmitted optical power with time constant τ. Critically, this technique is impervious to source amplitude fluctuations, and less sensitive to detector linearity, detection noise, and dynamic range limitations compared to other measurement techniques.



In cavity ringdown, the rate at which the intracavity field leaks out from a cavity is dependent on the total optical losses of the coatings.

With a measured value of τ and the known cavity length, L, the total optical loss $T + S + A$ of each supermirror is given by $T{+}S{+}A{=}L/(c\tau)$, where c is the speed of light. For conservation of energy, the total loss and the reflectivity must add up to 1.

Commonly, the cavity finesse $F{=}\,c\pi\tau\,/\,L$ is also used to describe the optical loss of a reference cavity. For a simple linear optical cavity consisting of two mirrors, the finesse is related to the reflectivity of each mirror by $F{=}\,\pi\sqrt{R}/(1{-}R)$.

CATALOG AND CUSTOM OFFERINGS

Thorlabs Crystalline Solutions offers a range of semiconductor supermirrors that exhibit ideal properties for use as end mirrors in optical reference cavities:

- Extremely High Reflectance
- Ultra-Low Optical Losses
- Minimal Brownian Noise

xtal stable™

In addition to mirror production, Thorlabs offers optical reference cavity assembly services. Customers can supply their own spacer and ultra-low expansion glass compensation rings, or provide their desired specifications and work with our expert staff to design and manufacture a custom spacer.

OPTICAL LOSS MAPPING SERVICE

The total optical loss of every supermirror we ship is measured using a custom-built cavity ringdown system.[5] Diode lasers are directly coupled – without optical isolation – into a linear cavity formed from a pair of crystalline supermirrors. The retroreflection of the cavity input coupler forms an extended cavity diode laser and narrows the laser linewidth. The narrowed linewidth increases the in-coupled optical power by pulling the laser close to the center wavelength of the coating, where the composite laser and external cavity typically has the lowest loss.

By mounting the supermirrors on motorized mounts with four degrees of freedom, the optical loss from each coating can be spatially mapped. While the development of this scanning cavity ringdown apparatus was initially developed for process development, we can now offer coating loss mapping as a service for mirrors operating at 1064 nm, 1156 nm, 1397 nm, 1550 nm, and 1572 nm.

CONCLUSION

Supermirrors are indispensable for modern optical metrology and find use in increasingly high-performance optical cavities from the cm to km length scales. Improvements in coating technology are now pushing the ultimate limits of optical performance. At the same time, the use of ultrahigh purity and low-mechanical-loss monocrystalline-semiconductor-based interference coatings are enabling order-of-magnitude reductions in elastic losses. The ability to fabricate mirrors with simultaneously excellent optical and mechanical properties using crystalline coatings has led to substantial progress beyond fundamental limitations in the length stability of cutting-edge optical resonators.

REFERENCES

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2) Harry, G., Bodiya, T., & DeSalvo, R. (Eds.). (2012). Optical Coatings and Thermal Noise in Precision Measurement. Cambridge: Cambridge University Press
3) Cole GD, Zhang W, Martin MJ, Ye J, and Aspelmeyer M. "Tenfold reduction of Brownian noise in high-reflectivity optical coatings." Nature Photonics. 2013 August; 7: 644-650.
4) Anderson DZ, Frisch JC, and Masser CS. "Mirror reflectometer based on optical cavity decay time." Applied Optics. April 15, 1984; 23: 1238-1245.
5) Truong GW, Winkler G, Zederbauer T, Bachmann D, Heu P, Follman D, White ME, Heckl OH, and Cole GD. "Near-infrared scanning cavity ringdown for optical loss characterization of supermirrors." Optics Express. June 24, 2019; 27: 19141-19149.