the ambient-to-cryogenic temperature gradient across the window.

The augmented method includes elements of laboratory implementation and data reduction that go beyond those of the established room-temperature-only method. The most straightforward aspect of the method is the use of an off-the-shelf interferometer and, to match the complex shape of the mirror under test, a custom CGH. Other aspects of the method, too complex to describe in detail, can be summarized as follows: The method calls for a complex combination of room-temperature and cryogenic test procedures and associated data-reduction procedures formulated to minimize systematic test errors and reveal subtle thermomechanical and optical effects, and thereby to characterize surface-figure errors at ambient and cryogenic temperatures. One notable feature of the method is the use of interferometric techniques to quickly align the mirror under test when it is in the cryogenic chamber. Once the mirror has been aligned and thermal equilibrium has been established, measurements are performed on both mirror and window surfaces to obtain the data needed to computationally eliminate the optical effects of the window.

Series-Coupled Pairs of Silica Microresonators

Pass bands are narrower and flatter than those of single microresonators.

NASA's Jet Propulsion Laboratory, Pasadena, California

Series-coupled pairs of whispering-gallery-mode optical microresonators have been demonstrated as prototypes of stable, narrow-band-pass photonic filters. Characteristics that are generally considered desirable in a photonic or other narrow-band-pass filter include response as nearly flat as possible across the pass band, sharp roll-off, and high rejection of signals outside the pass band. A single microresonator exhibits a Lorentzian filter function: its peak response cannot be made flatter and its roll-off cannot be made sharper. However, as a matter of basic principle applicable to resonators in general, it is possible to (1) use multiple resonators, operating in series or parallel, to obtain a roll-off sharper, and out-of-band rejection greater, relative to those of a Lorentzian filter function and (2) to make the peak response (the response within the pass band) flatter by tuning the resonators to slightly different resonance frequencies that span the pass band.

The first of the two microresonators in each series-coupled pair was a microtorus made of germania-doped silica (containing about 19 mole percent germania), which is a material used for the cores of some optical fibers. The reasons for choosing this material is that exposing it to ultraviolet light causes it to undergo a chemical change that changes its index of refraction and thereby changes the resonance frequency. Hence, this material affords the means to effect the desired slight relative detuning of the two resonators. The second microresonator in each pair was a microsphere of pure silica. The advantage of making one of the
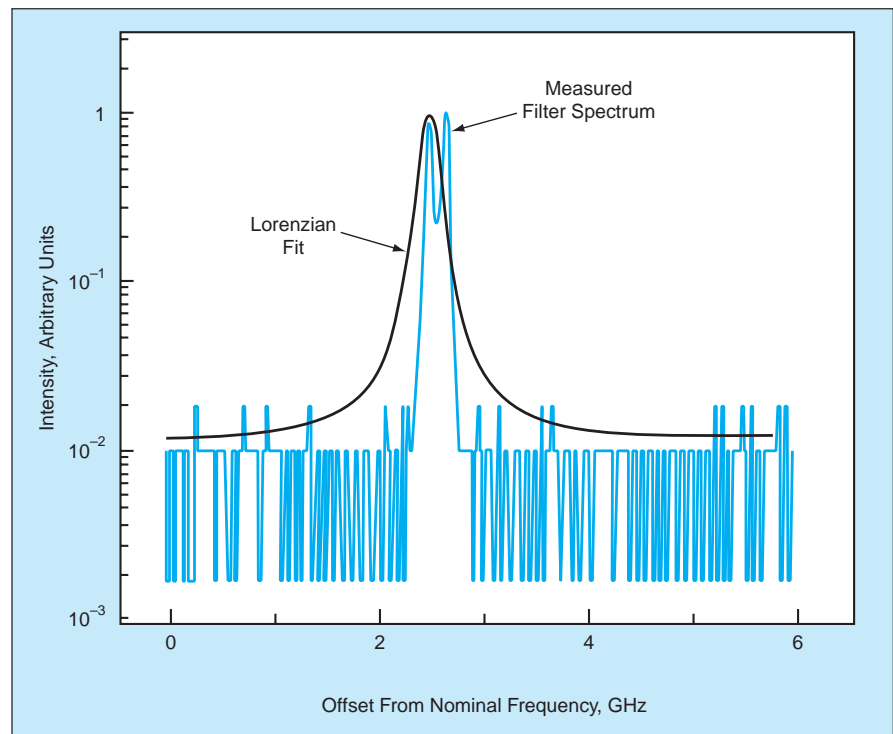
This **Second-Order Filter Spectral Response** was determined in measurements on a band-pass filter comprising a germania-doped silica microtorus series-coupled to a silica microsphere. A Lorentzian fit to the corresponding spectral response of a single microresonator is also shown for comparison.

resonators a torus instead of a sphere is that its spectrum of whispering-gallery-mode resonances is sparser, as needed to obtain a frequency separation of at least 100 GHz between resonances of the filter as a whole.

The two microresonators in each pair were mounted in proximity to each other so that the two were optically coupled. Half of the amplified light from a laser diode at a nominal wavelength of 1.55 μm was coupled into the first microresonator by means of an angle-polished optical fiber. The other half of the amplified laser light was passed through a Fabry-Perot cavity having a free spectral range of 20 GHz; this cavity served as both a reference to correct for laser frequency drift and a scale for measuring the difference between resonance frequencies. By use of a second angle-polished optical fiber, light was coupled out of the second microresonator to a photodiode.

An argon-ion laser operating at a wavelength of 351 nm (the wavelength

most efficient for producing the desired photochemical reaction) was focused into the germania-doped microresonator. The current applied to the photodiode was modulated with a sawtooth waveform in order to sweep the laser wavelength repeatedly through a frequency range that included the pass band and surrounding frequencies. Using knowledge of the laser frequency vs. time, along with the measurements of photocurrent vs. time, it was possible to determine the magnitude of the filter

spectrum. From time to time, the argon-ion laser was turned on to tune the germania-doped microresonator, and then the spectrum determined. Care was taken to discriminate against the transient contribution of laser-induced thermal expansion to the change in the spectrum. The process was repeated until the desired separation between the two resonance frequencies was obtained (for example, see figure).

This work was done by Anatoliy Savchenkov, Vladimir Iltchenko, Lute Maleki,

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Precise Stabilization of the Optical Frequency of WGMRs

This technique results in whispering gallery mode resonators with absolute frequency stability.

NASA's Jet Propulsion Laboratory, Pasadena, California

Crystalline whispering gallery mode resonators (CWGMRs) made of crystals with axial symmetry have ordinary and extraordinary families of optical modes. These modes have substantially different thermo-refractive constants. This results in a very sharp dependence of differential detuning of optical frequency on effective temperature. This frequency difference compared with clock gives an error signal for precise compensation of the random fluctuations of optical frequency. Certain crystals, like MgF_2, have "turnover" points where the thermo-refractive effect is completely nullified.

An advantage for applications using WGMRs for frequency stabilization is in the possibility of manufacturing resonators out of practically any optically transparent crystal. It is known that there are crystals with negative and zero thermal expansion at some specific temperatures. Doping changes properties of the crystals and it is possible to create an optically transparent crystal with zero thermal expansion at room temperature. With this innovation's stabilization technique, the resultant WGMR will have absolute frequency stability

The expansion of the resonator's body can be completely compensated for by nonlinear elements. This results in compensation of linear thermal expansion (see figure). In three-mode, the MgF_2 resonator, if tuned at the turnover

thermal point, can compensate for all types of random thermal-related frequency drift. Simplified dual-mode method is also available. This creates miniature optical resonators with good short- and long-term stability for passive secondary frequency ethalon and an active resonator for active secondary frequency standard (a narrowband laser with long-term stability).

Optical losses due to media imperfection were addressed through a multi-step, asymptotic processing of the res-

A **Nonlinear Thermal Compensator** for an optical WGM resonator consists of (1) a rigid metal frame, (2) a glass or metal wedge-shaped spacer, and (3) a WGM resonator sandwiched between rigid spacers on the top and bottom. Temperature tuning is realized with a heater (5), and the nonlinearity is introduced by a nonlinear element (4).

onator. This technique has been initially developed to reduce microwave absorption in dielectric resonators. One part of this process consists of mechanical polishing performed after high-temperature annealing by placing the fluorite WGMR in a 3-foot-long (0.91-m-long), air-filled, transparent tube of annealed fused silica and then into a 20-cm-long horizontal tube furnace with a heated furnace core. The annealing process improves the transparency of the material because an increased temperature results in the enhancement of the mobility of defects induced by the fabrication process, and also reduces any residual stress birefringence. The increased mobility leads to the recombination of defects and their migration to the surface. The straightforward annealing of a WGMR leads to $Q > 10^{11}$ at 1.55 μm.

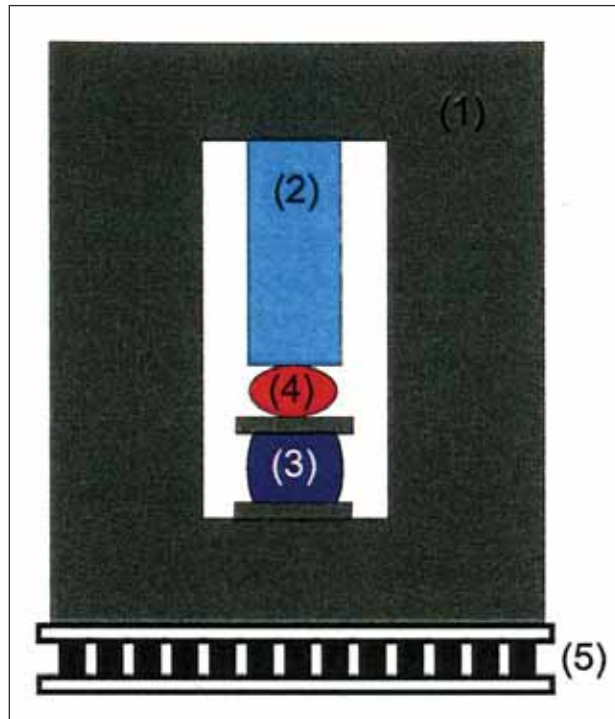*This work was done by Anatoliy Savchenkov, Andrey Matsko, Nan Yu, Lute Maleki, and Vladimir Iltchenko of Caltech for NASA's Jet Propulsion Laboratory.*