Graded-Index "Whispering-Gallery" Optical Microresonators

Improvements would include equidistant resonances and reduced evanescent field.

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Graded-index-of-refraction dielectric optical microresonators have been proposed as a superior alternative to prior dielectric optical microresonators, which include microspheres (described in several prior *NASA Tech Briefs* articles) and microtori wherein electromagnetic waves propagate along circumferential paths in "whispering-gallery" modes. The design and method of fabrication of the proposed microresonators would afford improved performance by exploiting a combination of the propagation characteristics of the whispering-gallery modes and the effect of a graded index of refraction on the modes.

The prior microresonators have been shown to be capable of functioning as compact, high-performance optical filters characterized by rarefied spectra of narrow resonance lines. For many applications, the frequency intervals between resonances are required to be equal. Unfortunately, the techniques used to fabricate the prior microresonators cannot be used to obtain equidistant resonances. The variation of frequency spacing of resonances is a consequence of the frequency dependence of the radial distribution of the whispering-gallery resonant modes: In a given microresonator that does not have a graded index of refraction, higher-frequency modes propagate on paths slightly closer to the surface, relative to lower-frequency modes. In other words, the higher-frequency modes propagate circumferentially at slightly larger radii and, consequently, slightly longer optical path lengths. The variation of optical path lengths results in nonuniform spacing of resonance frequencies.

Optical path length is a function of both distance (in the common geometrical sense) and the index of refraction. A microresonator according to the proposal would be fabricated from a graded-index-of-refraction cylinder. The parameters of the fabrication process would be chosen such that the index of refraction of the cylinder would decrease with radius by an amount calculated on the basis of the propagation characteristics of the desired resonances. Although higher-frequency modes would still travel geometrically longer distances, the indices of refraction at the larger radii would be lower (the waves would travel faster). With proper choice of the rate of decrease of the index of refraction with radius, the circumferential paths at all radii would have identical optical path lengths and consequently, to first order, the resonances would be equidistant in frequency.

Additional potential advantages of the proposal include the following:

- Fabrication should be straightforward: Graded-index-of-refraction optical components are widely available in the form of lenses and optical fibers. Such components can be formed into microresonators by use of standard mechanical- and flame-polishing techniques.
- The proposed grading of indices of refraction would push the whispering-gallery modes slightly deeper into the resonator material, so that the evanescent fields would be smaller. As a result, losses attributable to imperfections of surfaces would be less than in the prior microresonators.
- The designs of the prior microresonators exploit evanescent-field coupling via airgaps. Vibrations give rise to small changes in the airgaps, thereby causing fluctuations in coupling strength. In the proposed microresonators, the greater depth of propagation of the resonant modes would make it possible to use zero-gap coupling, so that vibration would no longer cause fluctuations in the strengths of coupled optical signals.

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

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Manufacture of Sparse-Spectrum Optical Microresonators

Multiple units having the same spectral parameters could be produced.

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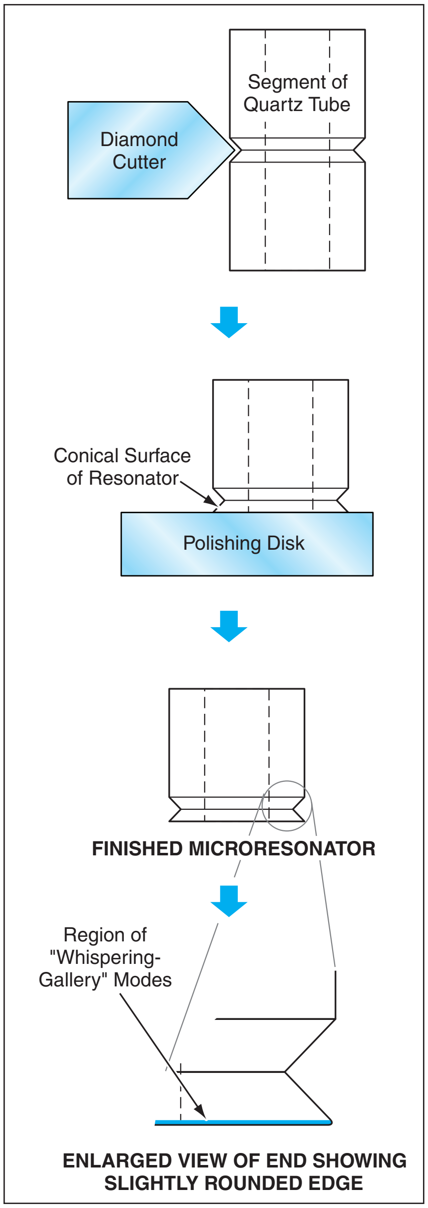
An alternative design for dielectric optical microresonators and a relatively simple process to fabricate them have been proposed. The proposed microresonators would exploit the same basic physical phenomena as those of microtorus optical resonators and of the microsphere optical resonators described in several prior *NASA Tech Briefs* articles. The resonances in such devices are associated with the propagation of electromagnetic waves along circumferential paths in "whispering-gallery" modes. The main advantage afforded by the proposal is that the design and the fab-



A **Microresonator Would Be Fabricated** from a length of silica tube by a process of diamond cutting, mechanical polishing, and fire polishing.

rication process are expected to be amenable to production of multiple microresonators having reproducible spectral parameters — including, most notably, high values of the resonance quality factor (Q) and reproducible resonance frequencies.

High-Q optical microresonators are key components in many contemplated advanced optoelectronic applications, including high-stability, narrow-line-width microlasers; spectrometers; remote-sensing systems; memory devices; and optical delay lines. In all such applications, there are requirements for stable and repeatable spectra that contain the resonance spectral lines of interest and do not contain unwanted lines: in other words, there are requirements for microresonators that exhibit high Q with reproducible sparse spectra. Although prior microsphere and microtorus optical resonators have been shown to have the potential to satisfy these requirements, the techniques used heretofore to fabricate them, involving melting individual resonators under manual control, do not yield reproducible spectral parameters and, therefore, are not suitable for production of multiple, functionally identical units.

The figure depicts a microresonator and the fabrication thereof according to the proposal. In preparation for fabrication of a batch of microresonators, one would choose a silica tube of precisely calibrated diameter (typically about 6 mm), so that all the resonators in the batch could be relied upon to have the same diameter. One would cut the tube into shorter segments — one for each resonator. By use of a diamond cutter, a circumferential V groove would be made on the outer surface of each segment. By polishing with a diamond disk, all the material would be removed from one end of the segment (the lower end in the figure), up to the edge of the groove. Thus, what would remain at the polished end of the tube would be a quasi-toroidal resonator structure having a conical outer surface.

The edge region would be fire-polished by use of a hydrogen/oxygen torch to eliminate the roughness of the cut edge and conical surface and the residual roughness of the mechanically polished end face of the tube segment. This smoothing of the surface would reduce the loss of light propagating in whispering-gallery modes, thereby helping to ensure high Q (anticipated to be 10^9). The fire polishing would also round the edge slightly, but the radius of curvature of the edge would be small enough that the spectrum would remain sparse.

This work was done by Anatoliy Savchenkov, Vladimir Iltchenko, Lute Maleki, and Dimitri Kossakovski of Caltech for **NASA's Jet Propulsion Laboratory.** *Further information is contained in a TSP (see page 1).*

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Exact Tuning of High-*Q* Optical Microresonators by Use of UV

Resonance frequencies can be shifted permanently by controlled amounts.

NASA's Jet Propulsion Laboratory, Pasadena, California

In one of several alternative approaches to the design and fabrication of a "whispering-gallery" optical microresonator of high resonance quality (high Q), the index of refraction of the resonator material and, hence, the resonance frequencies (which depend on the index of refraction) are tailored by use of ultraviolet (UV) light. The principles of operation of optical microresonators, and other approaches to the design and fabrication of optical microresonators, have been described in prior *NASA Tech Briefs* articles, including the two immediately preceding this one.

In this approach, a microresonator structure is prepared by forming it from an ultraviolet-sensitive material. Then the structure is subjected to controlled exposure to UV light while its resonance frequencies are monitored. This approach is applicable, for example, to the fabrication of optical microresonators from silica doped with germanium. This material exhibits low optical loss at a wavelength of 1,550 nm — a wavelength often used in optical communication systems. It is also highly sensitive to UV light: its peak sensitivity occurs at a wavelength of 334 nm, and