Compact Dielectric-Rod White-Light Delay Lines

Achievable group delays would be limited only by optical losses in materials.

NASA's Jet Propulsion Laboratory, Pasadena, California

Optical delay lines of a proposed type would be made from rods of such dielectric materials as calcium fluoride, fused silica, or sapphire. These would offer advantages over prior optical delay lines, as summarized below.

Optical delay lines are key components of opto-electronic microwave oscillators, narrow-band opto-electronic microwave filters, evanescent-field optical biochemical detectors, and some Fourier-Transform spectrum analyzers. Heretofore, optical delay lines used in such applications have been of two types: resonators and coiled long optical fibers, both of which have disadvantages:

- Resonators are compact, but excitation must be provided by narrow-band lasers. Wide-band (including noisy) laser light cannot be coupled efficiently to narrow-band resonators.
- When light is coupled into a narrow-band resonator from a source of reasonably high power, a significant amount of optical energy circulates within the resonator, causing nonlinear loss and significant noise.
- Typically, a coil-type optical delay line is made of fused-silica fiber, which exhibits fundamental loss. To overcome the limit imposed by the optical loss in fused silica, it would be necessary to use fibers having crystalline cores.
- Although space is saved by winding fibers into coils, fiber-coil delay lines are still inconveniently bulky.

The proposed compact dielectric-rod delay lines would exploit the special class of non-diffracting light beams that are denoted Bessel beams because their amplitudes are proportional to Bessel functions of the radii from their central axes. High-order Bessel beams can have large values of angular momentum. They can be generated with the help of whispering-gallery-mode optical resonators, as described, for example, in "Simplified Generation of High-Angular-Momentum Light Beams" (NPO-42965) *NASA Tech Briefs*, Vol. 31, No. 3 (March 2007), page 8a. In a delay line according to the proposal, the dielectric rod would be dimensioned to function as a multimode waveguide. Suitably chosen high-angular-momentum modes in such a waveguide exhibit low group velocity (hence, long delay) and no resonance. Such a delay line could perform well at any wavelength or range of wavelengths within the transparency wavelength band of the dielectric material, and the maximum possible group delay achievable through suitable design would be limited only by the optical loss in the rod material.

This work was done by Lute Maleki, Andrey Matsko, Anatoliy Savchenvkov, and Dmitry Strekalov of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).NPO-43459

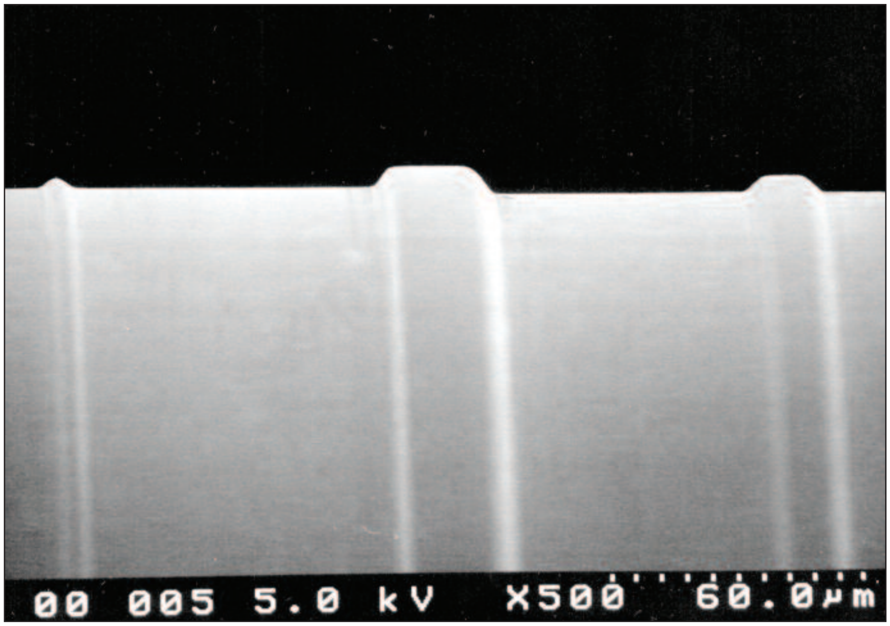
Single-Mode WGM Resonators Fabricated by Diamond Turning

Resonators having desired spectral responses can be reproduced efficiently.

NASA's Jet Propulsion Laboratory, Pasadena, California

A diamond turning process has made possible a significant advance in the art of whispering-gallery-mode (WGM) optical resonators. By use of this process, it is possible to fashion crystalline materials into WGM resonators that have ultra-high resonance quality factors (high *Q* values), are compact (ranging in size from millimeters down to tens of microns), and support single electromagnetic modes.

This development combines and extends the developments reported in "Few-Mode Whispering-Gallery-Mode Resonators" (NPO-41256), *NASA Tech Briefs*, Vol. 30, No. 1 (January 2006), page 16a and "Fabrication of Submillimeter Axisymmetric Optical Components" (NPO-42056), *NASA Tech Briefs*, Vol. 31, No. 5 (May 2007), page 10a. To recapitulate from the first cited prior article: A WGM resonator of this special type consists of a rod, made of a suitable transparent material, from which protrudes a thin circumferential belt of the same material. The



Circumferential Belts were formed by diamond turning on the initially cylindrical surface of a CaF_2 rod. The radial depths and axial widths of the belts were chosen to make some of the belts act as single-mode and some as multi-mode WGM resonators.

belt is integral with the rest of the rod and acts as a circumferential waveguide. If the depth and width of the belt are made appropriately small, then the belt acts as though it were the core of a single-mode optical fiber: the belt and the rod material adjacent to it support a single, circumferentially propagating mode or family of modes.

To recapitulate from the second cited prior article: A major step in the fabrication of a WGM resonator of this special type is diamond turning or computer numerically controlled machining of a rod of a suitable transparent crystalline material on an ultrahigh-precision lathe. During the rotation of a spindle in which the rod is mounted, a diamond tool is used to cut the rod. A computer program is used to control stepping motors that move the diamond tool, thereby controlling the shape cut by the tool. Because the shape can be controlled via software, it is possible to choose a shape designed to optimize a resonator spectrum, including, if desired, to limit the resonator to supporting a single mode. After diamond turning, a resonator can be polished to increase its *Q*.

By virtue of its largely automated, computer-controlled nature, the process is suitable for mass production of nominally identical single-mode WGM resonators. In a demonstration of the capabilities afforded by this development, a number of WGM resonators of various designs were fabricated side by side on the surface of a single CaF_2 rod (see figure).

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

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

Innovative Technology Assets Management
JPL
Mail Stop 202-233
4800 Oak Grove Drive
Pasadena, CA 91109-8099
(818) 354-2240
E-mail: iaoffice@jpl.nasa.gov

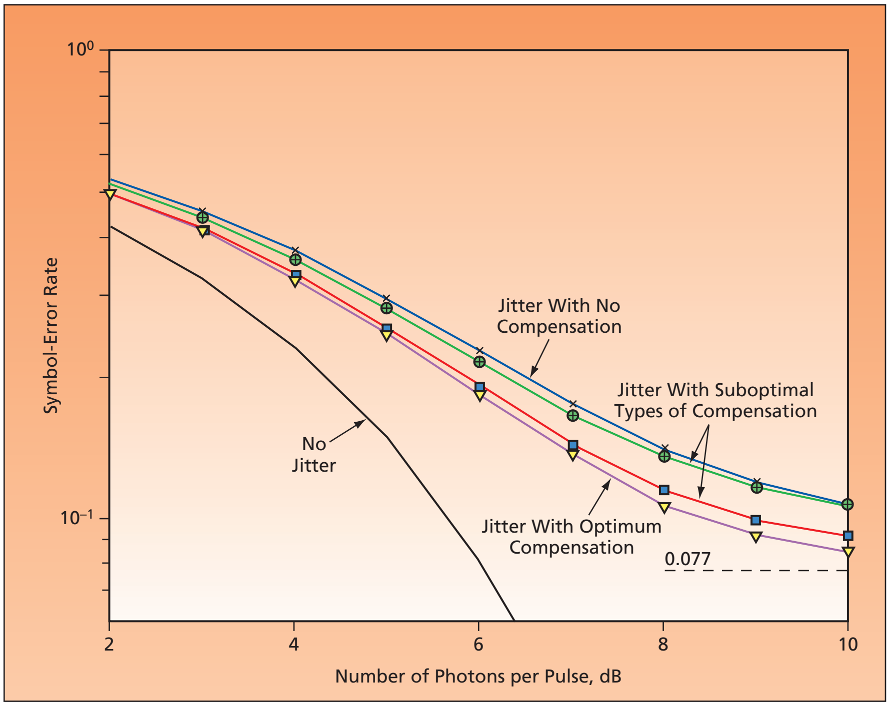
Refer to NPO-43070, volume and number of this NASA Tech Briefs *issue, and the page number.*

Mitigating Photon Jitter in Optical PPM Communication

Compensation based partly on photon-arrival statistics would yield gain.

NASA's Jet Propulsion Laboratory, Pasadena, California

A theoretical analysis of photon-arrival jitter in an optical pulse-position-modulation (PPM) communication channel has been performed, and now constitutes the basis of a methodology for designing receivers to compensate so that errors attributable to photon-arrival jitter would be minimized or nearly minimized. Photon-arrival jitter is an uncertainty in the estimated time of arrival of a photon relative to the boundaries of a PPM time slot. Photon-arrival jitter is attributable to two main causes: (1) receiver synchronization error [error in the receiver operation of partitioning time into PPM slots] and (2) random delay between the time of arrival of a photon at a detector and the generation, by the detector circuitry, of a pulse in response to the photon. For channels with sufficiently long time slots, photon-arrival jitter is negligible. However, as durations of PPM time slots are reduced in efforts to increase throughputs of optical PPM communication channels, photon-arrival jitter becomes a significant source of error, leading to significant degradation of performance if not taken into account in design.



Symbol-Error Rates were computed for a PPM receiver not subject to jitter and for PPM receivers subject to photon-arrival-jitter-induced inter-time-slot interference (neglecting inter-symbol interference), all for the case of 16-time-slot PPM words with an average of 0.2 noise photons per time slot and $\alpha = 0.2$ in a jitter-offset exponential distribution $f(\delta) = [1/(2\alpha)]e^{-|\delta|/\alpha}$, where δ is the jitter offset in units of one slot duration.

For the purpose of the analysis, a receiver was assumed to operate in a photon-starved regime, in which photon counts follow a Poisson distribution. The analysis included derivation of exact equations for symbol likelihoods in the presence of photon-arrival jitter. These equations describe what is well known in the art as a matched filter for a channel containing Gaussian noise. These equations would yield an optimum receiver if they could be implemented in practice.

Because the exact equations may be too complex to implement in practice, approximations that would yield suboptimal receivers were also derived. One