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:

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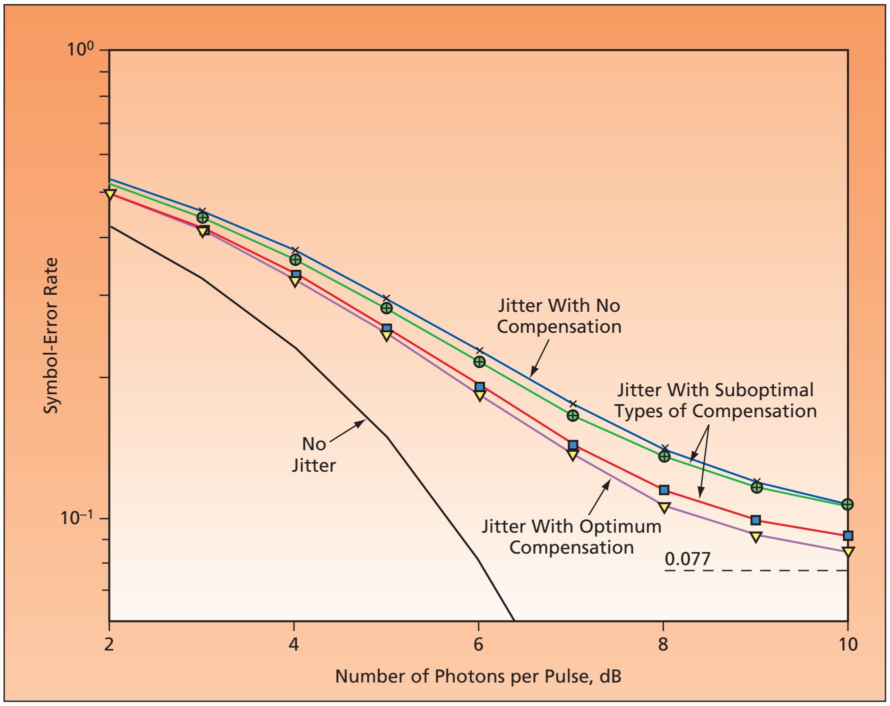
Refer to NPO-43070, volume and number of this NASA Tech Briefs *issue, and the page number.*

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 approximation is based on the assumption that the jitter in the arrival of each photon is independent. Another approximation is based on the assumption that only photon counts over finite time bins are available. Yet another approximation is based on the counts-over-finite-time-bins assumption with the additional assumption that the counts follow a Poisson distribution. For jitter with a standard deviation of 0.28 of a slot, computational-simulation tests have shown that receivers designed to compensate using the exact or approximate equations would exhibit error-rate reductions, relative to receiver designs based on neglect of photon-arrival jitter, equivalent to power increases of the order of 1 dB (see figure).

This work was done by Bruce Moision of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov.
NPO-45163

MACOS Version 3.31

NASA's Jet Propulsion Laboratory, Pasadena, California

Version 3.31 of Modeling and Analysis for Controlled Optical Systems (MACOS) has been released. MACOS is an easy-to-use computer program for modeling and analyzing the behaviors of a variety of optical systems, including systems that have large, segmented apertures and are aligned with the technology of wavefront sensing and control. Two previous versions were described in "Improved Software for Modeling Controlled Optical Systems" (NPO-19841) *NASA Tech Briefs*, Vol. 21, No. 12 (December 1997), page 42 and "Optics Program Modified for Multithreaded Parallel Computing" (NPO-40572) *NASA Tech Briefs*, Vol. 30, No. 1 (January 2006) page 13a. The present version incorporates the following enhancements over prior versions:

- A powerful system-optimization facility includes algorithms for linear, nonlinear, unconstrained, and constrained optimization of optical systems under a variety of settings.
- There is now enhanced capability to perturb optical components individually and on subsystem levels, and to optimize system performance by adjusting selected individual components as well as subsystems.
- Capabilities for modeling a variety of new optical aperture types have been added.
- Effects of multilayer thin-film coats on optical surfaces can now be taken into account when tracing polarized rays.
- Major software-engineering work was performed to make MACOS more reliable, flexible, and manageable for purposes of maintenance and further development.

This program was written by David Redding, John Lou, Scott Basinger and Norbert Sigrist of Caltech for NASA's Jet Propulsion Laboratory.

This software is available for commercial licensing. Please contact Karina Edmonds of the California Institute of Technology at (626) 395-2322. Refer to NPO-45030.

Fiber-Optic Determination of N_2, O_2, and Fuel Vapor in the Ullage of Liquid-Fuel Tanks

A fiber-optic sensor provides feedback control of onboard inert gas generation systems (OBIGGS) and reduces aircraft operational costs.

John H. Glenn Research Center, Cleveland, Ohio

A fiber-optic sensor system has been developed that can remotely measure the concentration of molecular oxygen (O_2), nitrogen (N_2), hydrocarbon vapor, and other gases (CO_2, CO, H_2O, chlorofluorocarbons, etc.) in the ullage of a liquid-fuel tank. The system provides an accurate and quantitative identification of the above gases with an accuracy of better than 1 percent by volume (for O_2 or N_2) in real-time (5 seconds). In an effort to prevent aircraft fuel tank fires or explosions similar to the tragic TWA Flight 800 explosion in 1996, OBIGGS are currently being developed for large commercial aircraft to prevent dangerous conditions from forming inside fuel tanks by providing an "inerting" gas blanket that is low in oxygen, thus preventing the ignition of the fuel/air mixture in the ullage.

OBIGGS have been used in military aircraft for many years and are now standard equipment on some newer large commercial aircraft (such as the Boeing 787). Currently, OBIGGS are being developed for retrofitting to existing commercial aircraft fleets in response to pending mandates from the FAA. Most OBIGGS use an air separation module (ASM) that separates O_2 from N_2 to make nitrogen-enriched air from compressed air flow diverted from the engine (bleed air). Current OBIGGS systems do not have a closed-loop feedback control, in part, due to the lack of suitable process sensors that can reliably measure N_2 or O_2 and at the same time, do not constitute an inherent source of ignition. Thus, current OBIGGS operate with a high factor-of-safety dictated by process protocol to ensure adequate fuel-tank inerting. This approach is inherently inefficient as it consumes more engine bleed air than is necessary compared to a closed-loop controlled approach. The reduction of bleed air usage is important as it reduces fuel consumption, which translates to both increased flight range and lower operational costs.

Numerous approaches to developing OBIGGS feedback-control sensors have been under development by many research groups and companies. However, the direct measurement of nitrogen (N_2) is a challenge to most OBIGGS ullage sensors (such as tunable diode laser absorption) as they cannot measure N_2 directly but de-