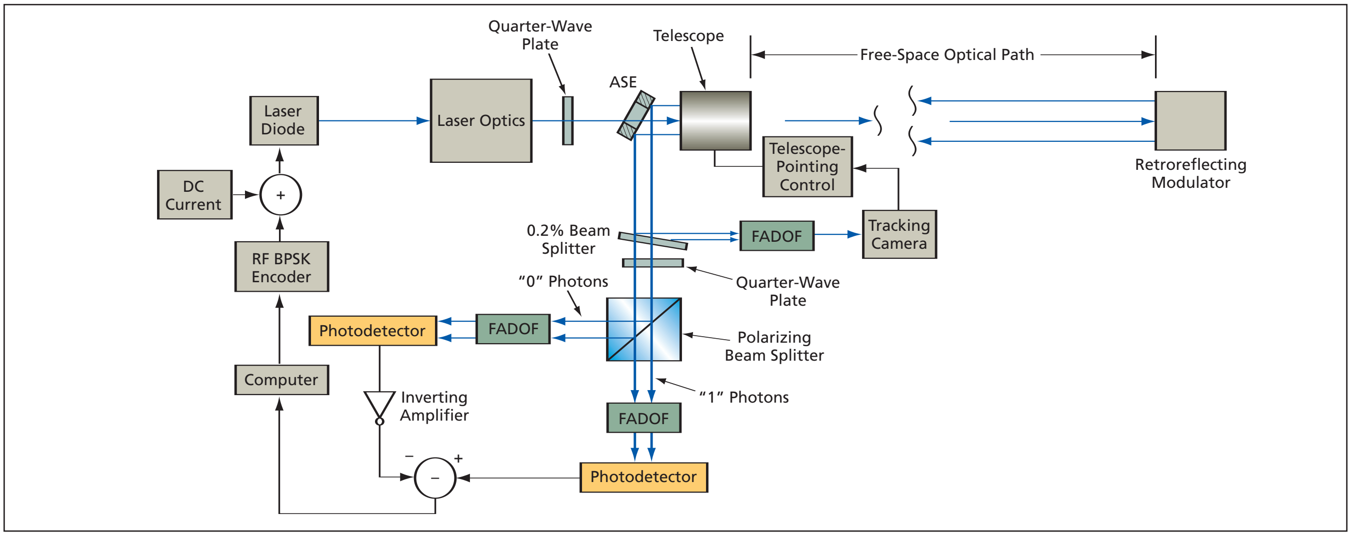

The **Laser at One End** of the free-space optical path would provide all of the beam power needed for transmission of data signals in both directions along the path.

lar polarization signifies the other binary level ("0" in this case). Hence, to transmit "0," the retroreflecting modulator would leave the right circular polarization of the retroreflected beam unchanged; to transmit "1," the retroreflecting modulator would flip the polarization of the reflected beam to left circular. Full-duplex operation would be possible because the CPK and the SC-PSK would be transparent to each other.

At the laser end, the reflected, CPK-modulated beam would return through the telescope and would then be reflected by the ASE into a receiver subsystem. A beam splitter would divert 0.2 percent of the beam power to a camera in the tracking system. The remainder of the beam would pass through the beam splitter to a quarter-wave plate, which would convert the circular polarization to two orthogonal linear polarizations. A polarizing beam splitter would then split the light in these two polarizations so that photons corresponding to "0" would go to one photodetector and photons corresponding to "1" would go to another photodetector.

It should be emphasized that this arrangement would yield a nonzero photodetector output of nominally the same magnitude for either "0" or "1." This is fundamentally different from on-off keying (OOK), in which "0" or "1" is represented by the absence or presence, respectively, of a signal. Taking advantage of this, prior to final digitization of the return signal at "0" or "1," the output of the "0" photodetector could be inverted, then subtracted from the output of the "1" photodetector to obtain twice the signal-to-noise ratio achievable in OOK.

The receiver subsystem would include Faraday-anomalous-dispersion optical filters (FADOFs), which would reject background light to such a high degree that the system could operate over a long path during daytime. The FADOFs would essentially prevent skylight from reaching the photodetectors while allowing about 80 percent of the signal photons to pass through. Without the FADOFs, it would be necessary to increase the laser power by a factor of 10 for daytime operation.

This work was done by D. A. Hazzard, J. A. MacCannell, G. Lee, E. R. Selves, D. Moore, J. A. Payne, C. D. Garrett, N. Dahlstrom, and T. M. Shay of New Mexico State University for **Goddard Space Flight Center**. *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:

New Mexico State University Las Cruces
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Las Cruces, NM 88003

Refer to GSC-14759-1, volume and number of this NASA Tech Briefs *issue, and the page number.*

Stabilizing Microwave Frequency of a Photonic Oscillator

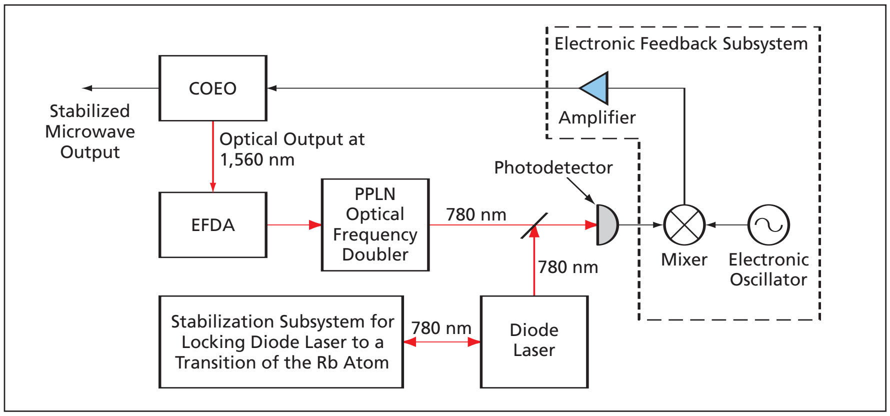
Microwave frequency is stabilized by stabilizing optical frequency to an atomic transition.

NASA's Jet Propulsion Laboratory, Pasadena, California

A scheme for stabilizing the frequency of a microwave signal is proposed that exploits the operational characteristics of a coupled optoelectronic oscillator (COEO) and related optoelectronic equipment. An essential element in the scheme is a fiber mode-locked laser (MLL), the optical frequency of which is locked to an atomic transition. In this scheme, the optical frequency stability of the mode-locked laser is transferred to that of the microwave in the same device. Relative to prior schemes for using wideband optical frequency comb to stabilize microwave signals, this scheme is simpler and lends itself more readily to implementation in relatively compact, rugged equipment. The anticipated development of small, low-power, lightweight, highly stable microwave oscillators based on this scheme would afford great benefits in communication, navigation, metrology, and fundamental sciences.

COEOs of various designs, at various stages of development, in some cases called by different names, have been described in a number of prior *NASA Tech Briefs* articles. A COEO is an optoelectronic apparatus that generates both short (picosecond) optical pulses and a steady microwave signal having an ultra-high degree of spectral purity. The term "coupled optoelectronic" in the full name of such an apparatus signifies that its optical and electronic oscillations are coupled to each other in a single device.

The present frequency-stabilization scheme is best described indirectly by describing the laboratory apparatus used to demonstrate it. The apparatus (see figure) includes a COEO that generates a comblike optical spectrum, the various frequency components of which interfere, producing short optical pulses. This spectrum is centered at a nominal wavelength of 1,560 nm. The spectrum separation of this comb is about 10 GHz, as determined primarily by the length of an optical loop and the bandpass filter in the microwave feedback loop. The optical loop serves as microwave resonator having a very high value of the resonance quality factor (*Q*). The optical frequency of MLL is then stabilized by locking it to an atomic transition as described below.



The **COEO Generates a Comblike Optical Spectrum** that is used to generate a microwave signal. The frequency stability of a diode laser signal locked to the frequency of an atomic transition is transferred to the microwave signal.

The COEO contains a tunable 1-nm band-pass optical filter and a piezoelectric-transducer (PZT) drum over which a stretch of fiber is wound. The 1-nm-wide pass band of the filter provides coarse tuning to overlap the frequency comb with the atomic transition frequency. Controlled stretching of the fiber by means of the PZT drum can be used in conjunction with temperature control for locking the laser frequency. To reference to an atomic resonance at 780 nm in this demonstration setup, the optical output of the COEO at 1,560 nm is fed through an erbium-doped-fiber amplifier (EDFA) to a frequency doubler in the form of a periodically poled lithium niobate (PPLN) crystal. The frequency-doubled output is combined with the output of a separate frequency-stabilized diode laser at a photodetector. As described thus far, the two 780-nm laser subsystems are nominally independent of each other and can, therefore, operate at different frequencies. Hence, at the photodetector, the two laser beams interfere, so that the output of the photodetector includes a beat note (a component at the difference between the two laser frequencies).

The beat note is used to stabilize the relative frequency between the two optical signals through a simple electronic feedback subsystem that adjusts the voltage applied to the PZT to lock the optical frequency of the COEO to that of the diode laser. The diode laser is frequency stabilized to the atomic absorption of Rb vapor through frequency modulation (FM) saturation spectroscopy. The fractional frequency stability of it has been shown to be 10^{-12} at 1 second. After further optimization of design to minimize destabilizing effects, it may be possible to attain a long-term stability at 10^{-13}. Such optical frequency stability can be transferred to the microwave in the COEO device where the optical and microwave oscillators are coupled, and hence producing a highly stable microwave signal.

This work was done by Lute Maleki, Nan Yu, and Meirong Tu of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP (see page 1).*
NPO-43026

Microwave Oscillators Based on Nonlinear WGM Resonators

Optical signals are phase-modulated with spectrally pure microwave signals.

NASA's Jet Propulsion Laboratory, Pasadena, California

Optical oscillators that exploit resonantly enhanced four-wave mixing in nonlinear whispering-gallery-mode (WGM) resonators are under investigation for potential utility as low-power, ultra-miniature sources of stable, spectrally pure microwave signals. There are numerous potential uses for such oscillators in radar systems, communication systems, and scientific instrumentation.

The resonator in an oscillator of this type is made of a crystalline material that exhibits cubic Kerr nonlinearity, which supports the four-photon parametric process also known as four-wave mixing. The oscillator can be characterized as all-optical in the sense that the entire process of generation of the microwave signal takes place within the WGM resonator. The resonantly enhanced four-wave mixing yields coherent, phase-modulated optical signals at frequencies governed by the resonator structure. The frequency of the phase-modulation signal, which is in the microwave range, equals the difference between the frequencies of the optical signals; hence, this frequency is also governed by the resonator structure. Hence, further, the microwave signal is stable and can be used as a reference signal.

The figure schematically depicts the apparatus used in a proof-of-principle experiment. Linearly polarized pump light was generated by an yttrium aluminum garnet laser at a wavelength of 1.32 µm. By use of a 90:10 fiber-optic splitter and optical fibers, some of the laser light was sent into a delay line and some was transmitted to one face of glass coupling prism, that, in turn, coupled the laser light into a crystalline CaF$_2$ WGM disk resonator that had a resonance quality factor (Q) of 6×10^9. The output light of the resonator was collected via another face of the coupling prism and a single-mode optical fiber, which transmitted the light to a 50:50 fiber-optic splitter. One output of this splitter was sent to a slow photodiode to obtain a DC signal for locking the laser to a particular resonator mode. The other output of this splitter was combined with the delayed laser signal in another 50:50 fiber-optic splitter used as a combiner. The output