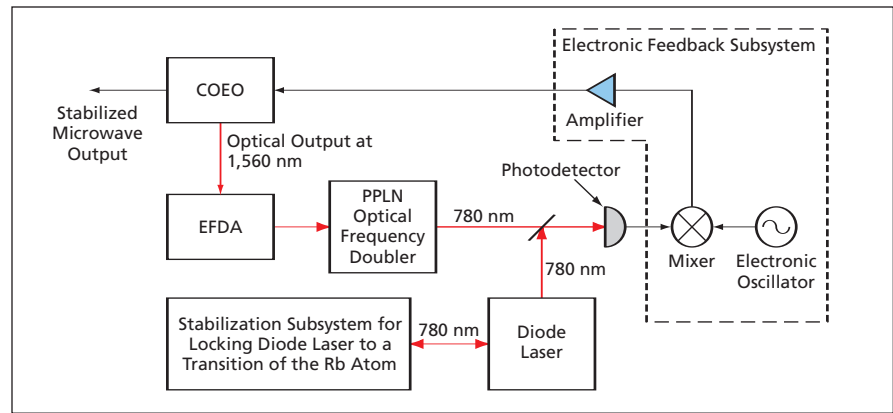


its optical and electronic oscillations are coupled to each other in a single device.

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 comb-like 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 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



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.

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 stabi-

lized 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

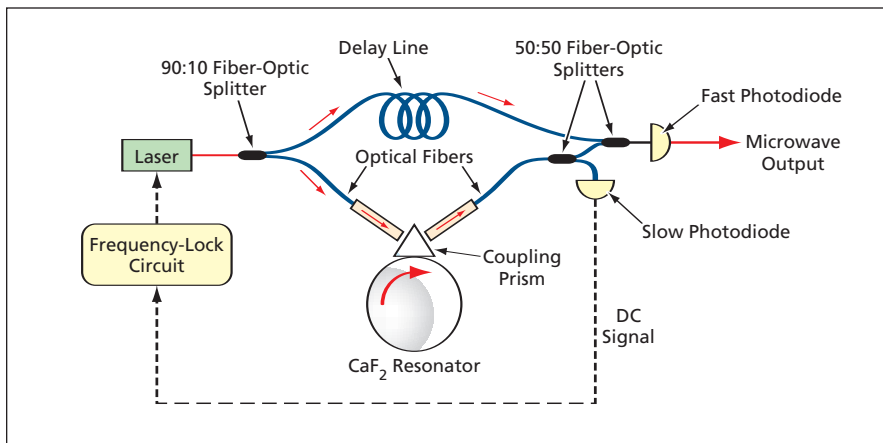
Optical oscillators that exploit resonantly enhanced four-wave mixing in nonlinear whispering-gallery-mode (WGM) resonators are under investigation for potential utility as low-power, ultra-miniature sources of stable, spectrally pure microwave signals. There are numerous potential uses for such oscillators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



This **Laboratory Setup** was used to demonstrate the basic principle of generating a microwave signal in a low-threshold hyperparametric process.

of the combiner was fed to a fast photodiode that demodulated light and generated microwave signal.

In this optical configuration, the resonator was incorporated into one arm of a Mach-Zehnder interferometer, which was necessary for the following reasons: It was found that when the output of the resonator was sent directly to a fast photodiode, the output of the photodiode

did not include a measurable microwave signal. However, when the resonator was placed in an arm of the interferometer and the delay in the other arm was set at the correct value, the microwave signal appeared. Such behavior is distinctly characteristic of phase-modulated light.

The phase-modulation signal had a frequency of about 8 GHz, corresponding to the free spectral range of the resonator.

The spectral width of this microwave signal was less than 200 Hz. The threshold pump power for generating the microwave signal was about 1 mW. It would be possible to reduce the threshold power by several orders of magnitude if resonators could be made from crystalline materials in dimensions comparable to those of microresonators heretofore made from fused silica.

This work was done by Lute Maleki, Andrey Matsko, Anatoliy Savchenkov, and Dmitry Strelakov 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-41074, volume and number of this NASA Tech Briefs issue, and the page number.

Pointing Reference Scheme for Free-Space Optical Communications Systems

A technique is proposed for referencing infrared transmit lasers with silicon detectors.

NASA's Jet Propulsion Laboratory, Pasadena, California

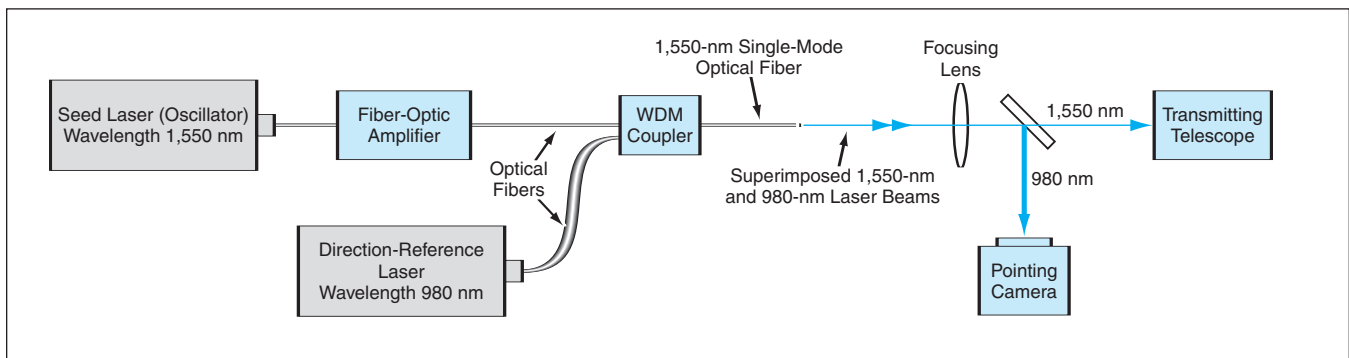
A scheme is proposed for referencing the propagation direction of the transmit laser signal in pointing a free-space optical communications terminal. This recently developed scheme enables the use of low-cost, commercial silicon-based sensors for tracking the direction of the transmit laser, regardless of the transmit wavelength. Compared with previous methods, the scheme offers some advantages of less mechanical and optical complexity and avoids

expensive and exotic sensor technologies.

In free-space optical communications, the transmit beam must be accurately pointed toward the receiver in order to maintain the communication link. The current approaches to achieve this function call for part of the transmit beam to be split off and projected onto an optical sensor used to infer the pointed direction. This requires that the optical sensor be sensitive to the wavelength of the transmit

laser. If a different transmit wavelength is desired, for example to obtain a source capable of higher data rates, this can become quite impractical because of the unavailability or inefficiency of sensors at these wavelengths. The innovation proposed here decouples this requirement by allowing any transmit wavelength to be used with any sensor.

We have applied this idea to a particular system that transmits at the standard



An **Example Implementation** is shown of the much simpler pointing reference scheme.