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 $6 \times 10^9$. 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...
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, Andrei Matsko, Anatoliy Savchenkov, and Dmitry Strekalov of Caltech for NASA’s Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).

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