conservation law and the phase-matching condition are satisfied. The photon-energy-conservation law can be stated simply as $\omega_p = \omega_s + \omega_i$, where ω is proportional to the frequency or energy of the photon denoted by its subscript and p, s, and i denote the pump, signal, and idler frequencies, respectively. The phase-matching condition is satisfied if the volume integral of the product of the complex amplitudes of the pump, signal, and idler electromagnetic fields differs from zero.

In the general case, phase matching of an optical field with a microwave field cannot be achieved in a WGM resonator because the indices of refraction of the bulk resonator material are different in the optical and microwave frequency ranges. However, the theory also shows that it is possible to tailor the spatial structures of the WGM modes, so as to obtain phase matching of fields at resonance frequencies that satisfy the photon-energy-conservation law, through appropriate tailoring of the size and shape of the WGM resonator. This is equivalent to matching of effective indices of refraction for the pump, signal, and idler fields.

Evidence that phase matching can be achieved through suitable choice of size and shape was obtained in experiments on an apparatus depicted schematically in the figure. In each experiment, laser light centered at a wavelength of ≈1,319 nm or ≈1,559 nm was sent through a polarization controller, a grating-index-of-refraction (GRIN) lens, and a diamond prism into a lithium niobate WGM resonator, and light was coupled out of the WGM resonator through the diamond prism, another GRIN lens, and optical fibers to a photodiode and an optical spectral analyzer. In one experiment, the spectrum of light coming out of the WGM resonator was found to include sidebands associated with strongly nondegenerate parametric oscillations that had been predicted theoretically. In other experiments, oscillations with, variously, confined or unconfined idler fields were observed.

This work was done by Anatoliy Savchenkov, Dmitry Strekalov, Nan Yu, Andrey Matsko, Makan Mohageg, and Lute Maleki of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). *NPO-45120*

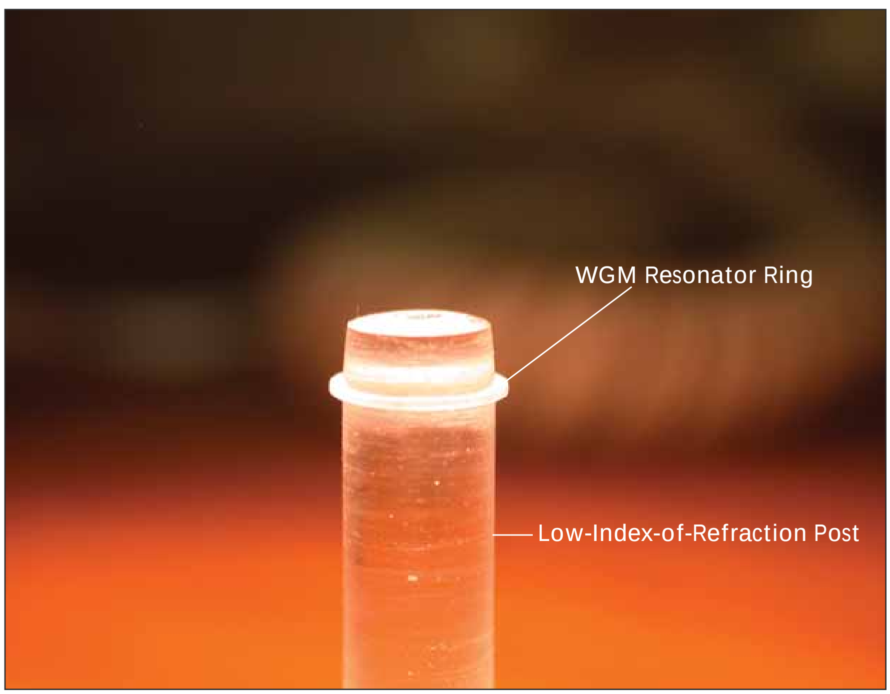
WGM Resonators for Terahertz-to-Optical Frequency Conversion

Receivers containing these devices are contemplated for astronomical and military uses.

NASA's Jet Propulsion Laboratory, Pasadena, California

Progress has been made toward solving some practical problems in the implementation of terahertz-to-optical frequency converters utilizing whispering-gallery-mode (WGM) resonators. Such frequency converters are expected to be essential parts of non-cryogenic terahertz-radiation receivers that are, variously, under development or contemplated for a variety of applications in airborne and spaceborne instrumentation for astronomical and military uses.

In most respects, the basic principles of terahertz-to-optical frequency conversion in WGM resonators are the same as those of microwave (sub-terahertz)-to-optical frequency conversion in WGM resonators, various aspects of which were discussed in the three preceeding articles. To recapitulate: In a receiver following this approach, a preamplified incoming microwave signal (in the present case, a terahertz signal) is up-converted to an optical signal by a technique that exploits the nonlinearity of the electromagnetic response of a whispering-gallery-mode (WGM) resonator made of $LiNbO_3$ or another suitable electro-optical material. Upconversion takes place by three-wave mixing in the resonator. To ensure the required interaction among the optical and terahertz signals, the WGM resonator must be designed and fabricated to function as an electro-optical modulator while simultaneously exhibiting (1) resonance at the required microwave and optical operating frequencies and (2) phase matching among the microwave and optical signals circulating in the resonator. Downstream of the WGM resonator, the up-converted signal is processed photonically by use of a tunable optical filter or local oscillator and is then detected.



A **WGM Resonator Ring** is mounted on a post made of a material having an index of refraction significantly lower than that of the ring to provide mechanical support without sacrificing confinement of the WGM modes in the ring.

The practical problems addressed in the present development effort are the following:

- Satisfaction of the optical and terahertz resonance-frequency requirement is a straightforward matter, inasmuch as the optical and terahertz spectra can be measured. However, satisfaction of the phase-matching requirement is more difficult. The approach followed in the present development is to perform computer simulations of the microwave and optical signals circulating in the resonator to test for phase matching.
- To enable excitation of the terahertz WGM resonator mode, it is also necessary to ensure phase matching between that mode and the incoming terahertz radiation. In the present development, the incoming signal is coupled into the WGM resonator via a tapered waveguide in the form of a fused silica rod. The phase-matching requirement is satisfied at one point along the taper; the rod is positioned with this point in proximity to the WGM resonator.
- To maximize the conversion efficiency, it is necessary to maximize the spatial overlap among the terahertz and optical modes in the WGM resonator. In the absence of a special design effort to address this issue, there would be little such overlap because, as a consequence of a large difference between wavelengths, the optical and terahertz modes would be concentrated at different depths from the rim of a WGM resonator. In the present development, overlap is ensured by constructing the WGM resonator as a ring (see figure) so thin that the optical and terahertz modes are effectively forced to overlap.

This work was done by Dmitry Strekalov, Anatoliy Savchenkov, Andrey Matsko, and Nan Yu of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).
NPO-45508

Determining Concentration of Nanoparticles From Ellipsometry

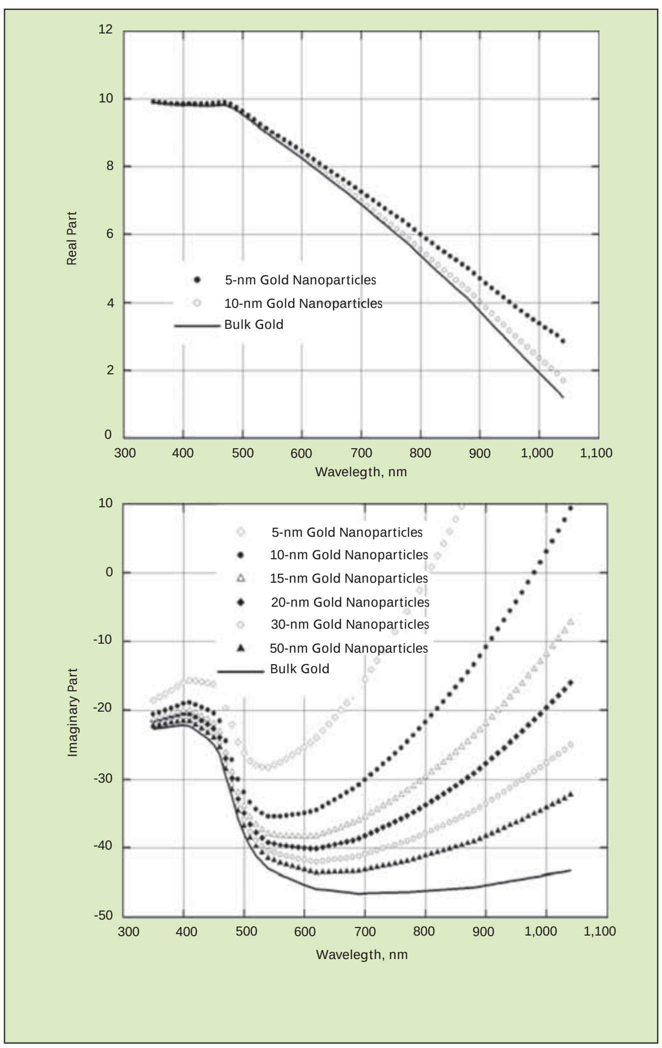
Counting of particles is not necessary.

Marshall Space Flight Center, Alabama

A method of using ellipsometry or polarization analysis of light in total internal reflection of a surface to determine the number density of gold nanoparticles on a smooth substrate has been developed. The method can be modified to enable determination of densities of sparse distributions of nanoparticles in general, and is expected to be especially useful for measuring gold-nanoparticle-labeled biomolecules on microarrays.

The method is based on theoretical calculations of the ellipsometric responses of gold nanoparticles. Elements of the calculations include the following:

- For simplicity, the gold nanoparticles are assumed to be spherical and to have the same radius.
- The distribution of gold nanoparticles is assumed to be a sub-monolayer (that is, sparser than a monolayer).
- The optical response of the sub-monolayer is modeled by use of a thin-island-film theory, according to which the polarizabilities parallel and perpendicular to the substrate are functions of the wavelength of light, the dielectric functions (permittivities expressed as complex functions of frequency or wavelength) of the gold and the suspending medium (in this case, the suspending medium is air), the fraction of the substrate area covered by the nanoparticles, and the radius of the nanoparticles.
- For the purpose of the thin-island-film theory, the dielectric function of the gold nanoparticles is modeled as the known dielectric function of bulk gold plus a correction term that is necessitated by the fact that the mean free path length for electrons in gold decreases with decreasing radius, in such a manner as to cause the imaginary part of the dielectric function to increase with decreasing radius (see figure). The correction term is a function of the nanoparticle radius, the wavelength of light, the mean free path and the Fermi speed of electrons in bulk gold, the plasma frequency of gold, and the speed of light in a vacuum.



Real and Imaginary Parts of complex dielectric functions were determined for bulk gold and for gold nanoparticles having various diameters.

These models are used to calculate ellipsometric responses for various concentrations of gold nanoparticles having an assumed