Gold Nanoparticle Labels Amplify Ellipsometric Signals

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The ellipsometric method reported in the immediately preceding article was developed in conjunction with a method of using gold nanoparticles as labels on biomolecules that one seeks to detect. The purpose of the labeling is to exploit the optical properties of the gold nanoparticles in order to amplify the measurable ellipsometric effects and thereby to enable ultrasensitive detection of the labeled biomolecules without need to develop more-complex ellipsometric instrumentation.

The colorimetric, polarization, light-scattering, and other optical properties of nanoparticles depend on their sizes and shapes. In the present method, these size-and-shape-dependent properties are used to magnify the polarization of scattered light and the diattenuation and retardance of signals derived from ellipsometry. The size-and-shape-dependent optical properties of the nanoparticles make it possible to interrogate the nanoparticles by use of light of various wavelengths, as appropriate, to optimally detect particles of a specific type at high sensitivity.

Hence, by incorporating gold nanoparticles bound to biomolecules as primary or secondary labels, the performance of ellipsometry as a means of detecting the biomolecules can be improved. The use of gold nanoparticles as labels in ellipsometry has been found to afford sensitivity that equals or exceeds the sensitivity achieved by use of fluorescence-based methods. Potential applications for ellipsometric detection of gold-nanoparticle-labeled biomolecules include monitoring molecules of interest in biological samples, *in-vitro* diagnostics, process monitoring, general environmental monitoring, and detection of biohazards.

This work was done by Srivatsa Venkatasubbarao of Intelligent Optical Systems, Inc. for Marshall Space Flight Center. For further information, contact Sammy Nabors, MSFC Commercialization Assistance Lead, at sammy.a.nabors@nasa.gov. Refer to MFS-32507-1.

Phase Matching of Diverse Modes in a WGM Resonator

Phase matching is necessary for exploitation of nonlinear optical phenomena.

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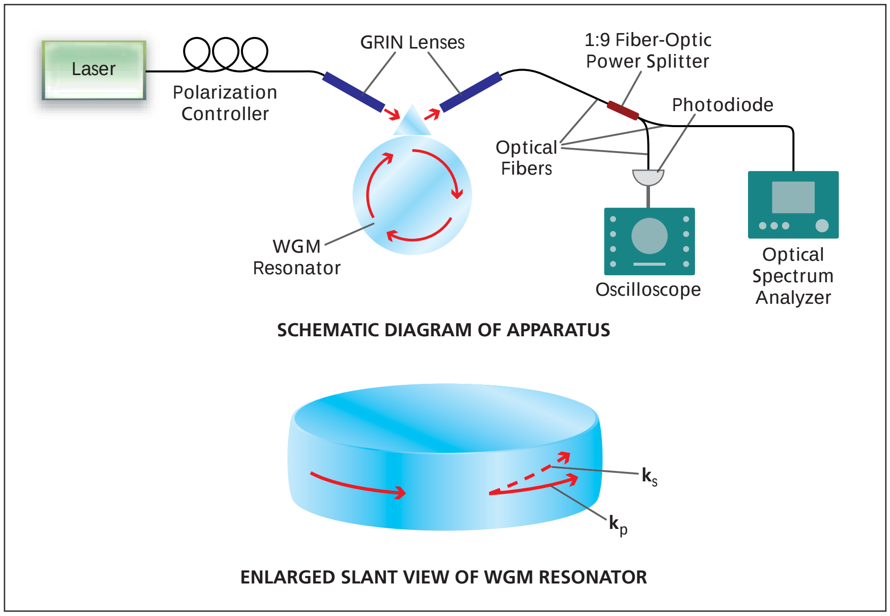
Phase matching of diverse electromagnetic modes (specifically, coexisting optical and microwave modes) in a whispering-gallery-mode (WGM) resonator has been predicted theoretically and verified experimentally. Such phase matching is necessary for storage of microwave/terahertz and optical electromagnetic energy in the same resonator, as needed for exploitation of nonlinear optical phenomena.

WGM resonators are used in research on nonlinear optical phenomena at low optical intensities and as a basis for design and fabrication of novel optical devices. Examples of nonlinear optical phenomena recently demonstrated in WGM resonators include low-threshold Raman lasing, optomechanical oscillations, frequency doubling, and hyperparametric oscillations.



SCHEMATIC DIAGRAM OF APPARATUS

ENLARGED SLANT VIEW OF WGM RESONATOR

Nonlinear Optical Phenomena are excited in a WGM resonator disk and the output spectrum is measured to obtain evidence of those phenomena. In the phenomenon of particular interest here, an optical pump photon of wave vector $\mathbf{k}_p$ is scattered into an optical signal photon of wave vector $\mathbf{k}_s$ and a microwave idler photon of wave vector $\mathbf{k}_i$. The idler photon is not necessarily confined within WGM resonator if its wavelength exceeds the thickness of the resonator disk.

The present findings regarding phase matching were made in research on low-threshold, strongly nondegenerate parametric oscillations in lithium niobate WGM resonators. The principle of operation of such an oscillator is rooted in two previously observed phenomena: (1) stimulated Raman scattering by polaritons in lithium niobate and (2) phase matching of nonlinear optical processes via geometrical confinement of light. The oscillator is partly similar to terahertz oscillators based on lithium niobate crystals, the key difference being that a novel geometrical configuration of this oscillator supports oscillation in the continuous-wave regime. The high resonance quality factors (*Q* values) typical of WGM resonators make it possible to achieve oscillation at a threshold signal level much lower than that in a non-WGM-resonator lithium niobate crystal.

The applicable theory states that the parametric interaction takes place in a WGM resonator if the photon-energy-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.

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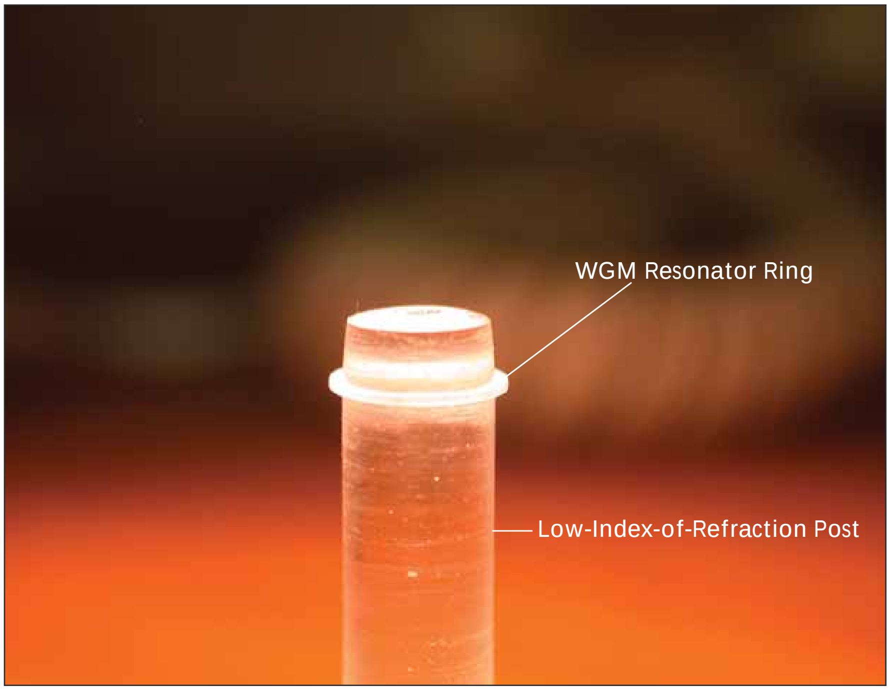
Progress has been made toward solving some practical problems in the implementation of terahertz-to-optical frequency converters utilizing whispering-gallery-mode (WGM) resonators. Such frequency converters are expected to be essential parts of non-cryogenic terahertz-radiation receivers that are, variously, 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: