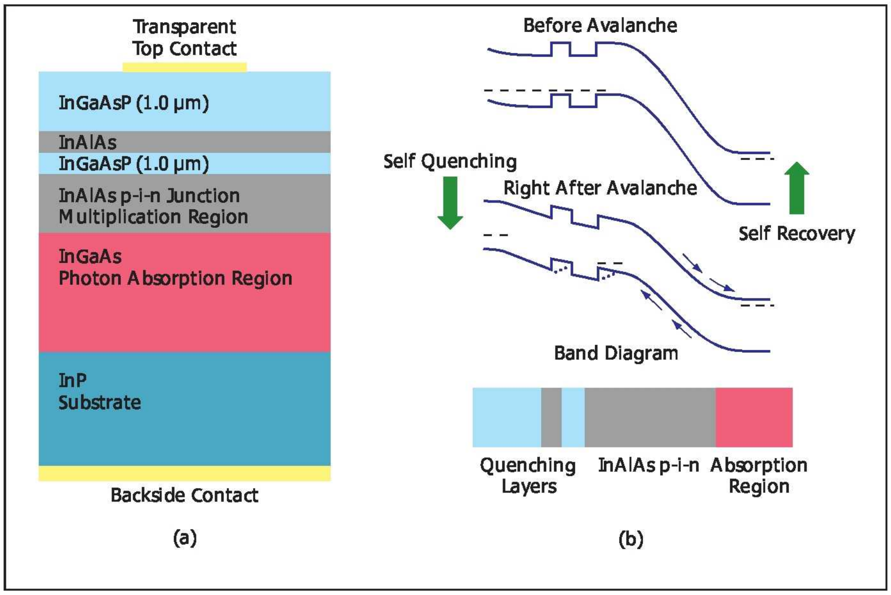


The schematic diagram of the **InGaAs-InAsAs SPAD Layer Structure** (a) and (b) the **Concept of Operation** for the structure showing the self-quenching and self-recovery processes.

the cathode. Holes created by the avalanche process gain large kinetic energy through the electric field, and are considered "hot". These hot holes are cooled as they travel across a p-InAlAs low field region, and are eventually blocked by energy barriers formed by the InGaAsP/InAlAs heterojunctions.

The composition of the InGaAsP alloy was chosen to have an 80 meV valance band offset with InAlAs, which is high enough to hinder the transport of the already cooled holes. Being stopped by the energy barrier, holes are accumulated at the junctions to shield the electric field, resulting in a decrease of the electric field in the multiplication region. Because the impact ionization rate is extremely sensitive to the magnitude of the electric field, the field-screening effect drastically reduces the impact ionization rate and quenches the output signals.

After the avalanche pulse signal is self-quenched, the accumulated holes at the InGaAsP/InAlAs interface escape the energy barrier through thermal excitation and tunneling and finally leave the device. The device is thus reset and ready for subsequent photon detection. This recovery time is controlled by the height of the energy barrier and the hole-cooling rate.

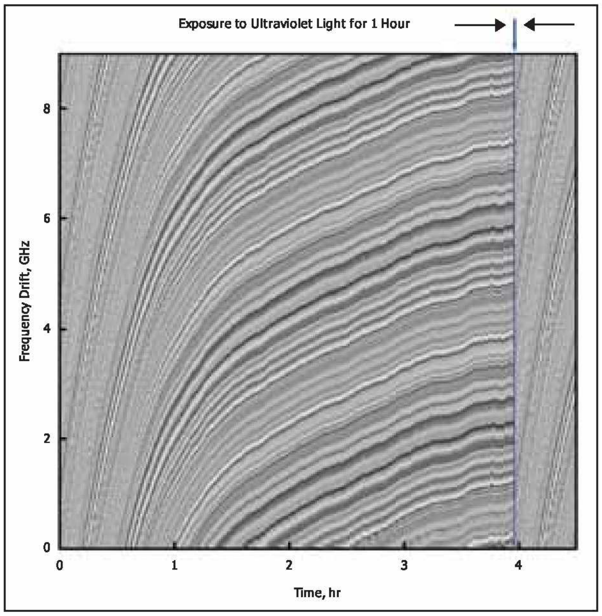
*This work was done by Kai Zhao and Yu-Hwa Lo of the University of California San Diego and William Farr of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).* NPO-45801

# Using Whispering-Gallery-Mode Resonators for Refractometry

## Refractive and absorptive properties are inferred by correlating predictions with measurements.

*NASA's Jet Propulsion Laboratory, Pasadena, California*

A method of determining the refractive and absorptive properties of optically transparent materials involves a combination of theoretical and experimental analysis of electromagnetic responses of whispering-gallery-mode (WGM) resonator disks made of those materials. The method was conceived especially for use in studying transparent photorefractive materials, for which purpose this method affords unprecedented levels of sensitivity and accuracy. The method is expected to be particularly useful for measuring temporally varying refractive and absorptive properties of photorefractive materials at infrared wavelengths. Still more particularly, the method is expected to be useful for measuring drifts in these properties that are so slow that, heretofore, the properties were assumed to be constant.



This **Time-vs.-Frequency Plot** shows a saturating drift of the spectrum of a WGM resonator made of a photorefractive material exposed to light. The discontinuity just before the 4-hour mark represents a 1-hour exposure to ultraviolet light, after which the drift of the spectrum recommenced.

The basic idea of the method is to attempt to infer values of the photorefractive properties of a material by seeking to match (1) theoretical predictions of the spectral responses (or selected features thereof) of a WGM of known dimensions made of the material with (2) the actual spectral responses (or selected features thereof). Spectral features that are useful for this purpose include resonance frequencies, free spectral ranges (differences between resonance frequencies of adjacently numbered modes), and resonance quality factors ($Q$ values).

The method has been demonstrated in several experiments, one of which was performed on a WGM resonator made from a disk of $LiNbO_3$ doped with 5 percent of MgO. The free spectral range of the resonator was ≈3.42

GHz at wavelengths in the vicinity of 780 nm, the smallest full width at half maximum of a mode was ≈50 MHz, and the thickness of the resonator in the area of mode localization was 30 μm. In the experiment, laser power of 9 mW was coupled into the resonator with an efficiency of 75 percent, and the laser was scanned over a frequency band 9 GHz wide at a nominal wavelength of ≈780 nm. Resonance frequencies were measured as functions of time during several hours' exposure to the laser light. The results of these measurements, plotted in the figure, show a pronounced collective frequency drift of the resonator modes. The size of the drift has been estimated to correspond to a change of $8.5 \times 10^{-5}$ in the effective ordinary index of refraction of the resonator material.

*This work was done by Andrey Matsko, Anatoliy Savchenkov, Dmitry Strekalov, Vladimir Iltchenko, and Lute Maleki of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov. NPO-42694*