The anode of an NiF$_2$/NaF:CaF$_2$/Ca cell consists of a solid Ca metal layer formed by pressing dendritic Ca into a disk shape and roughening the surface to enhance contact with the cathode/electrolyte/graphite. The conversion of the active anode material (Ca) to the main ingredient (CaF$_2$) of the electrolyte material during discharge is fortuitous in that the accumulation of this material facilitates further discharge, unlike in most other electrochemical power cells, wherein accumulation of discharge products hinders further discharge. Ideally, the anode would be fabricated as a Ca alloy containing approximately 5 mole percent of Na to form the desired NaF dopant for the CaF$_2$ electrolyte as the cell discharges. At 450 °C, this alloy would remain a solid solution.

Several NiF$_2$/NaF:CaF$_2$/Ca cells have been fabricated and tested. The figure presents results from one such test. For testing purposes, these cells have been treated as primary (non-rechargeable) cells, but it is possible that these cells are rechargeable. If further tests confirm that they are rechargeable, then some of the cost and risk associated with manufacture and use of high-temperature batteries could be reduced: Before being installed for use, batteries could be heated to operating temperatures; charged and discharged several times to verify that their voltages, capacities, and discharge-rate capabilities are as expected; then recharged; and finally cooled. In contrast, the voltages, capacities, and discharge-rate capabilities of non-rechargeable batteries cannot be verified prior to final use.

This work was done by William West, Jay Whitacre, and Linda Del Castillo of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-44643

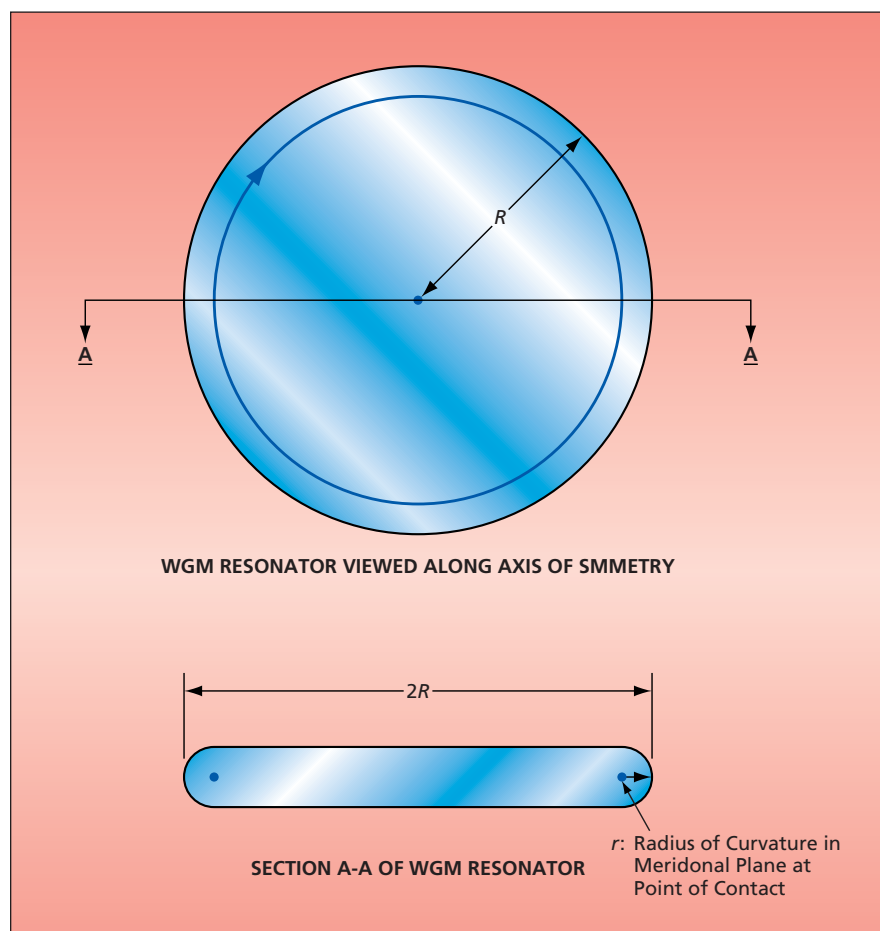# Critical Coupling Between Optical Fibers and WGM Resonators

Recipes address issues of phase matching, aperture matching, and suppressing intermodal coupling.

NASA's Jet Propulsion Laboratory, Pasadena, California

Two recipes for ensuring critical coupling between a single-mode optical fiber and a whispering-gallery-mode (WGM) optical resonator have been devised. The recipes provide for phase matching and aperture matching, both of which are necessary for efficient coupling. There is also a provision for suppressing intermodal coupling, which is detrimental because it drains energy from desired modes into undesired ones.

According to one recipe, the tip of the single-mode optical fiber is either tapered in diameter or tapered in effective diameter by virtue of being cleaved at an oblique angle. The effective index of refraction and the phase velocity at a given position along the taper depend on the diameter (or effective diameter) and the index of refraction of the bulk fiber material. As the diameter (or effective diameter) decreases with decreasing distance from the tip, the effective index of refraction also decreases. Critical coupling and phase matching can be achieved by placing the optical fiber and the resonator in contact at the proper point along the taper. This recipe is subject to the limitation that the attainable effective index of refraction lies between the indices of refraction of the bulk fiber material and the atmosphere or vacuum to which the resonator and fiber are exposed.

The other recipe involves a refinement of the previously developed technique of prism coupling, in which the light beam from the optical fiber is collimated and focused onto one surface of a prism that has an index of refraction greater than that of the resonator. Another surface of the prism is placed in contact with the resonator. The various components are arranged so that the collimated beam is focused at the prism/resonator contact spot. The recipe includes the following additional provisions:

WGM RESONATOR VIEWED ALONG AXIS OF SMMETRY

2*R*

R

SECTION A-A OF WGM RESONATOR

r: Radius of Curvature in Meridonal Plane at Point of Contact

A **Typical Whispering-Gallery-Mode Resonator** is characterized by, among other parameters, radii of curvature *r* and *R* that appear in the equations that describe the conditions for critical coupling.

- In fabricating the resonator, one strives to obtain

$$r = R[1-(n_d/n_p)^2],$$

where r is the vertical radius of curvature at the contact spot as defined in the figure; R is the horizontal radius of curvature, also as defined in the figure; n_d is the effective index of refraction of the desired mode in the resonator; and n_p is the index of refraction of the prism.
- The reason for this choice of r and R is that it ensures aperture matching with a Gaussian beam cross section at the contact spot.
- The numerical aperture (NA) of the collimated beam must be chosen to have the following value:

$$NA = \sin(\lambda/h),$$

where λ is the vacuum wavelength of the light that one seeks to couple into and out of the resonator, and h is a magnitude of the evanescent electromagnetic field of the resonator, given by

$$h \approx \lambda/[2\pi(n_d^2-n_p^2)^{1/2}].$$

- In practice, the fabrication process does not yield precisely the desired radius r: instead, it yields a slightly different value, r'. Therefore, after fabrication, in order to ensure phase matching, one must select a new desired mode for which the effective index of refraction is given by

$$n_d = n_p(1-r'/R)^{1/2}.$$

- Intermodal coupling is suppressed by use of what, at the time of writing this article, was reported to be a "single mode technique" but not otherwise described. The technique was reported to be described in "Morphology-dependent photonic circuit elements," *Optics Letters* Vol. 31, Issue 9, page 1313.

Microwave Temperature Profiler Mounted in a Standard Airborne Research Canister

NASA's Jet Propulsion Laboratory, Pasadena, California

Many atmospheric research aircraft use a standard canister design to mount instruments, as this significantly facilitates their electrical and mechanical integration and thereby reduces cost. Based on more than 30 years of airborne science experience with the Microwave Temperature Profiler (MTP), the MTP has been repackaged with state-of-the-art electronics and other design improvements to fly in one of these standard canisters.

All of the controlling electronics are integrated on a single 4×5-in. (≈10×13-cm) multi-layer PCB (printed circuit board) with surface-mount hardware. Improved circuit design, including a self-calibrating RTD (resistive temperature detector) multiplexer, was implemented in order to reduce the size and mass of the electronics while providing increased capability. A new microcontroller-based temperature controller board was designed, providing better control with fewer components. Five such boards are used to provide local control of the temperature in various areas of the instrument, improving radiometric performance. The new stepper motor has an embedded controller eliminating the need for a separate controller board.

The reference target is heated to avoid possible emissivity (and hence calibration) changes due to moisture contamination in humid environments, as well as avoiding issues with ambient targets during ascent and descent. The radiometer is a double-side-band heterodyne receiver tuned sequentially to individual oxygen emission lines near 60 GHz, with the line selection and intermediate frequency bandwidths chosen to accommodate the altitude range of the aircraft and mission.

Alternative Determination of Density of the Titan Atmosphere

NASA's Jet Propulsion Laboratory, Pasadena, California

An alternative has been developed to direct measurement for determining the density of the atmosphere of the Saturn moon Titan as a function of altitude. The basic idea is to deduce the density versus altitude from telemetric data indicative of the effects of aerodynamic torques on the attitude of the Cassini Saturn orbiter spacecraft as it flies past Titan at various altitudes. The Cassini onboard attitude-control software includes a component that can estimate three external per-axis torques exerted on the spacecraft. These estimates are available via telemetry.

The atmospheric torque vector is the product of (1) a drag coefficient (which is known from ground-based experiment and analysis), (2) the Titan atmospheric density that one seeks to determine, (3) the square of the Titan-relative spacecraft speed (which is known from navigation monitoring), and (4) the projected area of the spacecraft and the offset distance between the center of pressure and center of mass, both of which are known functions of the attitude of the spacecraft relative to the known velocity through the atmosphere. Hence, the atmospheric density is the only unknown and can be determined from the other quantities, which are known.