New refractometer system gives high-accuracy, cryogenic, refractive-index measurements

Douglas B. Leviton and Bradley J. Frey

Proper lens design relies on having an accurate knowledge of the optical glass-specific refractive index, a measure of bending power of the glass for each wavelength of light. Refractive index varies with temperature, so it is important to know the refractive index at the temperature at which the lens is to be used. This is particularly important for lenses in infrared (IR) instrumentation at cryogenic temperatures, which are far below room temperature. A specially-designed refractometer system measures refractive index to one to two orders of magnitude better accuracy than before. This new system has been used for many infrared lens materials down to temperatures as low as 15K.

Historically, few, if any, accurate measurements of refractive index have been made at cryogenic temperatures, even for popular IR lens materials. As a result, lenses for scientific instruments have often been designed using what amounts to guesswork for the refractive index. This has meant that much time and money has been wasted aligning the as-built lenses in repetitive, time-consuming cryogenic cycles, hoping to meet imaging performance requirements. In the end, performance is often sacrificed in favor of meeting schedules. If refractive index data of sufficient accuracy could be made available at design time, lenses could be assembled and aligned in only one or two iterations instead of a dozen or more. This is particularly important for lenses in the Near Infrared Camera (NIRCam) for NASA’s James Webb Space Telescope (JWST) as they must work at a temperature of 37K. NIRCam is not only the observatory’s primary science camera, it is also the telescope’s wavefront control sensor.

Fourier transform spectroscopy and other methods are not precise enough to yield useful index data for complex, modern, lens designs. Minimum deviation prism refractometry is widely known to provide the most precise index measurements. However, until now, no refractometer has been built that has an index accuracy down to a few parts in the fifth decimal place for samples at cryogenic temperatures. The issue has been particularly noticeable below 77K (the temperature of liquid nitrogen). At Goddard Space Flight Center, we have engineered an evacuated, minimum-deviation refractometer in which we have minimized every source of index uncertainty to obtain the most accurate possible index data.

Applying Snell’s law of refraction for a prism set at the condition of minimum deviation yields a simple expression for the prism’s index involving only its apex angle and the angle of deviation (the angle through which the prism bends a beam...
of monochromatic light). Apart from knowledge of the wavelength and sample temperature, the primary contributors to error in the measured index are errors in measuring those angles. In our refractometer, the prism and deviation-recording mirror rotate on super-accurate rotary bearings equipped with ultra-precise, absolute-shaft-angle encoders designed for cryostatic environments. A sophisticated, automated routine appeals to the encoders and concurrently determines the exact location of the refractometer’s deviated slit image to enable a high-accuracy, differential measurement of deviation angle.

Achieving thermal control (at very low temperatures) of a prism was a major challenge. The prism must rotate without being enclosed in a windowed dewar as that would degrade the accuracy of the deviation-angle determination. We devised a thermally-isolated, windowless, liquid helium (LHe)-cooled sample compartment through which the refractometer’s beams pass. The sample is conductively cooled on a rotating copper platform connected to the LHe vessel with flexible copper straps. The platform is very stiffly connected to, yet very effectively thermally-isolated from, the encoded rotary bearing below.

The lenses for NIRCam are triplets, made from ZnSe, BaF$_2$, and LiF, for collimating an image of the sky from the JWST and for re-imaging the sky through filters onto the instrument’s detectors. A prism of each of NIRCam’s lens materials is shown in the photo (Figure 1). Our measurements for the indices of the three materials are accurate to $\pm 1 \times 10^{-4}$, $\pm 1.5 \times 10^{-5}$, and $\pm 2 \times 10^{-5}$, respectively. For NIRCam and other future instruments, perhaps our most significant results have been the mapping of the exact way in which the index stops changing for different materials at different temperatures below 100K. Without these measurements, lens designs involving extrapolation of dispersion models to colder temperatures are on very shaky ground.

Using our new cryogenic refractometer, we have measured, with unprecedented accuracy, the absolute refractive indices of infrared lens materials for JWST’s NIRCam, from the mid-visible to the mid-infrared, and from room temperature down to as low as 15K. Good agreement with previous room-temperature studies of these materials has been demonstrated. We have identified the cryogenic temperature at which the refractive index stops changing in these materials. Measurements of other infrared optical materials, including synthetic fused silica, BK7, and BALKN3, have also recently been completed. Measurements of Si, ZnS, Ge, E-SF03, SF15, and CaF$_2$ are planned.