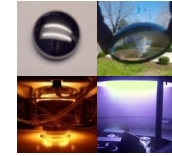




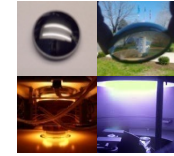
Next generation multi-spectral materials

Qualification of US Produced IRG Series Glass



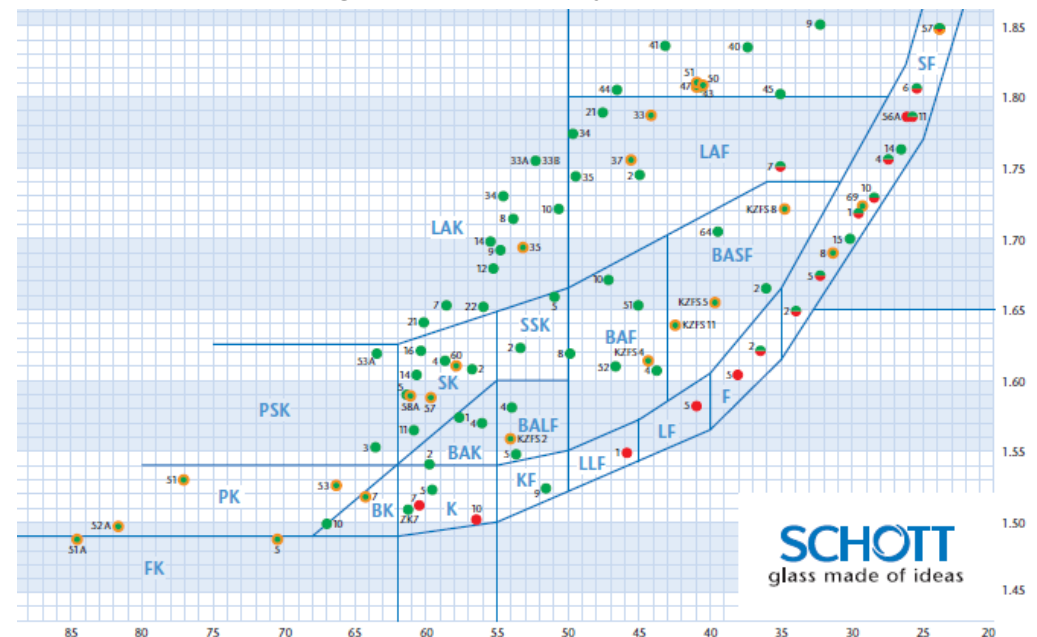
- All properties for IRG22 through IRG26 have been verified to published specifications or better
- Standard physical and thermal property metrology
- SCHOTT refractive index guaranteed to +/-0.001 (405nm to 12.2 μm)
- SCHOTT provides individual sample inclusion inspection at 0.1mm resolution (in house)
- IR interferometer under development for homogeneity and birefringence metrology
- Prism system for melt verification of index / dispersion; 0.0002 resolution
- All index measurements have been correlated with independent source
 - Reproducibility of measurements to 0.0002 RIU
 - dn/dT relative measurements from $-50\text{ }^{\circ}\text{C} \leq T \leq 75\text{ }^{\circ}\text{C}$ in 5 $^{\circ}\text{C}$ increments

Traditionally, optical designers use multiple lens materials to compensate for optical aberrations.

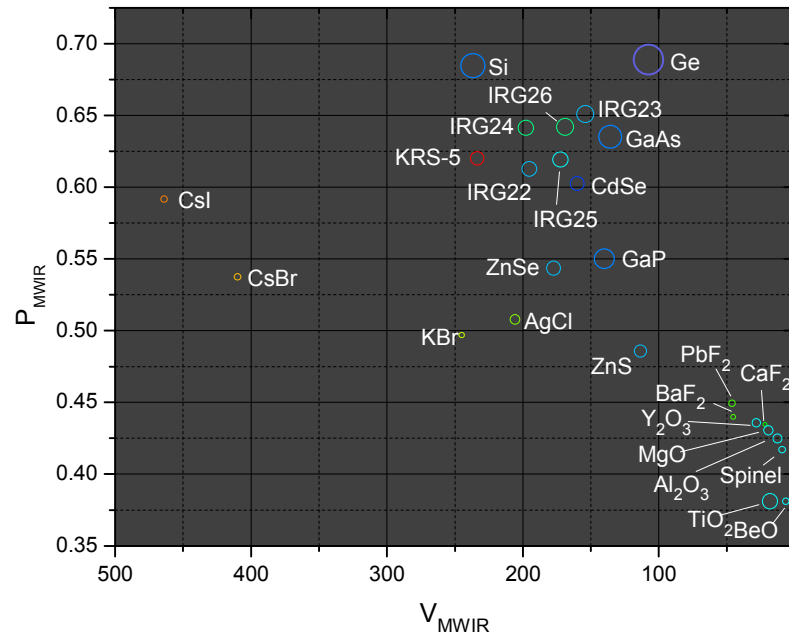
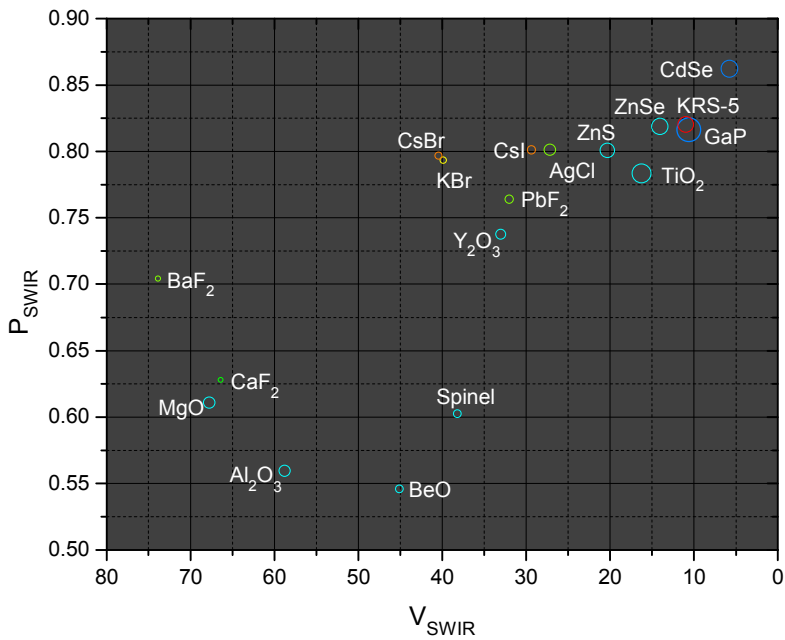
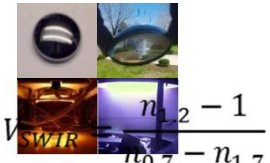


- Spherical curves create spherical aberration.
 - A positive spherical aberration may be balanced by a negative spherical aberration on another lens surface.
 - Same effect is true for coma, astigmatism, etc.
 - Each “free” surface allows the correction of one aberration.
- **Chromatic aberration leads to defocus of shorter or longer wavelengths.**
 - Is a function of the refractive index dispersion of the optical material.
 - The sum of the products of lens powers (P) and dispersions (v) must be zero. $\sum_i v_i P_i = 0$
 - Requires positive and negative elements of different refractive index and dispersion.
- Thermo-optic effect causes defocus with temperature change (particularly for IR).
 - Similar techniques to correct chromatic effects used to balance thermal effects but with CTE and dn/dT instead of n and v .

Origin of the SCHOTT glass catalog.



Using standard Abbe diagrams for broad band IR



$$V_{SWIR} = \frac{n_{1.2} - 1}{n_{0.7} - n_{1.7}}$$

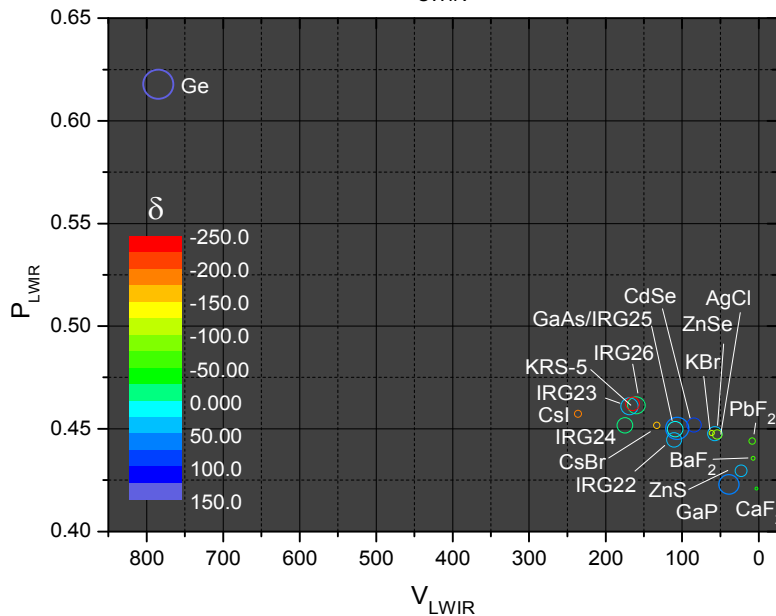
$$P_{SWIR} = \frac{n_{0.7} - n_{1.2}}{n_{0.7} - n_{1.7}}$$

$$V_{MWIR} = \frac{n_4 - 1}{n_3 - n_5}$$

$$P_{MWIR} = \frac{n_3 - n_4}{n_3 - n_5}$$

$$V_{LWIR} = \frac{n_{10} - 1}{n_8 - n_{12}}$$

$$P_{MWIR} = \frac{n_8 - n_{10}}{n_8 - n_{12}}$$

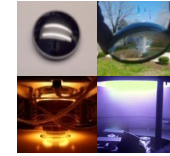


Dramatic changes to Abbe diagram depending on which band is examined

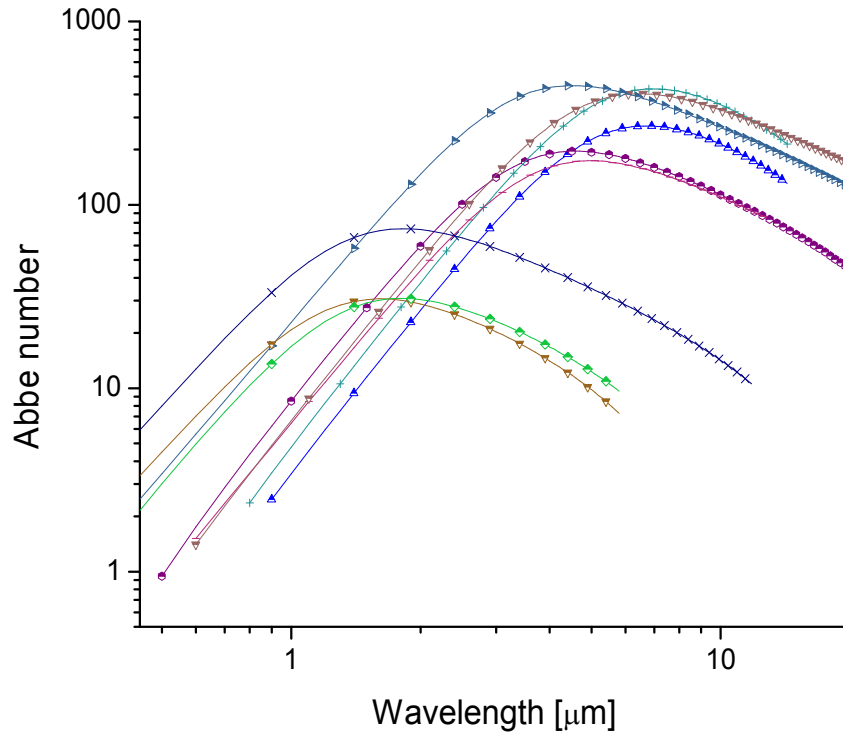
Typically, crown-type materials in LWIR become flints in SWIR and vice-versa.

How can we choose pairs/triplets for systems covering multiple bands simultaneously?

Instantaneous definitions from the Sellmeier



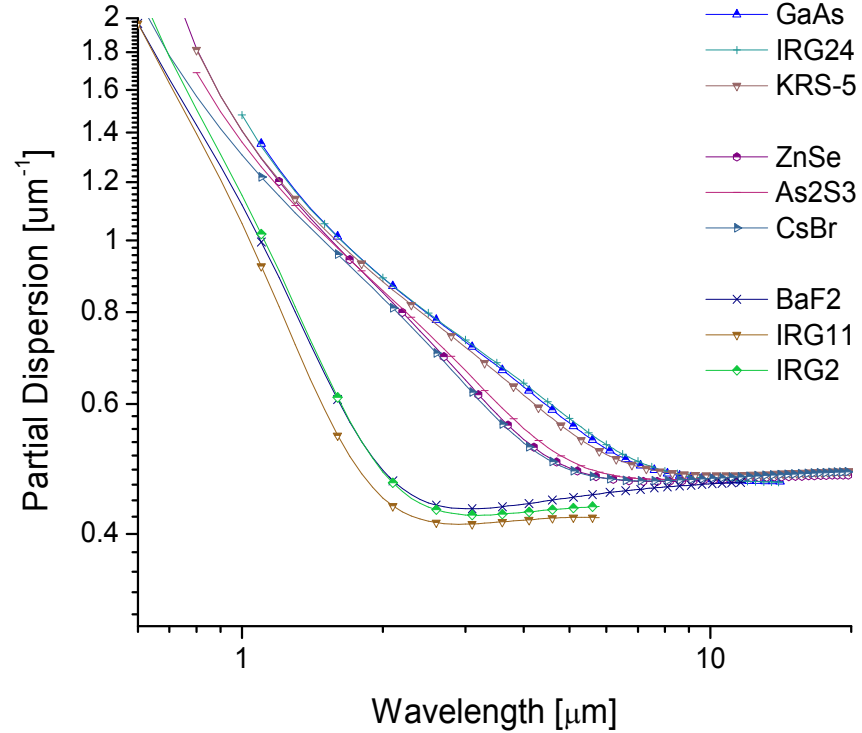
$$n^2 - 1 = \frac{B_1 \lambda^2}{\lambda^2 - C_1} + \frac{B_2 \lambda^2}{\lambda^2 - C_2} + \frac{B_3 \lambda^2}{\lambda^2 - C_3}$$



Instantaneous
Abbe Number

$$V'(\lambda) = -\frac{1}{2} \frac{n(\lambda) - 1}{v(\lambda)}$$

$$v = \frac{dn}{d\lambda} = n^{-1} \sum_i \frac{-B_i C_i \lambda}{(\lambda - C_i)^2}$$



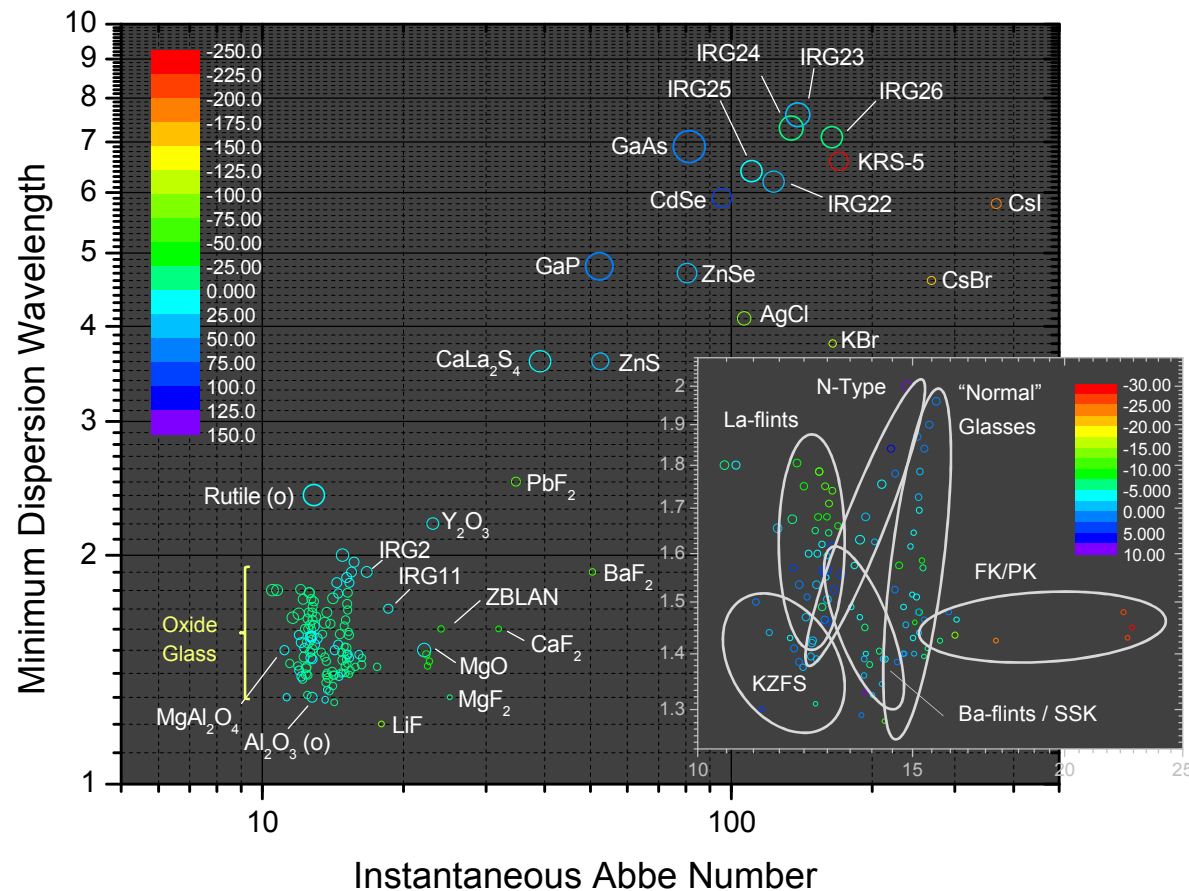
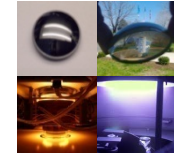
Instantaneous
Partial Dispersion

$$P'(\lambda) = \frac{1}{2} - \frac{1}{4} \frac{\varphi(\lambda)}{v(\lambda)}$$

$$\varphi = \frac{d^2 n}{d\lambda^2} = \sum_i \frac{B_i C_i (C_i - 3\lambda^2)}{(\lambda^2 - C_i)^3}$$

Materials which share similar minimum dispersion wavelengths also share similar partial dispersion at all wavelengths – ideal from achromats.

Redefining Abbe number for IR

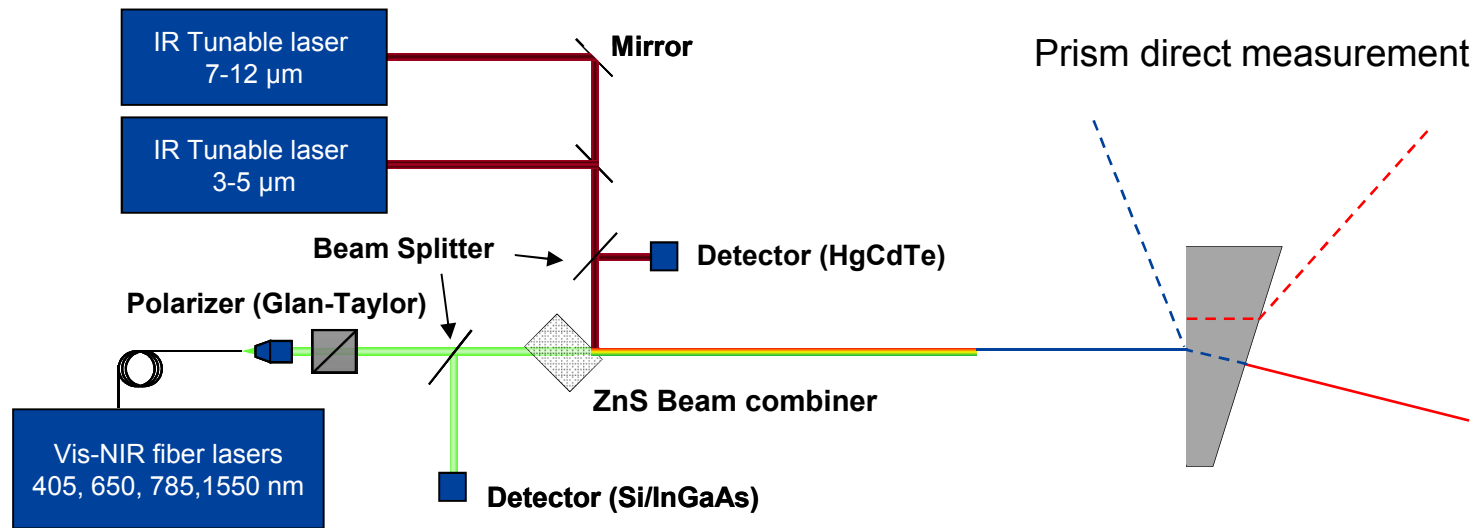


Several advantages to using instantaneous vs. standard Abbe.

- Trends between composition and optical properties become apparent.
- Fundamental to all materials rather than varying with wavelength.
- Any material may be included in the diagram.
- Accentuates similarities between materials rather than differences

- Comparing Oxide glasses to IR materials shows lack of available selection and very large range of properties (Particularly thermo-optical).
- Significant improvement over using many simultaneous Abbe diagrams for multi-band designs.
- All needed information is inside the Sellmeier equation:

Vis-IR refractometer



~10-30° wedge prism preferred (angle need not be precise).

- 4 reflections measured: 2x first surface, 2x refracted second surface \Rightarrow 1x prism angle + 2x index meas.
- Equivalent to minimum deviation measurement (inherently symmetrical), but with only 1 moving part.
- Same sample as used for 3rd party minimum deviation measurement (M3MSI) – useful for validation.

Environmental chamber for sample stabilization and dn/dT measurement:

- Samples should be held at temp for ~5 minutes to stabilize.

Limited to ± 0.0002 by rotary stage repeatability

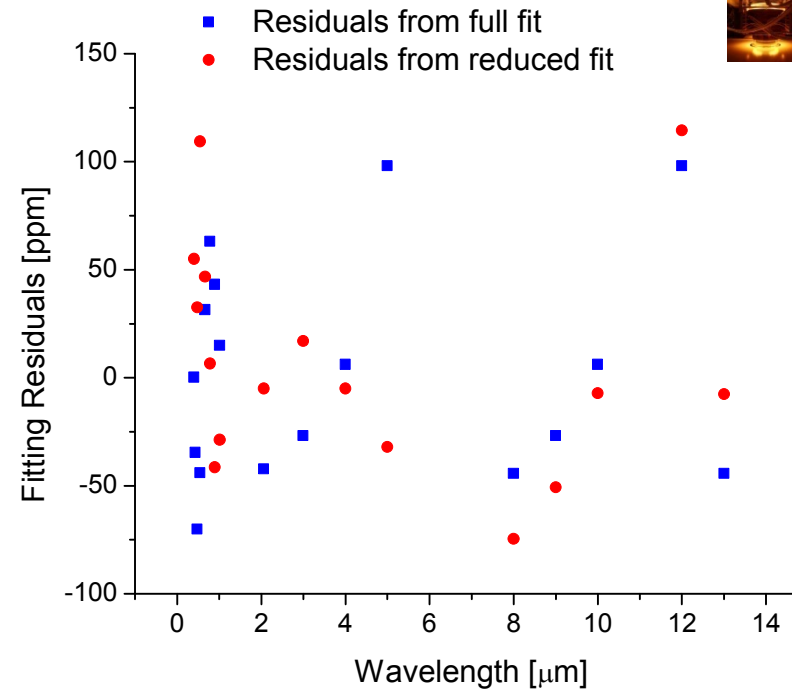
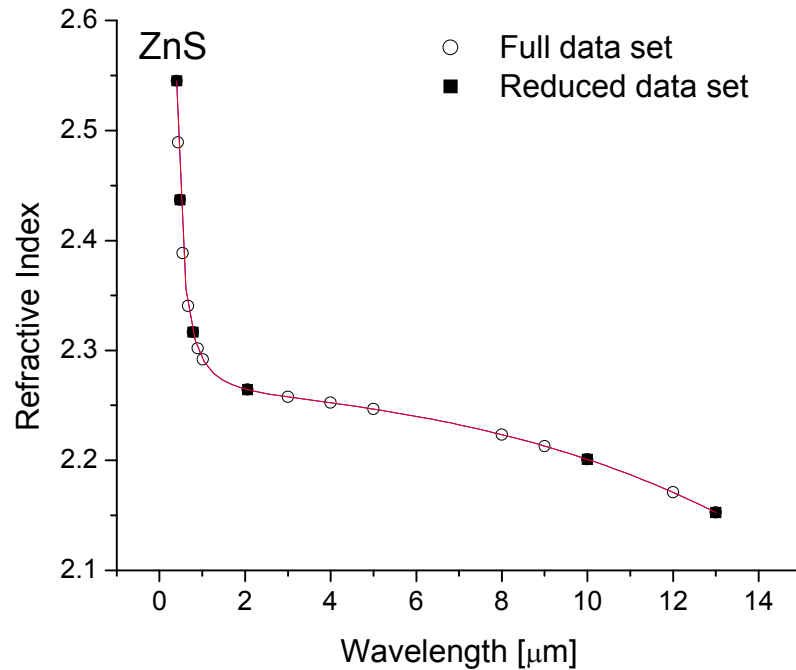
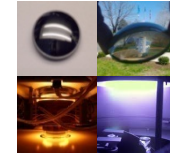
- Sufficient for QA and optical designs, but non-ideal for dn/dT measurements

Improved wavelength accuracy needed for Vis-NIR wavelengths.

- 4 reflections detected: 2x first surface, 2x refracted second surface \Rightarrow 1x prism angle + 2x index meas.
- Equivalent to minimum deviation measurement, but with only 1 moving part.
- Same sample as used for 3rd party minimum deviation measurement – useful for validation.



Index measurements and fitting

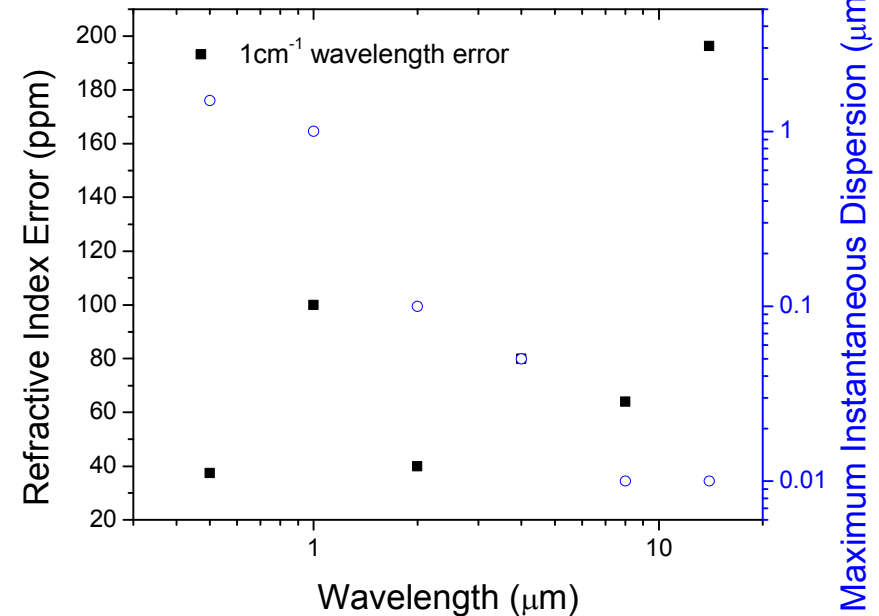
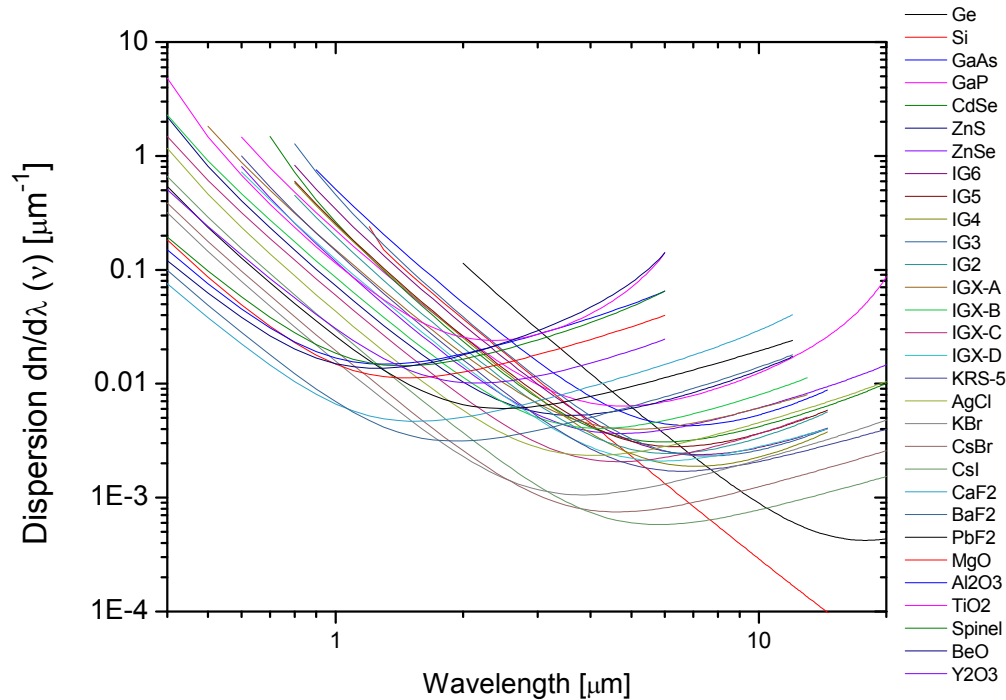


$$n = \frac{B_1 \lambda^2}{\lambda^2 - C_1} + \frac{B_2 \lambda^2}{\lambda^2 - C_2} + \frac{B_3 \lambda^2}{\lambda^2 - C_3}$$

B_1	B_2	B_3	C_1	C_1	C_3
2.07621	0.18252	0.53704	0.00915	0.07742	1022.3
B_1	B_2	B_3	C_1	C_1	C_3
2.06227	0.19652	0.53667	0.00879	0.07583	1021.0

- Used minimum data to specify terms (6 points) and no reduction of quality of fit.
- Large numbers of wavelengths improves immunity to errors, but are not required.
- Placement of wavelengths is important: 2 per term pair, don't extrapolate beyond available data.
 - $\lambda = 1\text{-}1.5x$ absorption edge (C_1), $3\text{-}6x$ absorption edge (C_2), $0.5\text{-}1x$ IR multi-phonon cut-off (C_3).
- Works out to about even spacing in terms of index (~ 0.8 RIU for ZnS).
- Wavelengths should be chosen based on material properties, not absolute.
- Standardization is needed for useful comparisons of reference data.

Index measurements continued

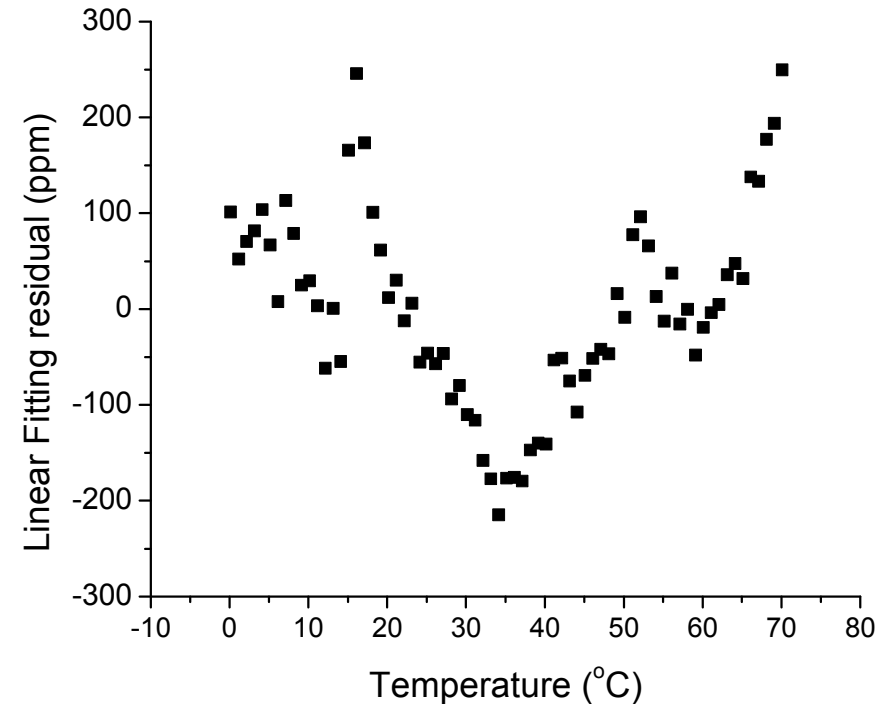
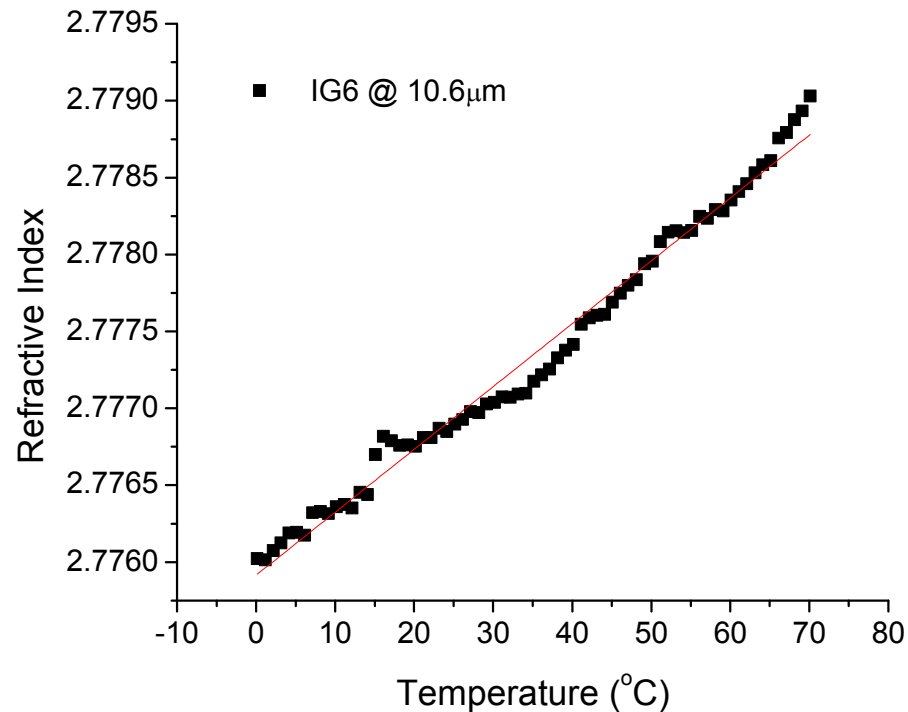
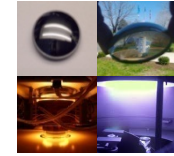


As seen before, large numbers of wavelengths are not needed, but wavelength must be well-known.

1 cm⁻¹ or better wavelength precision recommended ($\pm 0.02\text{nm}$ @ $\lambda = 500\text{nm}$).

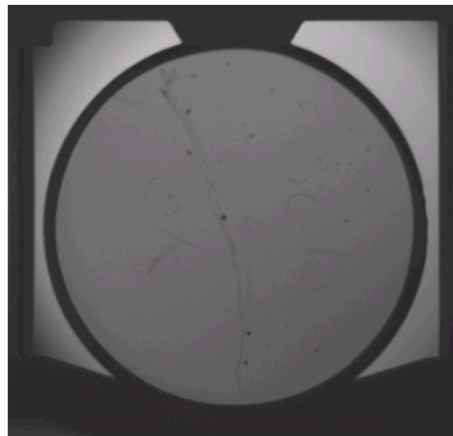
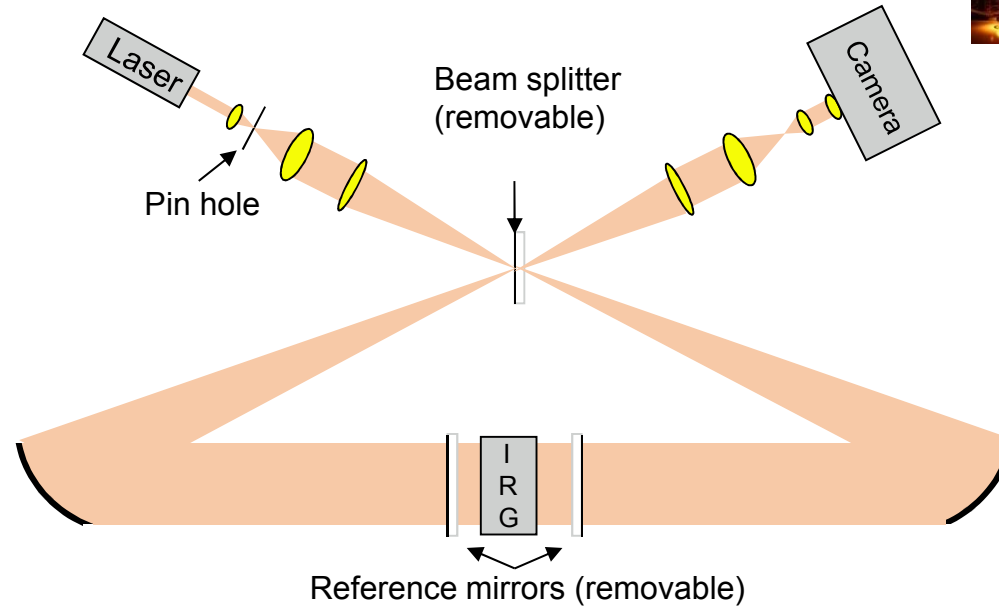
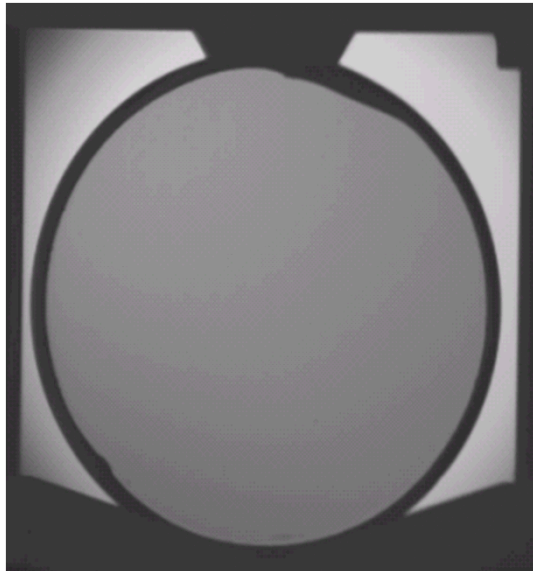
- Calibrated gratings, scanning FP cavities, gas lamps, gas lasers, DFB or EC diode lasers.
- Diode lasers can be modulated to allow high SNR and throughput.
 - Current system @ SCHOTT uses 20kHz modulation for < 1 hour full curve measurement.
- Rotating prism sample itself forms a high precision monochromator.
 - Broadband excitation and detector arrays may possibly be a better solution.

Improvements needed for dn/dT measurements

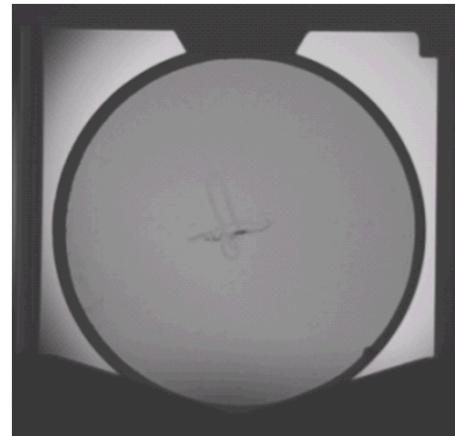


- dn/dT is clearly nonlinear, average value will depend on the temperature range used.
- Wavelength-dependence of the nonlinearity has not yet been determined.
- Importance of this effect is not yet known, but is expected to be most significant at extreme temperatures.
- **Recommend use of high precision etalon / interferometry techniques versus index measurement over temperature.**
- **Should also be used for relaxation / index drop, ie. for molding applications.**

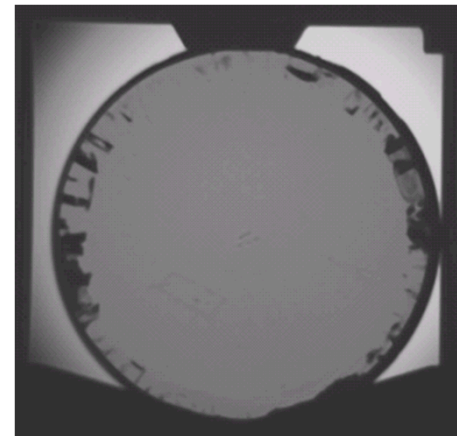
IR Quality Inspection



Inclusions

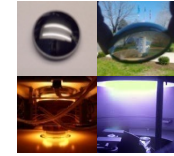


Striae



Sub-surface damage

IR Quality Inspection - continued



Birefringence:

- Polarizer and analyzer may be used in order to check residual stress.
- 4-point bend stress-optic instrumentation has been constructed.
 - Currently going through validation measurements.

Working with multi-spectral glasses (IGX program) to define homogeneity grades H-1 through H-5 similar to traditional oxide glasses.

Full homogeneity measurements via IR interferometry have been requested.

IR adhesives have recently been developed at SCHOTT.

- Thermal cure is required due to UV opaque optics and low IR transmission of polymers.
- IR active alignment tools will be required along with process development.