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Novel materials and design methods for broad-band IR optics.

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Photonics West, 2/6/2013

SCHOTT IR Glass- Overview

We currently sell the IGx family of chalcogenide glasses (IRG22-IRG26)

- Technology licensed from Vitron (Europe) FY10
- *US production that began Q3 FY11 in Duryea PA*
- *Product name changed from IG2 – IG6 due to specification differences.*

Technology and Production Facility investment with Initial US production

- Fully Qualified Production of Materials (Q1 FY12), Components (Q2 FY12) and Coatings (Q2 FY12)
- $2.9M production Investment in Production capability in FY10 and FY11.
- Unique capabilities for refractive index and internal quality analysis in infrared materials.

Novel IR glasses for increased performance and bandwidth (Vis through LWIR performance—Began Q3 FY11

- Enable more Achromatic Designs over Vis./SWIR + LWIR bands
- Reduces the need for Kinoforms
- Surfaces freed for performance enhancements

Benefits:

⇒ Passive athermality from 0-50 °C

⇒ Decreased Component Count

⇒ Batch Costs $ for IR Glass ½ to 1/3 Lower than Germanium!

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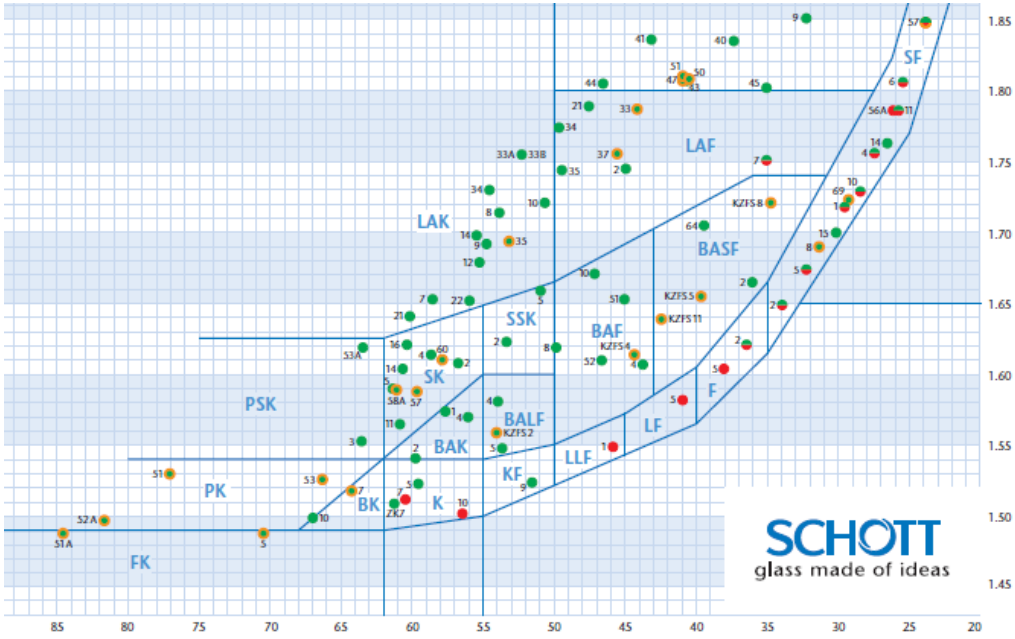
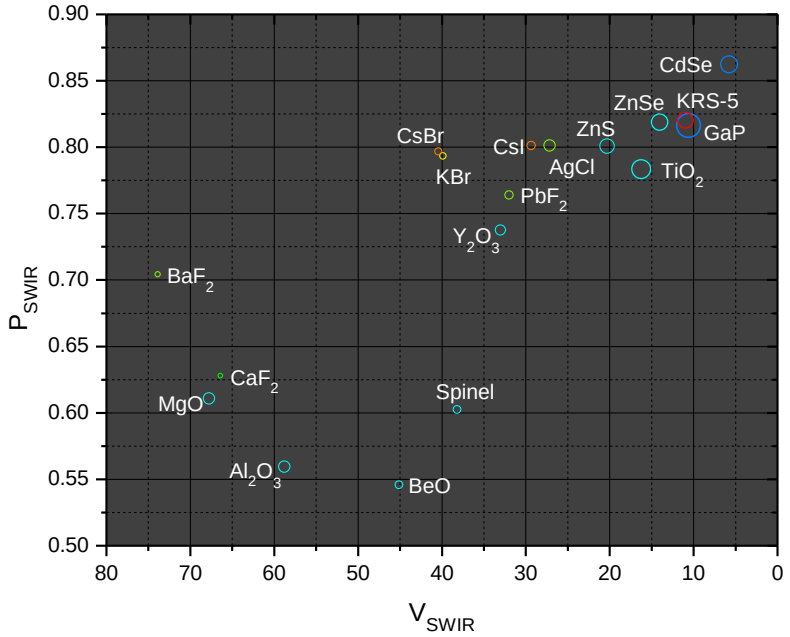
Traditionally, optical designers use multiple lens materials to compensate for optical aberrations.

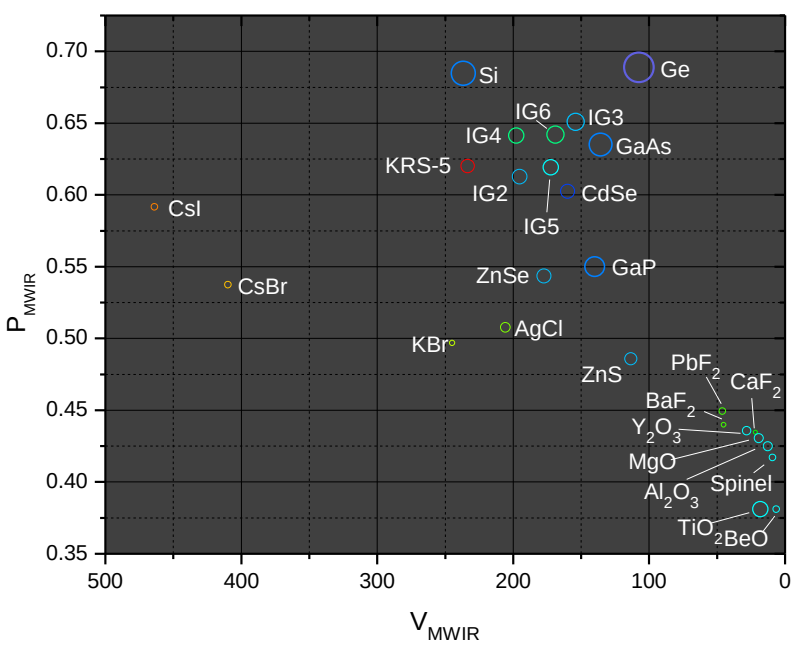
- **Spherical curves create spherical aberration.**
  - A positive spherical aberration may be balanced by a negative spherical aberration on another lens surface.
  - Same effect is true for coma, astigmatism, etc.
  - Each “free” surface allows the correction of one aberration.
- **Chromatic aberration 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 (φ) and dispersions (ν) must be zero. $\sum_i \nu_i \varphi_i = 0$
  - 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 ν.

Origin of the abbe diagram - “glass map”.



Using standard Abbe diagrams for broad band IR





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

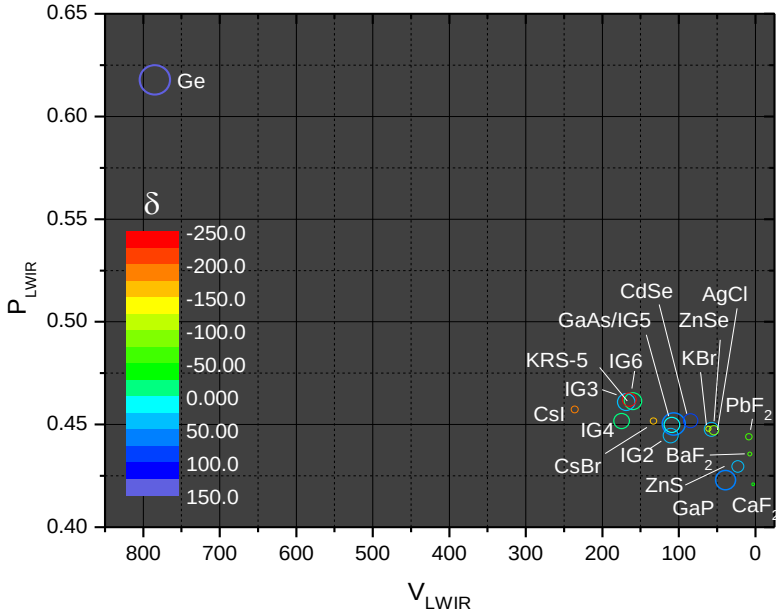
$$P_{SWIR} = \frac{n_{0.7} - n_{1.2}}{n_{0.7} - n_{1.7}}$$

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

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

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

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



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?

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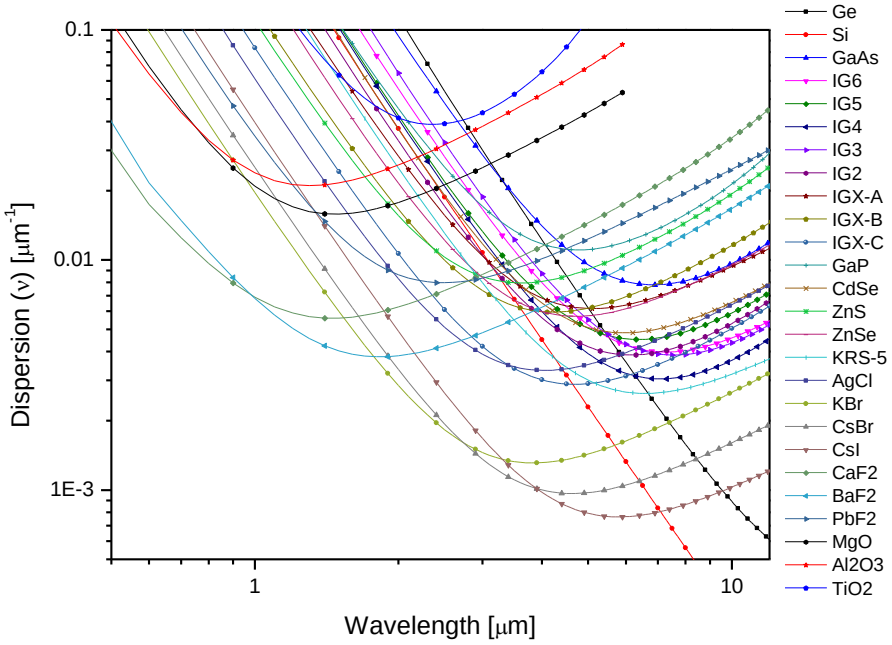
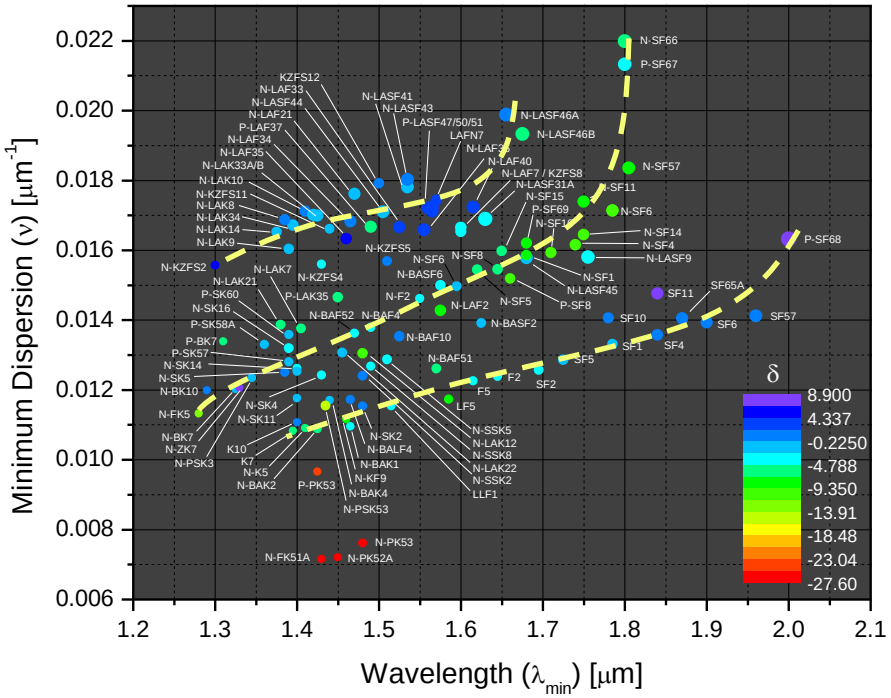
Examining dispersion from first principles





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

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

$$\delta = \frac{\mathrm{d}n/\mathrm{d}T}{n-1} - \alpha$$

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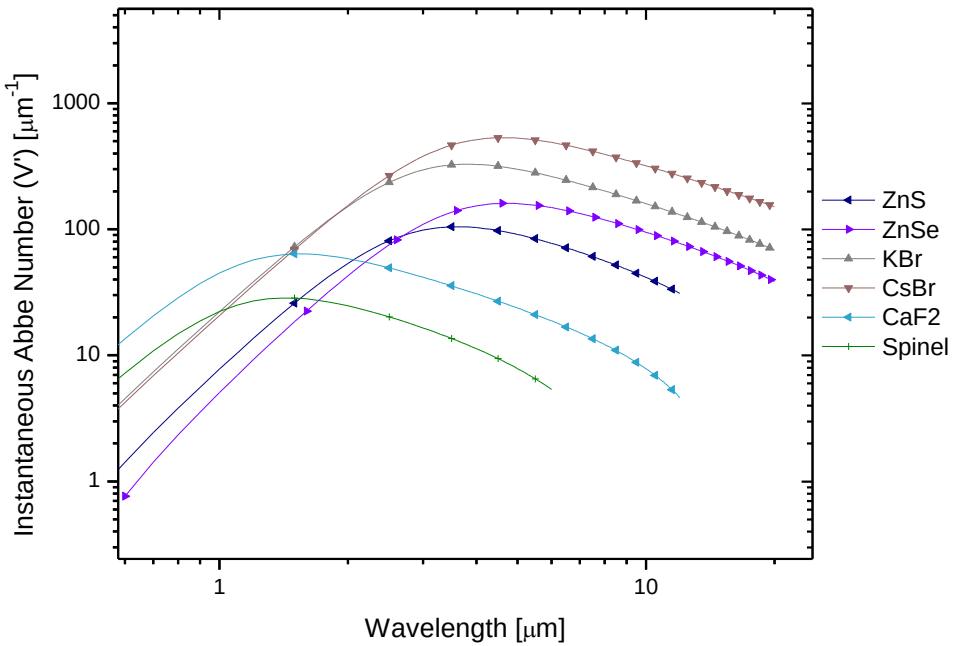
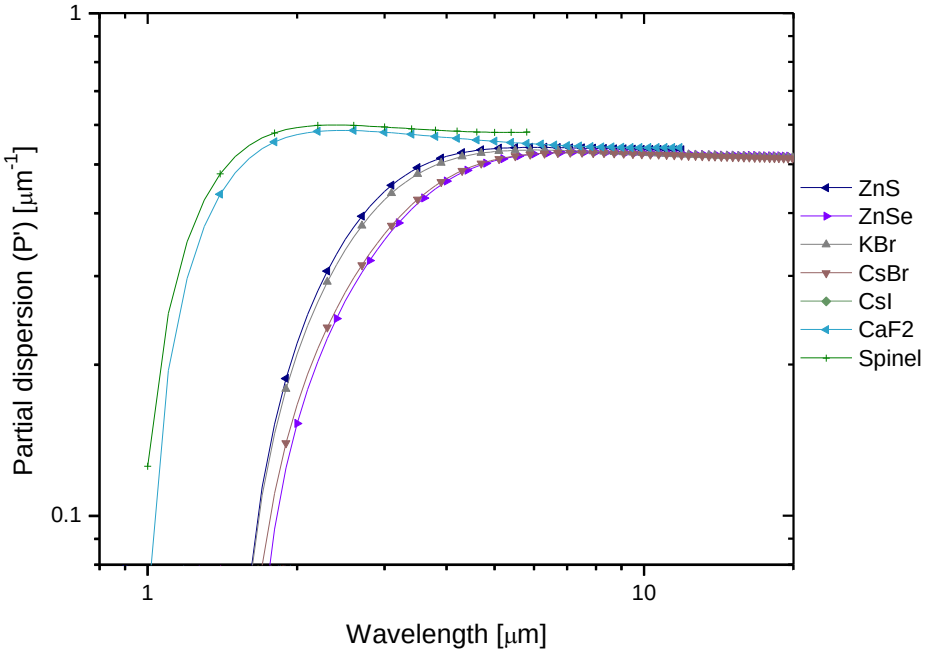
Reconstructing Abbe number and Partial dispersion





Instantaneous Abbe No. $V'(\lambda) = -\frac{1}{2}\frac{n(\lambda)-1}{\nu(\lambda)} \quad V = V'(\Delta\lambda)$

Instantaneous Partial Disp. $P'(\lambda) = \frac{1}{2} - \frac{1}{4}\frac{\varphi(\lambda)}{\nu(\lambda)} \quad P = P'(\Delta\lambda)$

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

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

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

- Two materials with similar dispersion minima will have similar partial dispersions over a wide range of wavelengths… V'_1/V'_2 will be near-constant. $\sum_i \frac{B_i C_i (C_i - 3\lambda^2)}{(\lambda^2 - C)^3} = 0$

➢ Implies $\sum_i \frac{K_i}{V_i} = 0$ can be satisfied over broad band for achromatic doublets.

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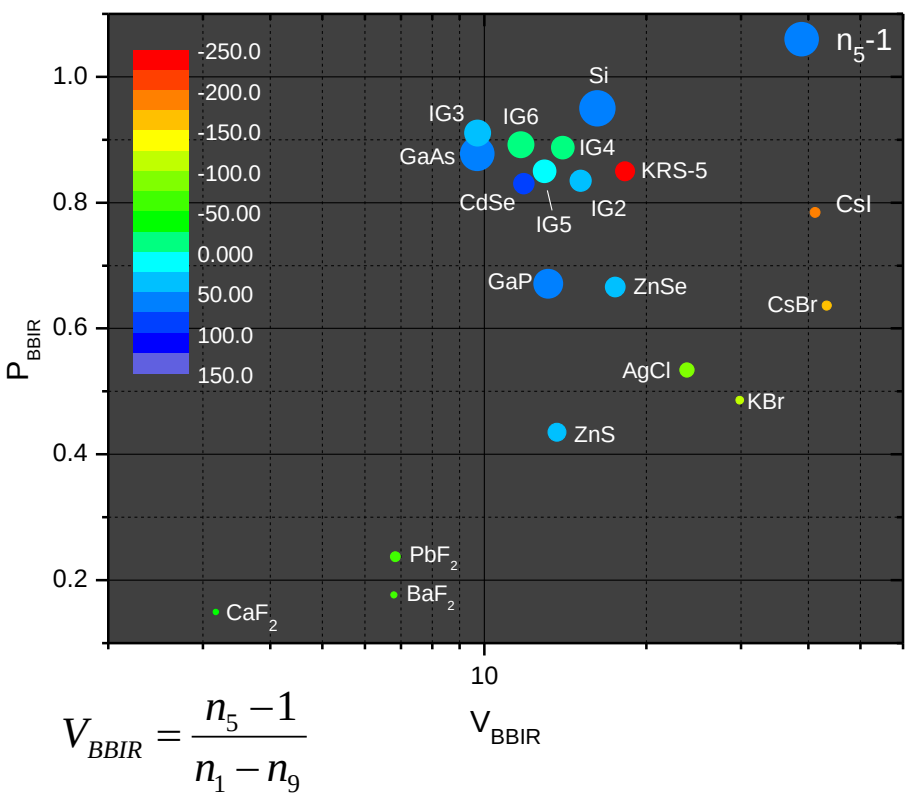
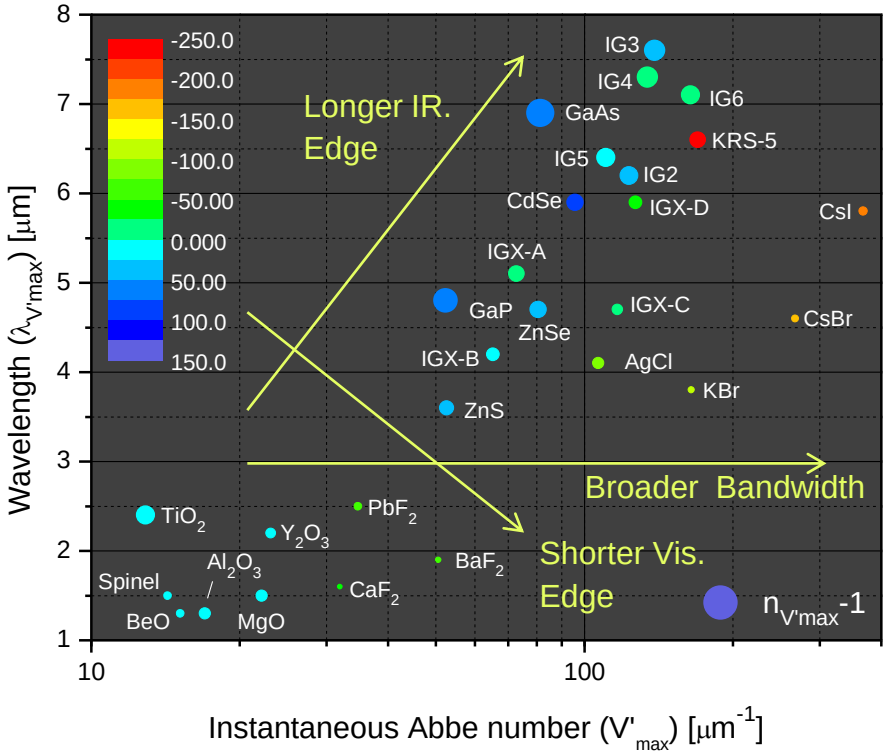
Classic Abbe Diagram and Instantaneous Dispersion compared



$$V_{BBIR} = \frac{n_5 - 1}{n_1 - n_9}$$



Difference between both methods become clear, yet relative positions of materials are similar.

- May be used as direct replacement for Abbe diagram for IR materials.
- Instantaneous Abbe number preserves more information from material trends.
- Any material may be represented without modifying method.
- Can be extend arbitrarily to any wavelength range UV, FIR, etc.
- Traditional P-V diagram may still be helpful when working very close to short-wavelength transmission edge due to high, rapidly changing dispersion – index asymptote near band-gap.

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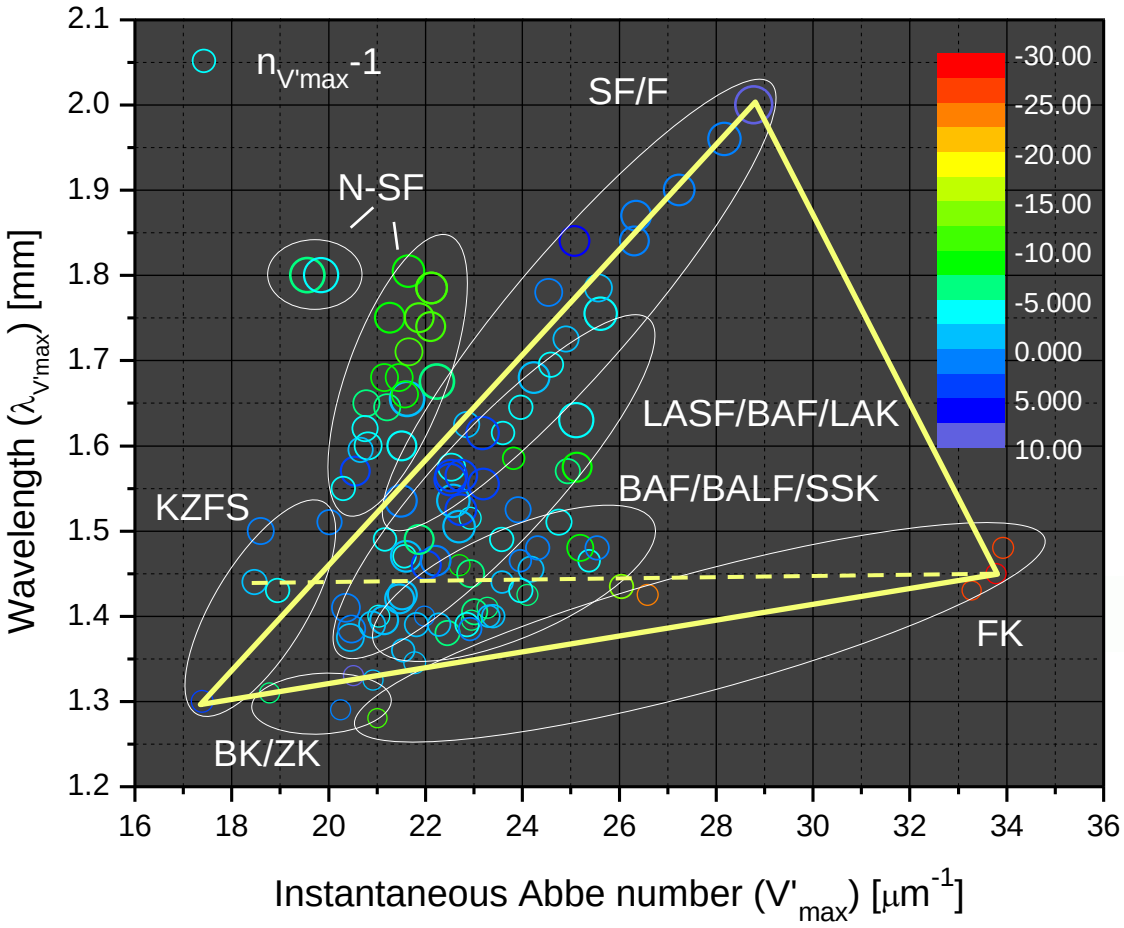
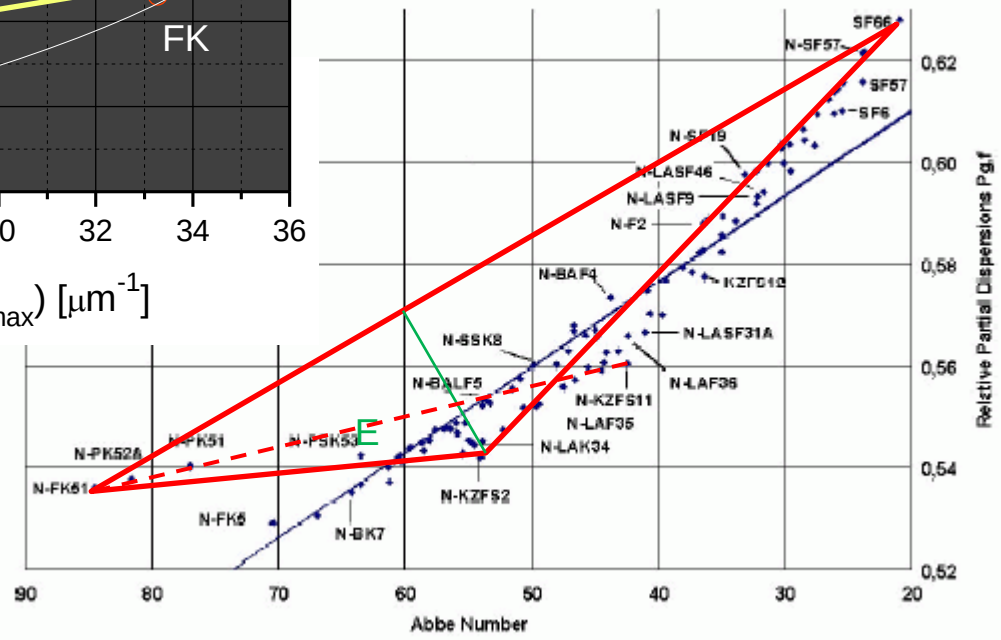
Glass selection: New rules versus old

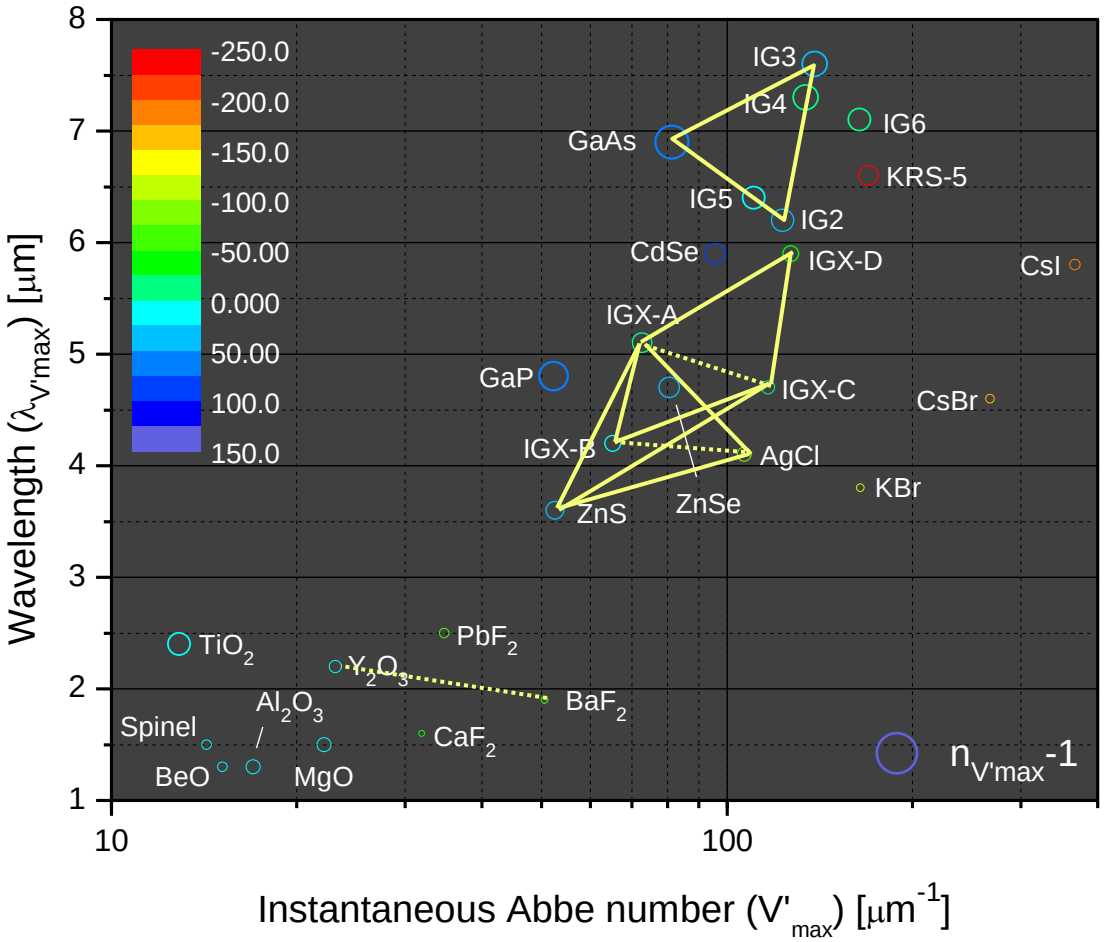


New rules (for NIR/SWIR):
- Doublet – Select two glasses with large Δν and small Δλ (FK51A/KZFS4).
- Triplet – Select two flints widely separated and crown with λ between these with maximum Δν (FK51A/KZFS2/N-SF66)
- If triangle is obtuse, one flint will end up switching roles.
- Both rules give same selection of glasses in NIR, but this works better for SWIR



Old rules (for VIS):
- Doublet – Select two glasses with large ΔV and small ΔP.
- Triplet – Select three glasses with deviation (E) as large as possible – maximize inscribed area
- Both rules give same selection of glasses in NIR, but this works better for VIS.

Materials Selections for broadband IR.



Selection rules for BBIR:

- Doublet – Select two glasses with large Δν and small Δλ (IGX-A/IGX-C IGX-B/AgCl).
- Triplet – Select two flints widely separated and crown with λ between these with maximum Δν (IGX-A/B/C) or 1 flint + 2 crowns (IGX-A/C/D)
- If triangle is obtuse, one flint will end up switching roles.

Achromatic criterion: $$\sum_i \frac{K_i}{V_i} = 0$$

Must also keep thermal effect in balance.

- Choices should be in δ = 0 to -50 range.

$$\sum_i K_i \delta_i = 0 \qquad \delta_2 = \frac{V_1(\alpha_{Al} - \delta_1)}{V_2}$$

This is the major advantage of chalcogenide glasses of crystalline materials. (alkali halides and semiconductors).

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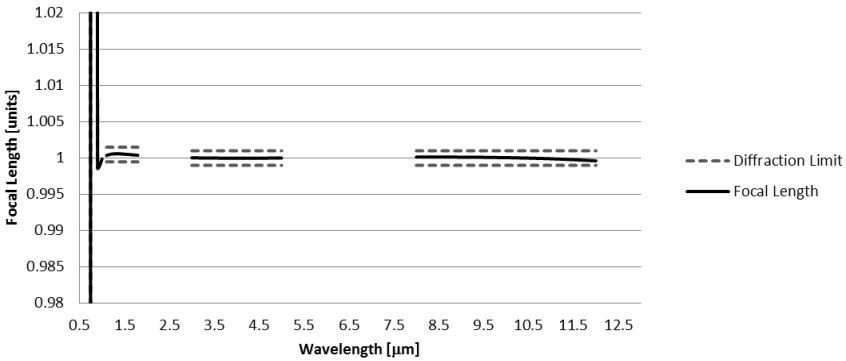
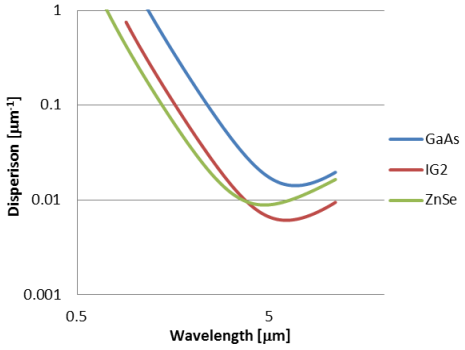
Example designs based on selection rules

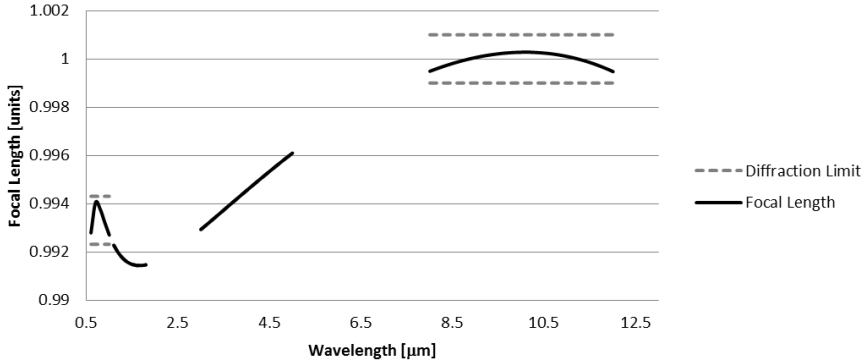
SWIR-MWIR-LWIR



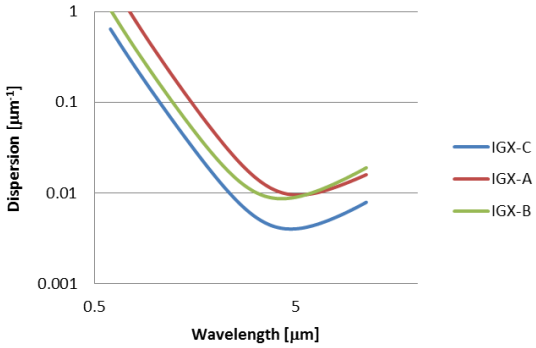
Material	$C = 1/R_1+1/R_2$	V_{min}	δ (ppm/K)
GaAs	-0.877	81	58
IG2	2.632	123	32
ZnSe	-0.658	81	35
Housing CTE			22.0



VIs/NIR-LWIR



Material	$C = 1/R_1-1/R_2$	V_{min}	δ(ppm/k)
IGX-B	-0.184	0.009	14
IGX-C	2.541	0.004	-24
IGX-A	-0.856	0.010	-19
Housing CTE			36.0



- Initial Designs only - based on Thin Lens, Paraxial and Unit focal length approximations.
- Spacing, thickness, aspheric surfaces, kinoform may be added using full design codes (Code V / Zemax).
- Diffraction limited chromatic focal shift for systems as fast as f/1.
- Possible to construct passively athermal designs – enabled by low dn/dT chalcogenides.

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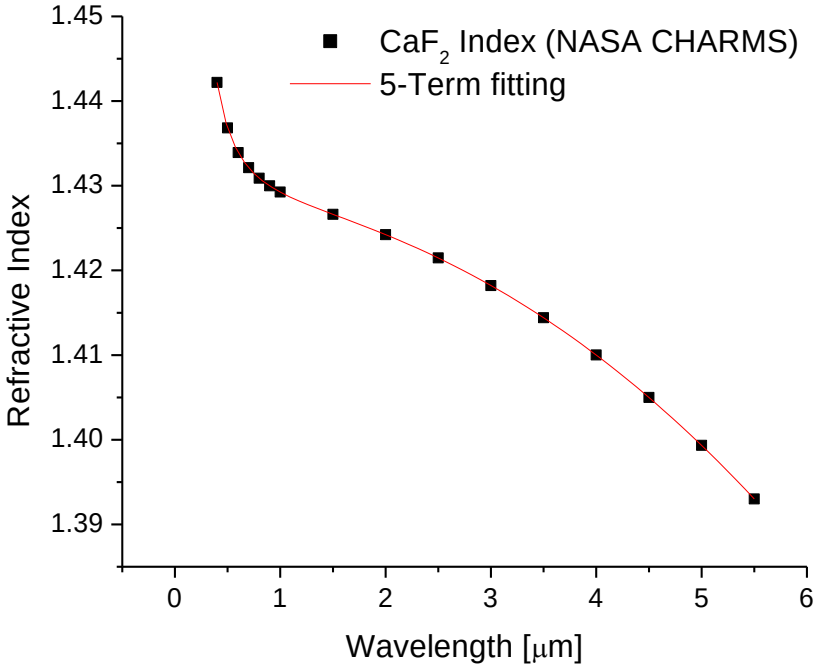
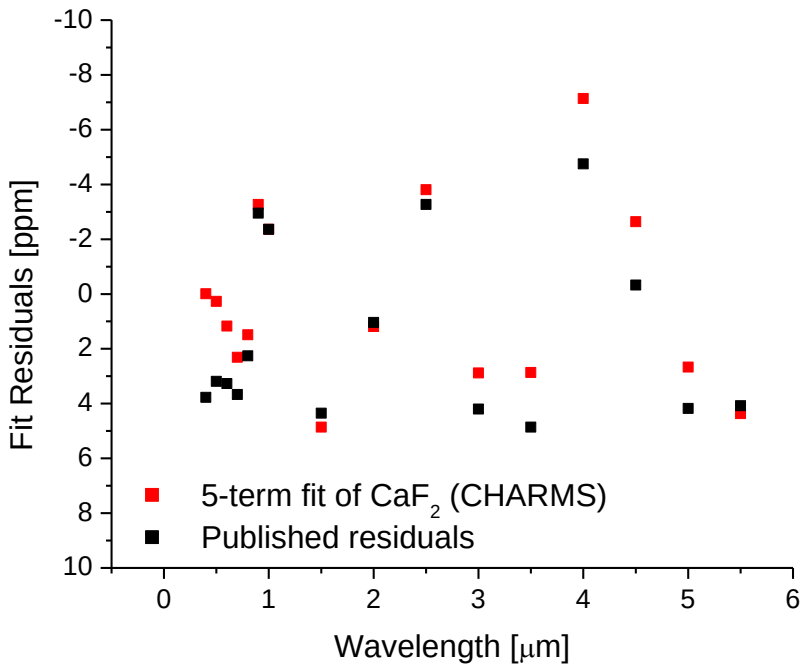
Recommendations for measurements and fitting





6-term $$n = \frac{S_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{S_2\lambda^2}{\lambda^2 - \lambda_2^2} + \frac{S_3\lambda^2}{\lambda^2 - \lambda_3^2}$$

5-term $$n = A\frac{B_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{B_2\lambda^2}{\lambda^2 - \lambda_2^2}$$

S_1	S_2	S_3	λ_1	λ_1	λ_3
0.5723	0.4674	4.1079	0.0482	0.1017	35.7723
A	**B_1**	**B_2**	**λ_1**	**λ_2**	
1.3397	0.7000	4.1838	0.0938	36.092	

- No significant increase in CaF_2 fit residuals using 5-term equation versus reference 6-term fitting.
- 5-term equation converges more easily, and is less sensitive to small experimental errors.
- Can be temperature corrected using cubic expression on 3 terms only (A and B's)
- NASA reference data is temperature corrected using quartic on all 6 terms.
- This comparison is NOT true for all materials (or even all data sets).

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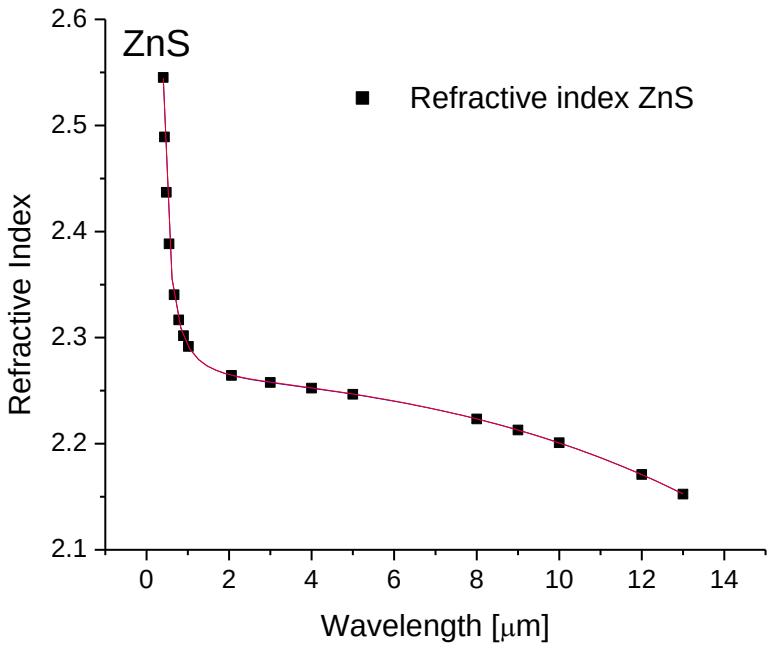
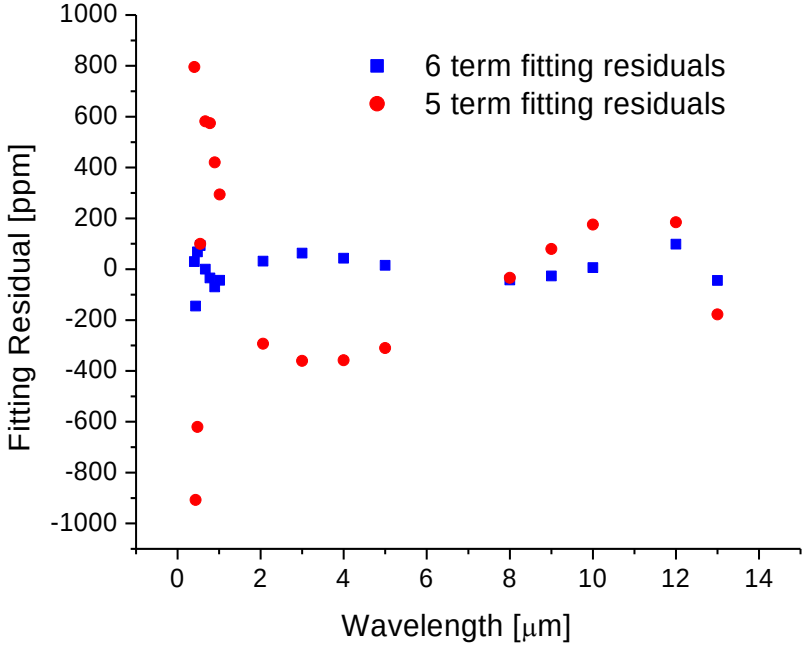
Recommendations for measurements and fitting

λ [µm]	n
0.4047	2.54515
0.4358	2.48918
0.48	2.43691
0.5461	2.38838
0.6678	2.34033
0.78	2.31669
0.8943	2.30183
1.014	2.29165
2.0581	2.26442
3	2.25772
4	2.25231
5	2.24661
8	2.22334
9	2.2129
10	2.20084
12	2.17101
13	2.15252





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

B_1	B_2	B_3	C_1	C_1	C_3
2.07621	0.18252	0.53704	0.00915	0.07742	1022.3

5-term $$n = A + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2}$$

A	B_1	B_2	C_1	C_2
1.65699	0.60244	0.6165	0.0526	1143.5

- ZnS Index data fit with 6 term and 5 term Sellmeier expressions.
- 6-term gives lower residuals, but for many materials fit will not uniquely converge (eg. IG glasses).
- 5-term gives unique solution, but for some reference data (ZnS, ZnSe, KRS-5) gives poor fit.
- For most reference data, 5 terms is indistinguishable from 6 terms: Ge, GaAs, fluorides, salts.
- Why are 6 terms needs for ZnS but only 5 for CaF_2?

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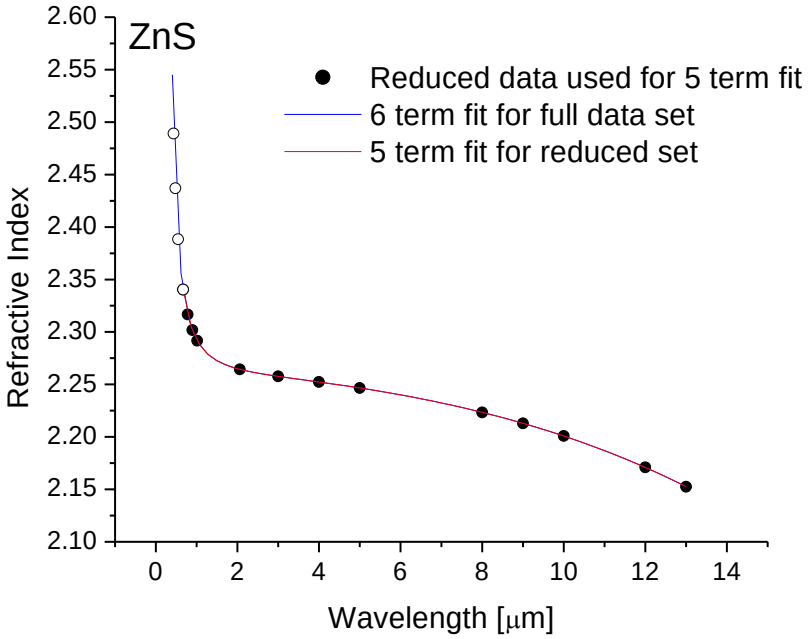
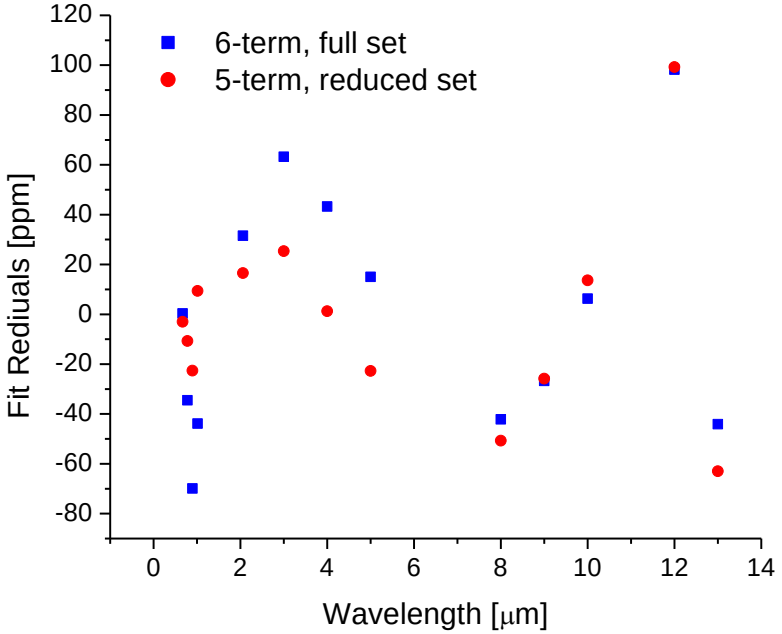
Recommendations for measurements and fitting





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

5-term $$n = A + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2}$$

B_1	B_2	B_3	C_1	C_1	C_3
2.07621	0.18252	0.53704	0.00915	0.07742	1022.3

A	B_1	B_2	C_1	C_2
1.51883	0.73998	0.54381	0.04437	1032.6

- Similar residuals using either 5-term or 6-term expression for reduced data.
- 6-term fit will not uniquely converge using reduced data, but 5-term fit does.
- 5-term fit is also sufficient for CaF_2 Vis-MWIR data. If data starts in UV, then 6 terms are needed.
- Should use 6 terms only if data extends to $\lambda \leq 4C_1^{0.5}$ on 5-term, or about $\lambda \leq$ 2x absorption edge.
- Measurement range should be chosen based on material properties, not absolute.
- Standardization is needed for useful comparisons of reference data.

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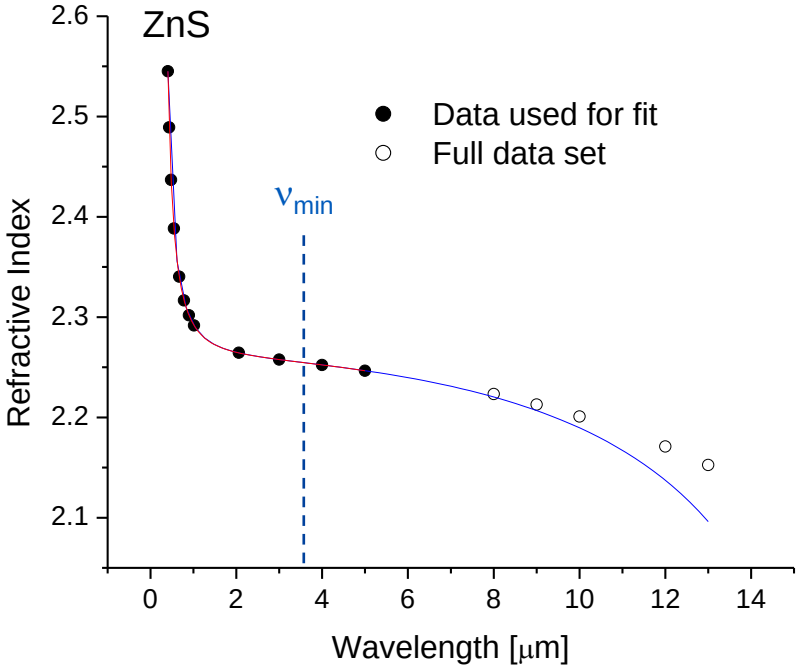
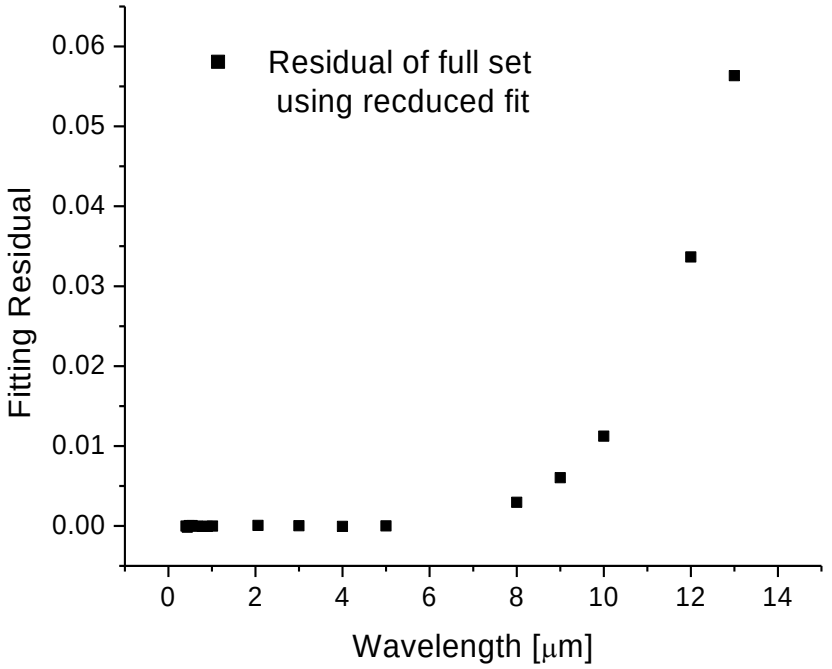
Recommendations for measurements and fitting





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

B_1	B_2	B_3	C_1	C_1	C_3
2.08801	0.17054	0.17084	0.0095	0.0788	346.61

- Removed long-wave to simulate some reference data sets, but allow examination of error.
- At least 2 points beyond ν_{min} are needed for fit to converge.
- ν_{min} occurs just after knee in refractive index curve.
- Extrapolation is of MWIR data to LWIR is strongly affected by small measurement errors.
- Similar to extrapolating data to shorter wavelengths… don't do it!
- Wavelengths should be chosen based on material properties, not absolute.
- Standardization is needed for useful comparisons of reference data.

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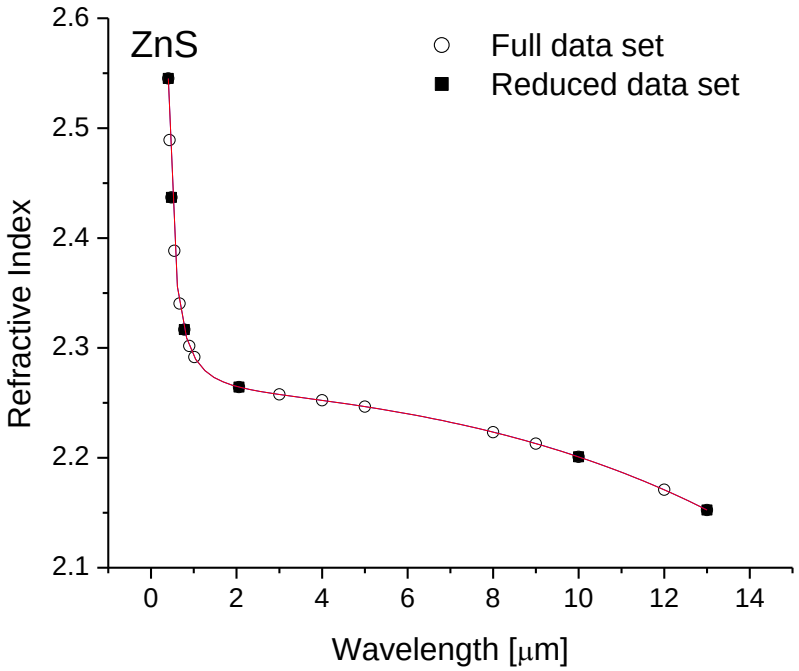

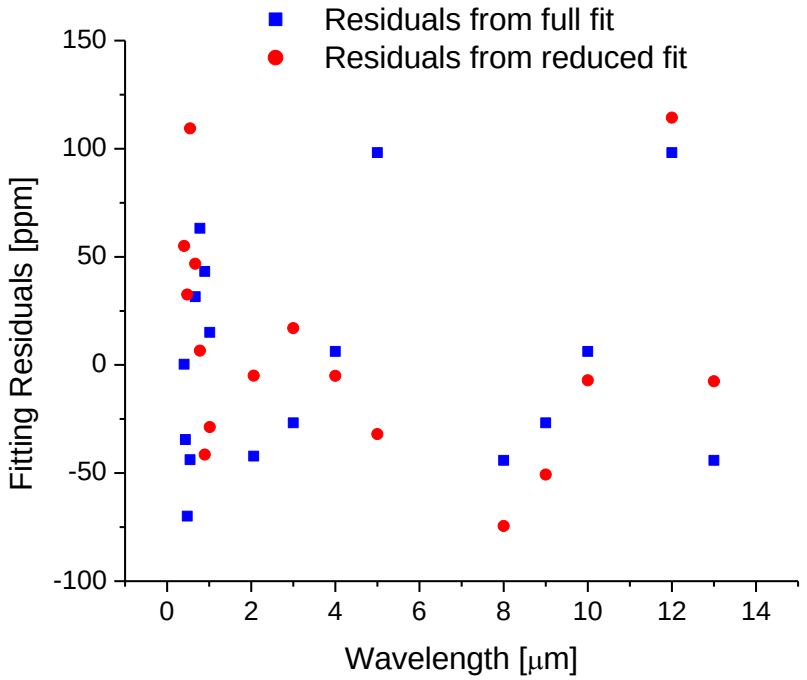

$$n = \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}$$

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.
  - λ = 1-1.5x absorption edge (C_1), 3-6x absorption edge (C_2), 0.5-1x IR multi-phonon cut-off (C_3).
- Works out to about even spacing in terms of index (~0.8RIU for ZnS).
- Wavelengths should be chosen based on material properties, not absolute.
- Standardization is needed for useful comparisons of reference data.

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