ALON® GRIN Optics for Visible-MWIR Applications

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ABSTRACT

Surmet continuously strives to develop novel, advanced optical ceramics products for current and future defense and commercial systems. Using conventional powder processing techniques, Surmet has made substantial progress in its ability to manufacture large ALON® sensor windows, lenses, domes and transparent armor. In addition to transparency, Surmet has demonstrated the ability to incorporate other capabilities into its optical ceramic components, including: EMI shielding, heating, internal antennas and cooling channels.

Working closely with the University of Rochester, Surmet has developed gradient index (GRIN) optics in ALON for use in the visible through the MWIR applications. Surmet has demonstrated the ability to tailor the refractive index of ALON® Optical Ceramic by either varying its composition or through the addition of dopants. Smooth axial and radial gradient profiles with ~0.055 change in refractive index, over depths of 1-8 mm (axial) and over 20 mm radius (radial) have been demonstrated. Initial design studies have shown that such elements provide unique capabilities. Radial gradients in particular, with their optical power contribution, provide additional degrees of freedom for color correction in broadband imaging systems.

Surmet continues to mature ALON® GRIN technology along with the associated metrology. Surmet is committed to the development of its ALON® GRIN capability as well as finding insertion opportunities in novel imaging solutions for military and other commercial systems.

Keywords: Surmet, ALON® Optical Ceramic; refractive index, dopant, gradient index (GRIN), axial GRIN, radial GRIN,

1. INTRODUCTION

Surmet has advanced its manufacturing capability to produce and fabricate very large and transparent ALON® windows, lenses and domes [1, 2]. ALON is made by conventional ceramic powder processing. Surmet has developed novel processes to produce domes, windows and other components with internal architecture, Including: channels, metal patterns, 3-D structures [3] and engineered refractive index profiles. The engineered windows, domes etc. retain their high optical performance while the internal architecture provides additional functionality, including:

- Enhanced toughness, and structural integrity
- Internal antennas
- Buried grids for EMI shielding
- Internal cooling channels
- Internal heaters
- Controlled or graded refractive index profile

These processes have been demonstrated in ALON® Optical Ceramic and are also being developed for magnesium aluminate spinel ($MgAl_2O_4$) Optical Ceramic as well.

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ALON® Optical Ceramic

Aluminum Oxynitride (ALON® Optical Ceramic) is a transparent ceramic material which combines transparency from the UV to the MWIR with excellent mechanical properties. The addition of a small amount of nitrogen converts the rhombohedral crystal structure of alumina into the cubic spinel structure of ALON. By virtue of its cubic crystal structure, ALON has isotropic optical and mechanical properties. Consequently, ALON is transparent even in polycrystalline form, allowing it to be produced by conventional powder processing techniques. This combination of optical, mechanical properties and affordable manufacturability make ALON suitable for a range of applications including IR windows, domes, lenses and transparent armor.

ALON's manufacturing process begins with the synthesis of the ALON powder from precursor materials. The powder is then formed into a green part, using one of a number of forming techniques which includes: cold isostatic pressing, slip-casting and injection molding. The green part is then heat treated to full optical density, cut, ground and polished into a final component. A schematic of this process is shown in Figure 1.

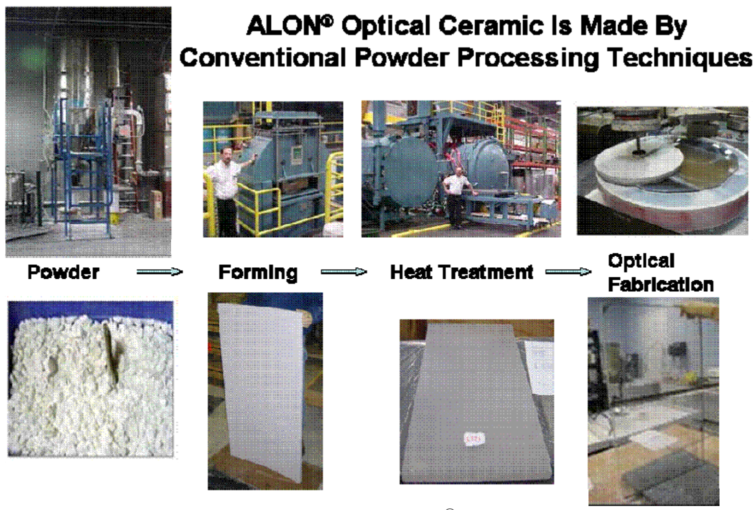

Figure 1 Schematic of process for producing ALON® Optical Ceramic

ALON® Optical Ceramic with Internal Architecture

Surmet has produced Multi-Functional ALON® windows with a wide range of internal architectures [3]. Examples of such windows include windows with internal antennas, windows and domes with internal grids for EMI shielding or heating and windows with internal cooling channels are shown in Figure 2.

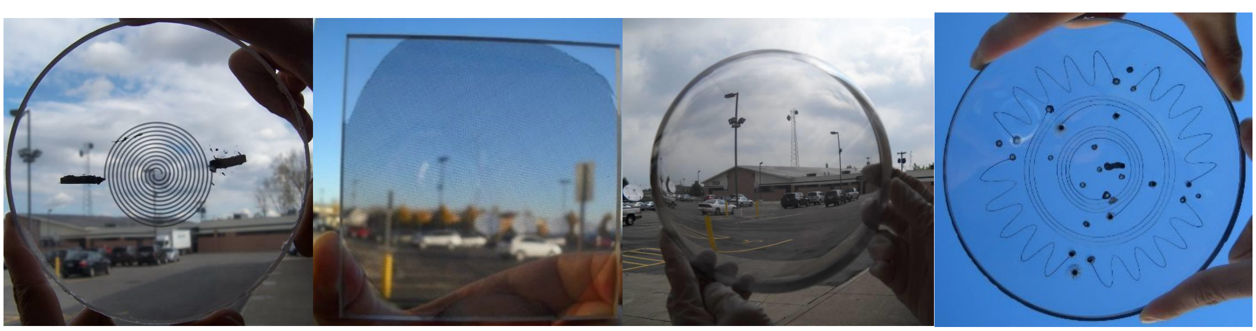

Figure 2 Examples of ALON window with internal RF Dipole Antenna (left); window and dome with embedded mesh (center) and ALON window with internal cooling channels (right)

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ALON® Optical Ceramics with varying Index of Refraction

ALON has a cubic structure, isotropic optical properties and refractive index of 1.79 [4] at visible wavelengths. Surmet has developed expertise in varying ALON's refractive index through the addition of appropriate dopants (Figure 3). By exercising precise control, both doped and un-doped ALON powder have been consistently produced. Proprietary processes follow a working model that accurately predicts the lattice constants of the as-synthesized powders (Figure 4). Additional process control enables us to vary the index of refraction in the range of 1.77 to 1.83 with excellent optical clarity (Figure 3). Additionally, transparent samples with index of refraction ranging from 1.72 to 1.85 have been processed.

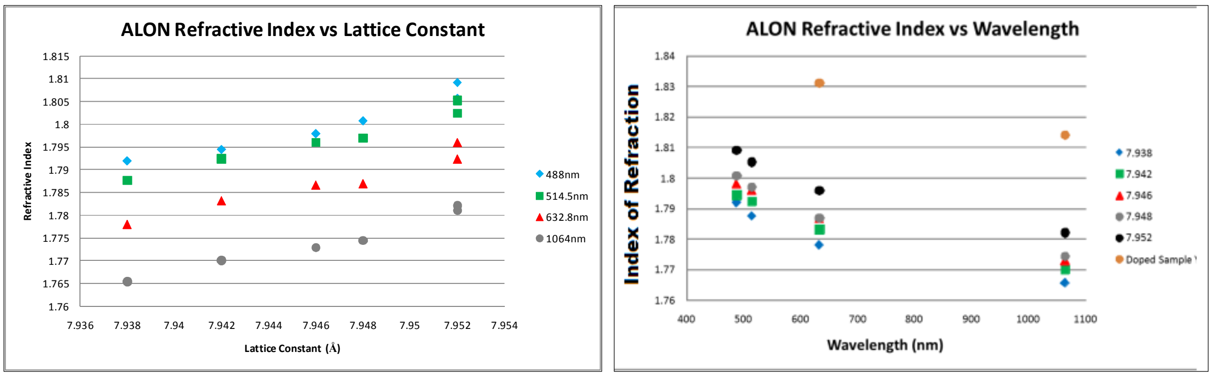

Figure 3 Variation of cubic crystal in ALON leading to change in index of refraction

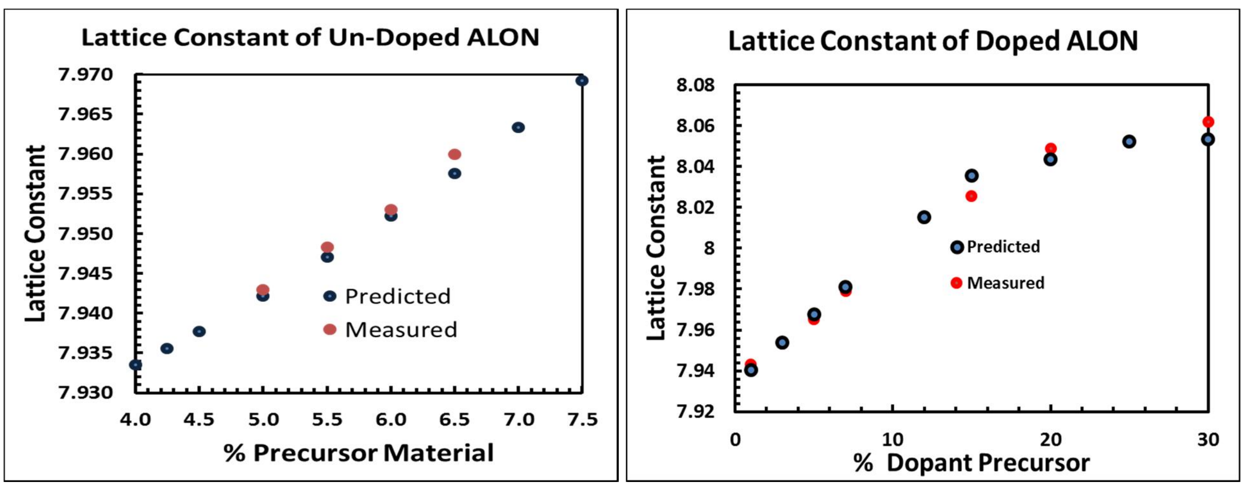

Figure 4 Surmet exercises precise lattice control over as-synthesized powders - undoped ALON® (left) and doped ALON® (right) powders

2. ALON® OPTICAL CERAMIC WITH GRADED INDEX OF REFRACTION PROFILE

ALON is transparent from visible wavelengths, through the NIR, SWIR, and MWIR wavebands. Surmet, working closely with the University of Rochester, has developed gradient index (GRIN) optics in ALON for use in the visible through the MWIR bands [5].

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Surmet has developed the ability to produce ALON® green bodies in the form of flexible tapes with precise control of thickness and composition. The flexible tapes are produced by “Tape casting” – a conventional ceramic powder processing technique which permits thickness control. Surmet with adequate process control has demonstrated flexible tapes ranging from 30-2000μm in thickness. These flexible tapes can be cut into shapes, laminated together and heat-treated to transparency as shown in figure 5. By layering few tapes or by layering more than 60 tapes, samples have been fabricated from 1 – 20 mm. Thicker blanks (>45mm) have also been processed to fabricate prism for measurement of optical dispersive properties (Figure 5).

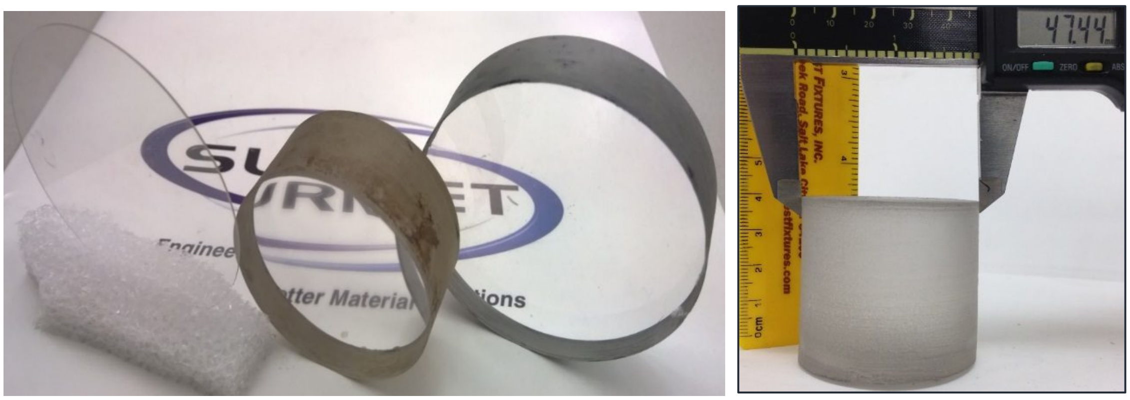

Figure 5 Homogenous Undoped and Doped ALON processed from thin ~500μm tapes. Samples of 2-20mm thickness have been processed to high optical clarity (left) and blanks up to 48 mm thickness (right) have processed to fabricate prisms for dispersion measurements

Surmet has developed the capability to produce a graded refractive index (GRIN) profile by layering tapes of different powder compositions in a defined axial or radial geometry to form a laminate (Figure 6). Using carefully controlled heat treatment processes, the interfaces between varying layers are eliminated to yield a high quality optical material. Stepwise discrete transitions between adjacent layers are smoothed out through dopant diffusion during heat treatment (Figure 7). Through the appropriate selection of tape thicknesses, compositions and dopant levels, continuous and smooth refractive index gradients have been achieved.

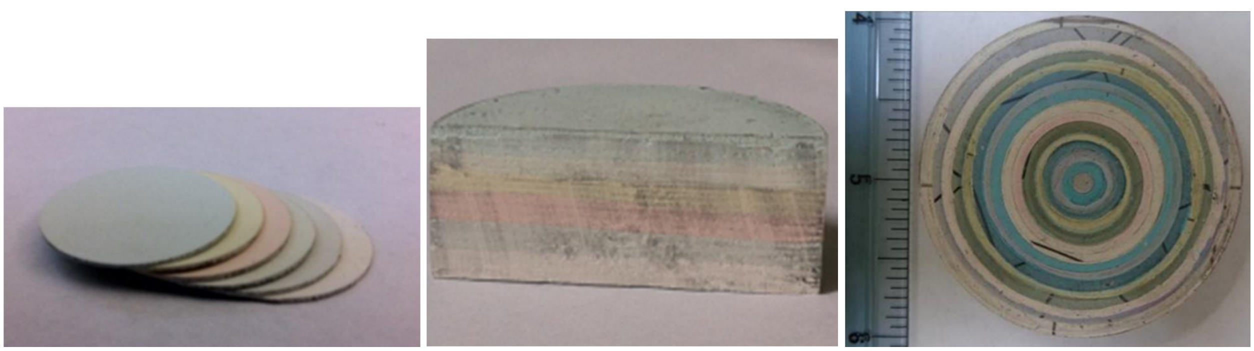

Figure 6 ALON® compositions processed as thin tapes are cut into discs (left) and laminated in axial (center) or radial (right) stacks. The stacking sequence of compostions control the resultant GRIN profile

Along with the development process technologies, appropriate metrology tools have also been developed to analyze the resultant GRIN profile. The GRIN profiles are measured using a single pass Mach–Zehnder interferometer wherein, the interference patterns are dependent on the index change, the thickness of the sample and the wavelength of the laser source.

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Through the addition of various dopants to ALON, Surmet has demonstrated the ability to vary the index of refraction of ALON. Using a single dopant, Surmet has demonstrated smooth axial and radial gradient profiles in refractive index (Δn ~ 0.028), over depths of 1-8 mm in axial (Figure. 8) and over 20 mm in radial (Figure 9). In creating larger radial GRIN profile (Δn ≥ 0.05 over 40 mm), Surmet has relied on radial stacking of multiple ALON compositions and subsequent diffusion to achieve a continuously varying index of refraction profile. In one such example (Figure 10), four rings with differing dopant compositions were layered together and heat treated to achieve Δn of 0.055 over 40 mm. The four rings have been selected with compositions spaced apart to achieve a "staircase profile". Presently, necessary tools and process are being developed to select appropriate compositions and stacking sequence to achieve a smooth radial profile of ~0.05 over a distance of 40mm.

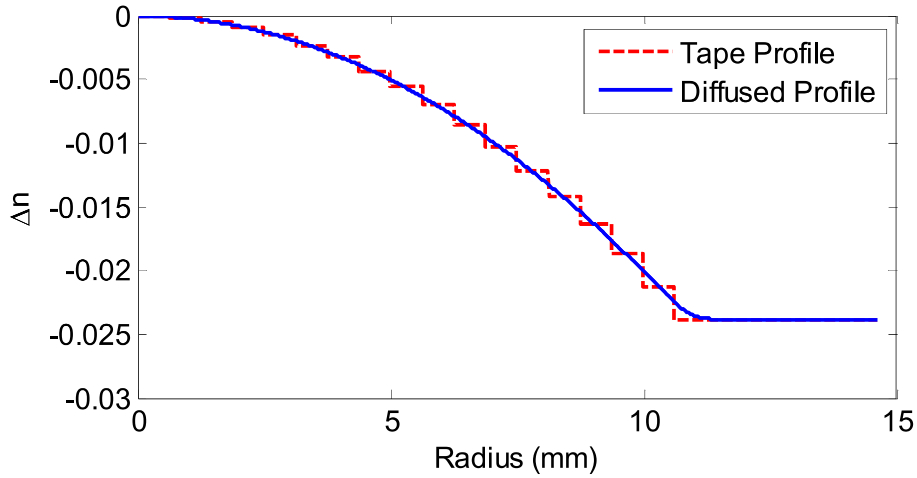

Figure 7 Modeled Diffusion Profile with 0.75mm Radial Step Size. The modeled diffusion profile matches design profile refractive index to within $4x10^{-6}$ P-V

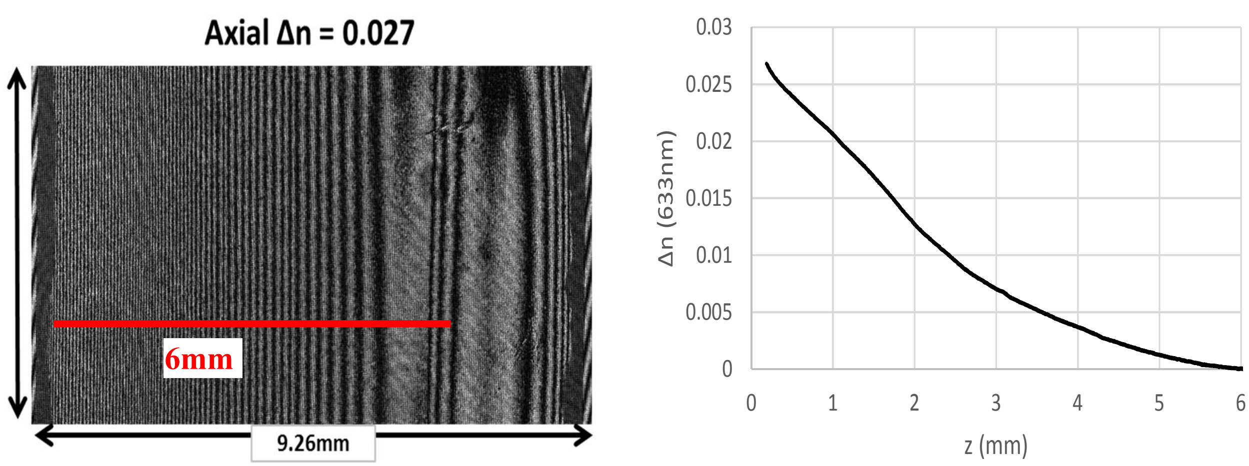

Figure 8 Axial GRIN profile generated by diffusion between multiple layers with differing compositions

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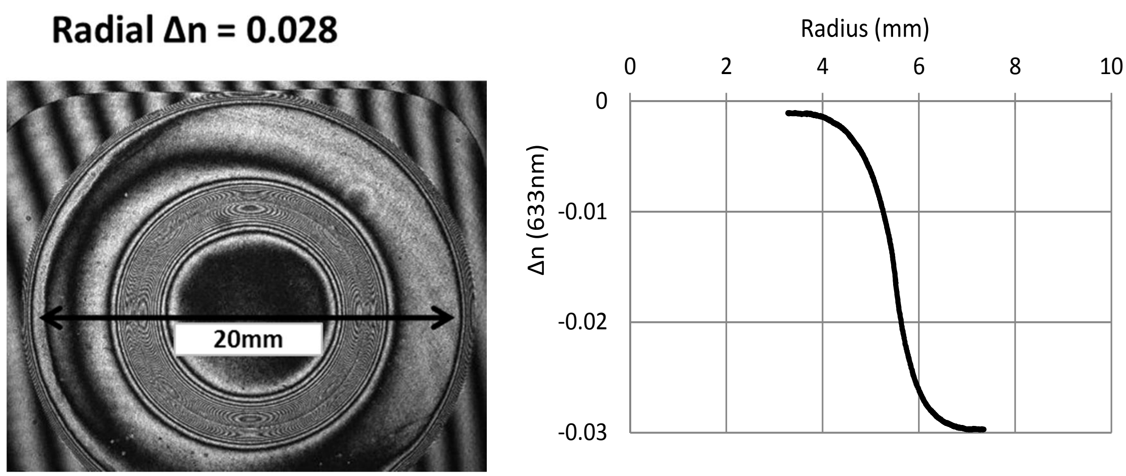

Figure 9 Radial GRIN profile in a diffusion couple between two different dopant composition

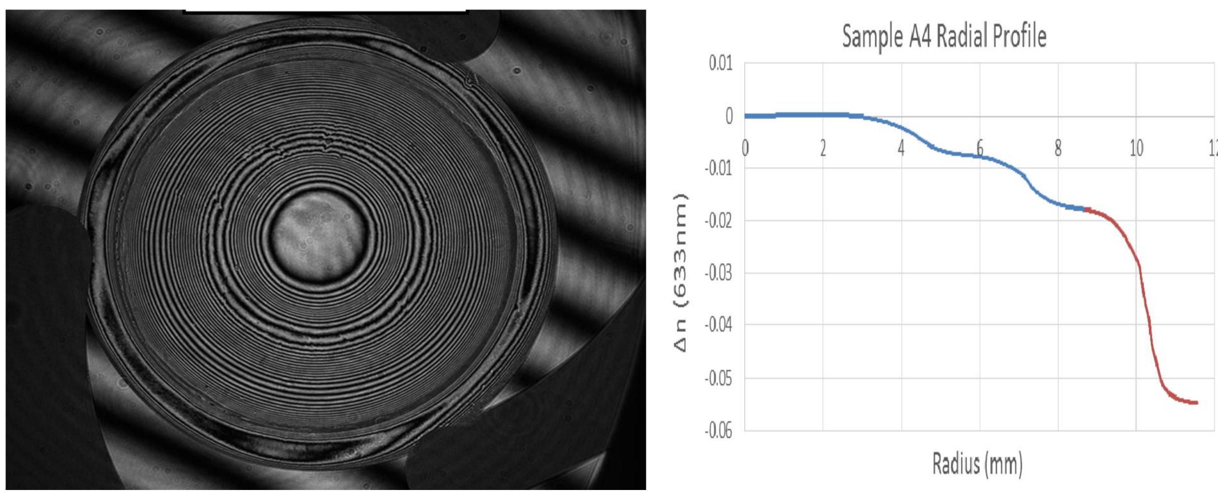

Figure 10 Radial "Staircase" GRIN profile by diffusion through 4 radial rings with differing compositions

3. BENEFITS OF ALON® GRADED INDEX OF REFRACTION PROFILE

Preliminary analysis suggests that as a single element with a radial gradient, to achieve color correction, ALON will be most useful in the 0.8 to 3 micron region [6]. Figure 11 shows the dispersion of the homogeneous ALON material and the ALON gradient as a function of center wavelength. A single GRIN element has two contributions to optical power with separate chromatic properties, essentially acting as a doublet in a single element, as shown in Figure 12. The power required in each element of an achromatic doublet is inversely proportional to the difference in Abbe number between the two components. The difference between the homogeneous and GRIN Abbe numbers for ALON is largest at a center wavelength of 1.5 µm, leading to the smallest optical power magnitudes for a color corrected system. Further, alternative materials are not transparent throughout this wavelength range pointing to ALON as the only potential GRIN option for improving broadband imaging performance over this waveband.

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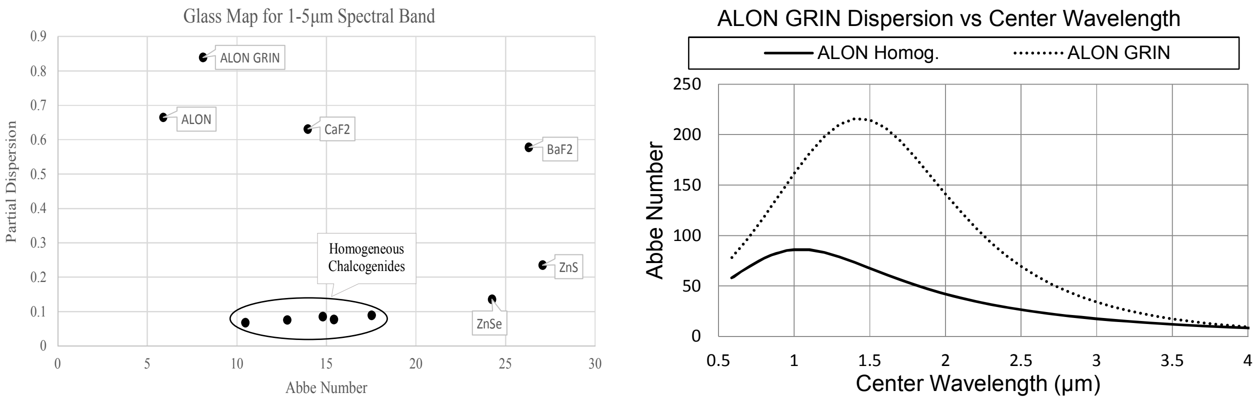

Figure 11 Dispersion of the homogeneous ALON material and the ALON gradient as a function of center wavelength

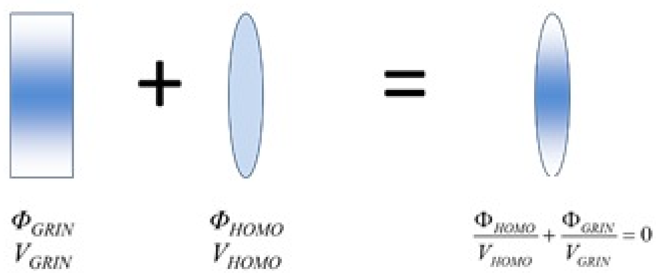

Figure 12 Chromatic Benefits of Radial GRIN

4. DESIGN WITH ALON® GRIN OPTICS

ALON® GRIN optics can be used in multispectral applications and initial design studies have shown ALON GRIN elements to provide uniquely advantageous color correction characteristics over multispectral wavebands [7]. The new material option and degrees of freedom are expected to be beneficial in the design of broadband imaging systems and could result in improved performance with a given element count, or, reduced size, weight, and element count, while maintaining the desired first-order specifications and performance. Figure 13 shows a design example where a traditional doublet can be replaced with an ALON axial GRIN singlet in order to improve performance and gain multi-spectral operation in a laser collimator application [8, 9].

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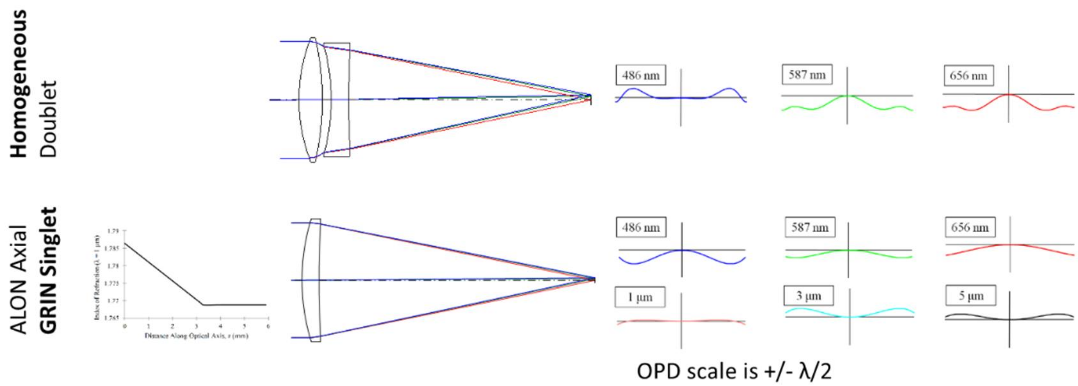

Figure 13 Example of Axial GRIN ALON® singlet benefit over a homogenous doublet [8, 9]

University of Rochester is actively engaged in incorporating ALON® GRIN optics into commercial lens design software. As shown in figure 14, homogeneous ALON samples with different lattice constants have been measured in the visible spectrum and mid-wave infrared. These measurements have been used to confirm the ALON index model that is used in Code V to properly constrain the chromatic properties of the gradient. Figure 13 below shows a comparison of the measured dispersion curves (with Sellmeier fit) for two significantly different ALON composition (corresponding to lattice constants of 7.938Å and 7.952Å). Further refractive index data with improved precision and spectral sampling are to be obtained on homogeneous prisms of various concentrations using the minimum deviation method.

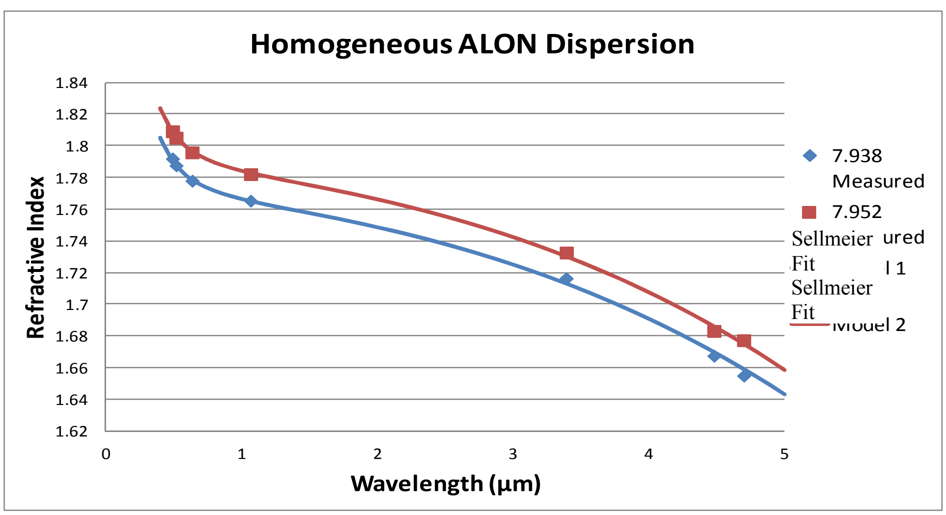

Figure 14 Sellmeier fits for two homogeneous ALON samples with different lattice constant

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5. SUMMARY

Surmet has made substantial progress in its ability to manufacture large ALON® sensor windows, lenses, domes and transparent armor. Working with the University of Rochester, Surmet has developed gradient index (GRIN) optics in ALON for use in the visible through the MWIR bands. Surmet has demonstrated the ability to tailor the refractive index of the ALON® material by either varying its composition or through the addition of dopants. Surmet developed smooth axial and radial gradient profiles with ~0.055 change in refractive index, over depths of 1-8 mm (axial) and over 20 mm radius (radial) by varying dopants and layering patterns. Initial design studies with ALON GRIN showed the ability to provide uniquely advantageous color correction characteristics over multispectral wavebands. Radial gradients in particular, with their optical power contribution, are expected to provide additional degrees of freedom for color correction in broadband imaging systems. Applications for such an advanced ceramic include military and commercial systems.

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