NEW OPTICAL ARCHITECTURES

A range of new manufacture methods promise gradient-index (GRIN) lenses of arbitrary distribution and an expanded range of refractive index variation. These novel materials offer a new class of optical systems with improved size and mass and reduced optical component count. The new GRIN processes also offer opportunities in both visible and infrared wavebands. In this article, we explore the new optical architectures enabled by these new degrees of freedom, such as multispectral imaging optics and low-mass avionic displays, as well as the challenges ahead in design, manufacture, metrology and environmental qualification to bring this technology to mass production.

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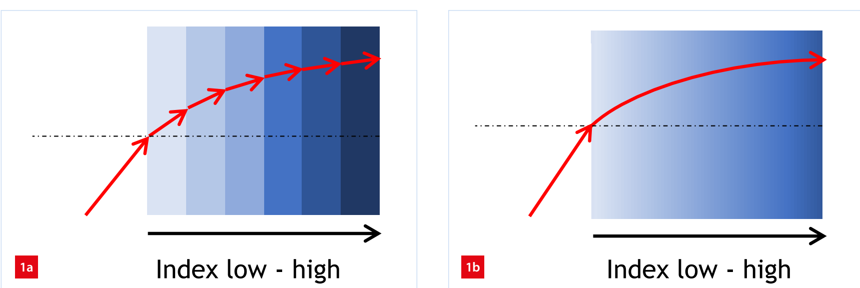
Introduction

Gradient-index (GRIN) optics make use of continuous variation in their refractive index as a function of space to effect an optical function. Notably, they have the effect of forcing light to follow curved trajectories through the gradient-index medium. An intuitive explanation of this effect is shown in Figure 1. A set of plates with discrete and incremental refractive index causes light to progressively refract more into a material according to Snell's law (Figure 1a).

We consider the case where the number of plates tends towards infinity (Figure 1b). The increment in refractive index becomes smaller and the length of each ray segment correspondingly so. The result is a smooth curve in the ray paths, or continuous refraction.

A similar example is shown in Figure 2. This time, we consider a similar arrangement of nested tubes of incremental refractive index. As the variation in index is now perpendicular to the direction of the light, we must consider this system in terms of wavefronts. Higher refractive indices cause light to slow down more, and the resulting effect on an incident wavefront is similarly shown in Figure 2, where a higher refractive index causes the centre of a wavefront to lag behind the edge. Applying the same principle of making the nested tubes progressively finer in width and index, we see that the wavefront becomes curved; we have created a focusing lens.



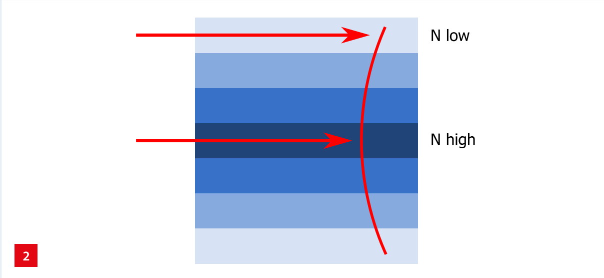
Light refraction.
(a) Refraction into a discrete set of plates of incremental refractive index.
(b) Smooth continuous refraction in the case where the number of plates tends to infinity.

More rigorously, light in gradient-index media propagates according to Fermat's principle, whereby the optical path length of any local ray trajectory is an extremum. The trajectories of rays in general GRIN media are calculated by numerical solution of a second-order differential equation, with analytical solutions only existing for some well-known examples, such as the fisheye lens of James Clerk Maxwell.

GRIN in nature

GRIN effects are widely observed in nature. Mirages are a GRIN effect generated when a thermal gradient causes a refractive index (N) gradient in the air above a hot road or similar surface. In an imaging context, GRIN is observed very widely in the biological eye. All biological eyes measured to date feature some kind of GRIN [1], with the effect particularly prevalent in aquatic organisms that must see in low light levels while the refracting power of the cornea is diminished by immersion in water.

For example, goldfish (N = 1.35-1.56) and octopus (N = 1.357-1.51) have very strong index gradients. Notably, the eyes of these two organisms are examples of convergent evolution, where both have evolved similar imaging structures after diverging from a common ancestor. GRIN lensing was first observed however in the compound eyes of insects by Exner and Matthiessen, which is where the story of synthetic GRIN lenses begins.



Curvature (and therefore optical focusing power) imparted to a wavefront by propagation through a radially varying refractive index.

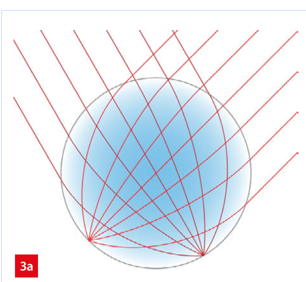
GRIN lens manufacture and use to date

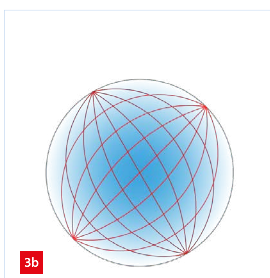
Exner and Matthiessen also observed they could artificially generate the focusing effect seen in insect eyes by soaking gelatine cylinders in water. This process was further refined by Robert W. Wood, who developed focusing GRIN cylinders with planar faces, which we now refer to eponymously as a Wood lens [2].

Across a similar timeframe, the potential of GRIN media for aberration correction of imaging systems was observed by several authors. Famously, the perfect imaging systems of Maxwell and Luneburg (Figure 3) showed how GRIN media could be used in optical systems, although no optical technology could create them at the time.

The foundations of aberration theory for GRIN media were laid by Buchdahl [3]. This set the scene for a flurry of research activity in the latter half of the 20th century, as computational ray-tracing allowed analysis of more general GRIN problems when it was realised that GRIN lenses could provide improved aberration correction over systems of spherical lenses, potentially reducing size, mass and cost or improving image quality. In more modern times, these improvements fall under a widely adopted industry acronym, SWaP-C (size, weight and power, for minimised cost).

A myriad of GRIN manufacture techniques and designs were generated during this time [5]. Techniques such as ion-exchange/stuffing, neutron irradiation and CVD growth all showed promise as means to prepare GRIN lenses.





Perfect imaging designs [4].
(a) Luneburg.
(b) Maxwell.

Concurrently however, the development of cheaper aspheres (that offered comparable theoretical SWaP-C improvements to GRIN) through processes such as CNC polishing, diamond turning, and injection moulding meant that GRIN lenses were commercially restricted to niche commercial applications, such as precision borescopes, coupling lenses, copier arrays, and most ubiquitously, optical fibre. Processes developed during this period were less well suited to large-diameter lenses required in more general imaging applications.

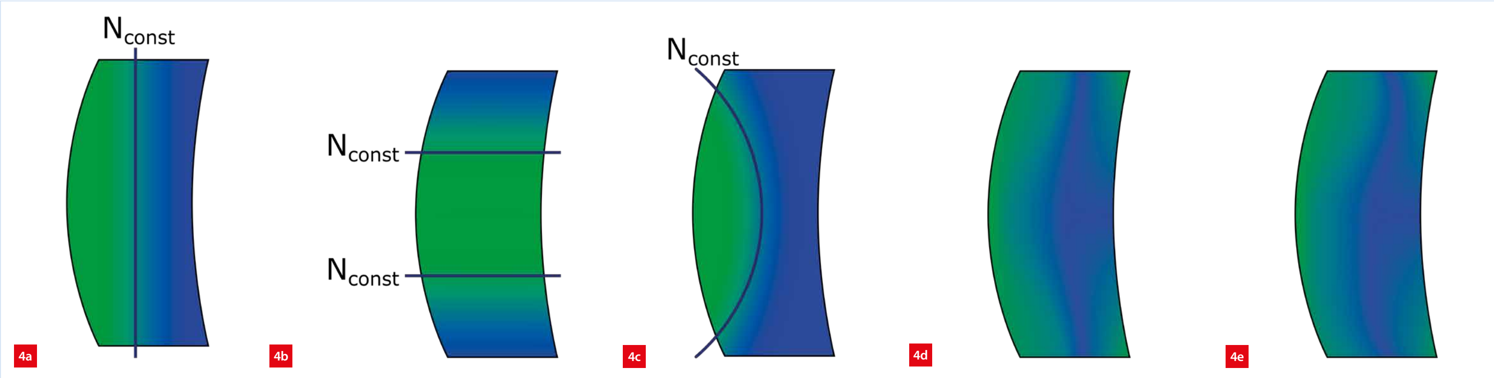
New GRIN technologies

In the 21st century, new industrial technologies in adjacent fields have enabled new means to generate GRIN lenses (Figure 4). Multilayer co-extrusion of polymers enabled a new layer-based GRIN technology allowing manufacture of spherical and axial GRINs with arbitrary index distribution in one dimension (Figure 4c) [6].
Additive manufacture has enabled new processes for the assembly of GRIN media from multiple base materials and with arbitrary distribution [7][8], while the industrialisation of ultra-fast laser pulses has allowed the development of means to directly "write" index variation into homogeneous optical materials [9][10].

It is the generation of an arbitrary GRIN distribution with increased index variation (often referred to as ΔN) that is a particularly exciting prospect for GRIN optics, allowing new applications where GRIN offers benefits beyond those of aspheres or diffractive surfaces. In the past, GRINs tended to belong to one of a few basic distribution types, such as axial, radial, or spherical (as shown in Figures 4a and 4b), with fine control of the index distribution dictated by natural processes such as diffusion. This ultimately limited the distribution and ΔN of the GRIN, and with it, the aberration correction potential.

With these new emerging technologies, previous limitations are progressively being overcome, with manufacture of an arbitrary GRIN distribution (Figures 4d and 4e) now a reality. ΔN in excess of 0.2 is now offered by several GRIN processes. Excitingly, additive manufacture processes also enable tailored control over the chromatic dispersive properties of the GRIN. Chromatic aberration is generated by all conventional singlet homogeneous lenses when presented with a finite waveband. Blue light is refracted more than red light resulting in the focus shifting for each wavelength in the system (Figure 5a).
A well-known metric by which the dispersive properties of optical materials are measured is the Abbé V value, defined for three sequential wavelengths spanning the waveband of the design problem of interest ($\lambda_{short} < \lambda_{mid} < \lambda_{long}$):

$$V = (N_{mid} - 1) / (N_{short} - N_{long})$$



GRIN distribution types with increasing manufacture complexity from left to right.
(a) Axial.
(b) Radial.
(c) Spherical.
(d) General rotationally symmetric.
(e) Freeform.

For visible waveband materials, the quantities N_d and V_d are very widely used. N_d indicates refractive index at the Fraunhofer 'd' line of 587.6 nm. The quantity V_d is defined for the Fraunhofer C, d, and F spectral lines (656.3 nm, 587.6 nm, and 486.1 nm, respectively). GRIN materials have their own V value, defined by the index delta between constituent materials at the same wavelengths:

$$V_{GRIN} = \Delta N_{mid} \,(\Delta N_{short} - \Delta N_{long})$$

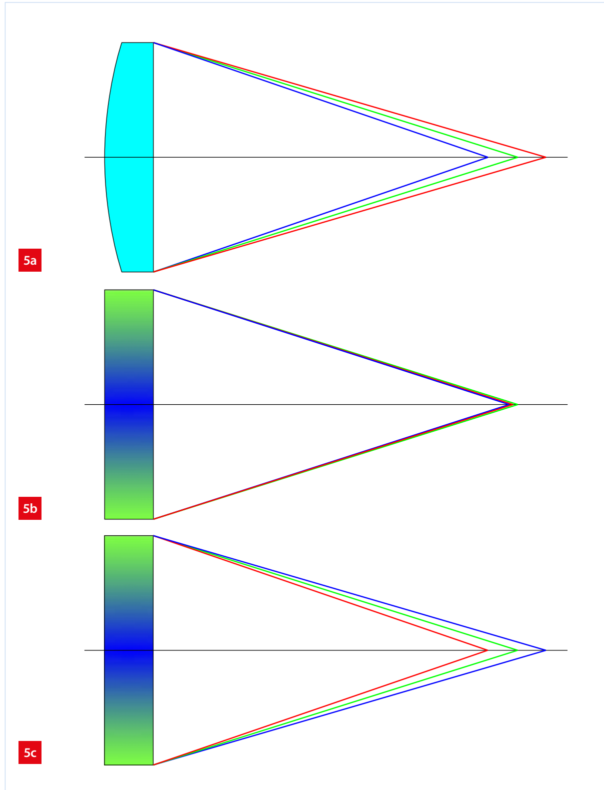
V_{GRIN} can take on a very wide range of values compared to the V value of homogeneous materials (which typically ranges between 20 and 90 for visible-waveband materials). V_{GRIN} can be very small (highly dispersive, more so than homogeneous materials), near infinite (non-dispersive, see Figure 5b) or even negative (which produces chromatic aberration of negative sign, see Figure 5c). Various quantities of example combinations of GRIN constituent materials produced by NanoVox are shown in Table 1 and Table 2. These materials are generated by doping of UV-curable monomers with refractive-index-modifying nanoparticles.

Table 1
NanoVox nanoparticle-doped polymer properties.

Material	N_d	V_d	Density (g/cm³)
VYIX1060	1.45621	24.0	1.42
VZBX2000	1.62308	46.7	1.15
VZAX1500	1.70432	18.6	1.44

Table 2
NanoVox GRIN-combination optical properties.

Combination	ΔN_d	V_{GRIN}
VYIX1060-VZBX2000	0.167	–29.52
VYIX1060-VZAX1500	0.248	13.16
VZBX2000-VZAX1500	0.081	3.32



Chromatic aberration as generated by different lens types.
(a) Conventional homogeneous lens displaying chromatic aberration.
(b) GRIN lens with near-zero chromatic aberration.
(c) GRIN lens with negative chromatic aberration.

Applications of modern GRIN technologies

With the wide variation available in chromatic properties of GRIN media, a natural key application of this technology is chromatic aberration correction. Figure 6 illustrates three common means via which this is achieved. The first, well-known means is via an achromatic doublet. Two lenses of dissimilar V values and opposing signs of focal length are cemented together such that net positive focusing power is generated, but chromatic aberration is cancelled out according to the achromatic condition:

$$1/(f_1 V_1) + 1/(f_2 V_2) = 0$$

This approach has excellent heritage, but fundamentally relies on multiple glass components to achieve this goal. This can add mass (which is critical in some applications). The spherical interface between components also generates a higher-order combination of spherical aberration and chromatic aberration known as spherochromatism (chromatically varying spherical aberration).

A second approach shown in Figure 6 makes use of diffractive optics. Diffractive surfaces are extremely negatively dispersive and are well known for their colour correction ability. They can be readily applied to polymer substrates, which can save mass, yet they typically also suffer from stray-light effects due to higher-order diffraction into spurious orders. This stray light can be objectionable in certain applications.

GRIN represents a third option for this application; due to the development of polymer-based GRIN materials, a low-mass solution can be generated, while the wide variation in chromatic properties of GRIN materials enables effective colour correction. Dependent on process, GRIN lenses can also consist of three or more materials, which also opens the opportunity to correct higher chromatic aberrations such as secondary spectrum (the residual left behind when correcting primary chromatic aberration). Ternary GRINs are also able to correct for the spherochromatism that affects conventional doublets and triplets at higher apertures.

Avionic display using freeform GRIN

A further benefit of arbitrary GRINs is that their distributions are not limited to rotational symmetry. Use of "freeform GRIN media" can be a very powerful tool in optical applications that would otherwise rely on freeform mirrors or lenses. Figure 7 shows one such example of this.

Using the materials from Table 1, it is possible to reduce the complexity of a conventional head-mounted display relay lens from six elements to two, with a corresponding decrease in the optical mass. The freeform distribution of the GRIN elements can perform the aberration correcting function of several tilted and decentred homogeneous lens elements, while the chromatic properties of the GRIN can be tailored such that the lens surfaces and medium work together to provide a colour-corrected solution. The result in this example is a 50% reduction in optical mass for equivalent performance.

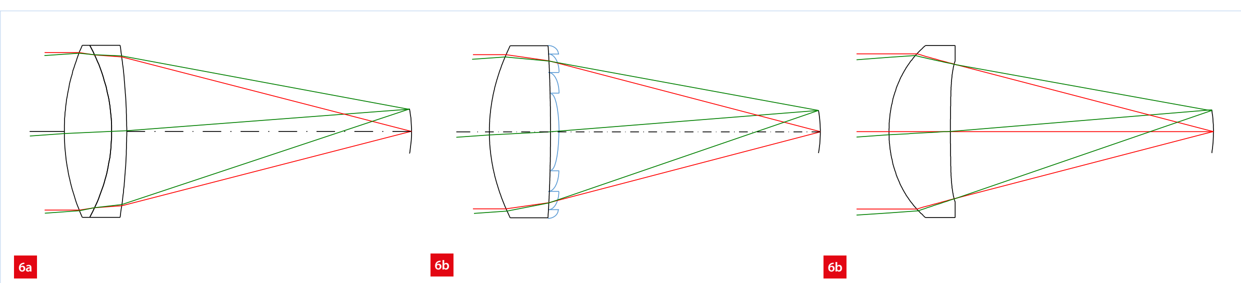
Infrared multispectral GRIN

Colour correction is one of the most powerful applications of GRIN, and this is demonstrated particularly strongly in the correction of optical systems that must image multiple wavebands simultaneously on a common focal plane. Multispectral optics suffer from two challenges: first, the wider waveband means that more degrees of freedom are required to suppress secondary spectrum and other chromatic effects; and secondly, the available material space that can be applied to an optical design diminishes as the waveband widens due to transmission loss.

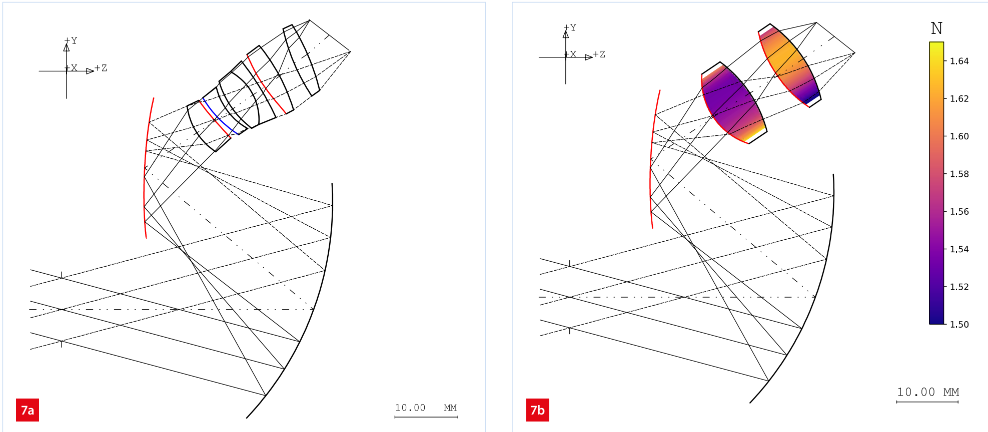
Conventional glasses and polymers are unsuitable for infrared wavelengths beyond ~2 μm, while some infrared crystals such as germanium do not transmit below 2 μm wavelength. The result of solving such an extreme optical problem with a restricted material set, is complex optics that perform poorly and can also be heavier than two single-waveband optics.

In Figure 8a, we see an example of a conventional imaging design spanning the SWIR-LWIR wavebands (1-12 μm). This design requires several toxic and fragile materials, such as the thallium crystal KRS-5, while significant aberration persists in the design. A large amount of the lens space envelope is taken up by lenses of opposing optical power.

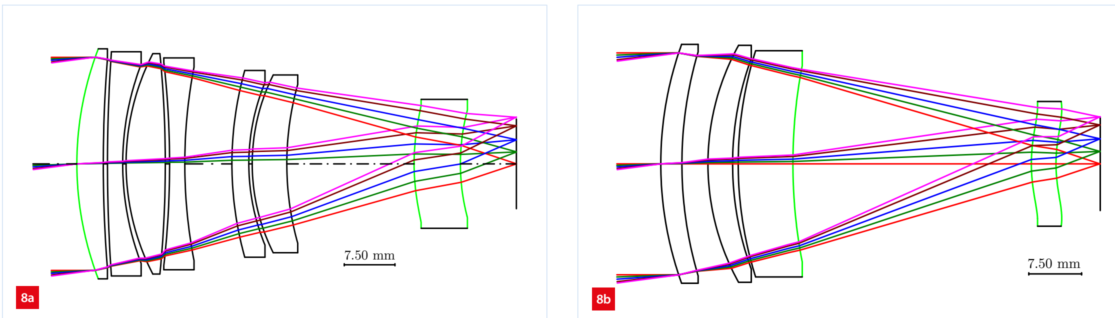
By contrast, a GRIN design effectively "collapses" the stack of lenses into a single element, by adding the positive and negative lens powers in superposition. The GRIN profile can also control higher-order chromatic effects such as spherochromatism. The end result is improved performance and significantly reduced mass, as shown in Figure 8b. The gradient-index properties of this lens are further indicated in Figure 9.



Common chromatic aberration correction techniques.
(a) Achromatic (cemented) doublet.
(b) Diffractive hybrid.
(c) GRIN.



Reducing the complexity of a head-mounted display (HMD) relay lens [11].
(a) Six-element conventional homogeneous HMD featuring aspheric and toric glass and polymer lenses.
(b) Two-element GRIN solution with freeform distributed elements.



Imaging designs spanning the SWIR-LWIR wavebands [12].
(a) Objective lens with homogeneous elements.
(b) GRIN equivalent system.

GRIN micro-optics

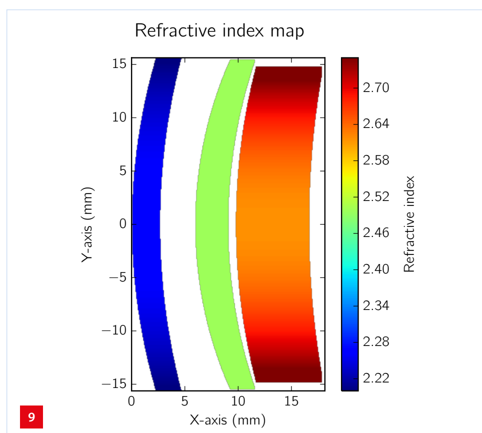
The development of targeted modification techniques allows GRIN structures to be generated even at very small length scales. Work published by Ocier *et al.* in 2020 [9] demonstrated a wide range of optical structures, by extending recent developments in direct laser writing to produce GRIN media. Their approach, which varies the refractive index by modulating laser exposure time over a porous "scaffold" medium, yields a large range of index variation ($\Delta N > 0.3$ in porous silica) with an arbitrary distribution limited spatially by the spot size of the laser. This approach led to the generation of a Luneburg lens, a first at optical wavelengths with a diameter of 15 μm. Once elegant theory, this lens is now a reality.

Challenges in GRIN

At the time of writing, GRIN materials show significant promise, yet are not widely industrialised. Some challenges remain for generalised GRIN manufacture processes. In particular, the localised means of material deposition/modification leaves behind residual errors along similar length scales. This manifests itself in the form of mid-spatial frequency errors in the wavefront of GRIN optics.

An example of such inhomogeneity is shown in Figure 10. This material was generated via 3D printing and acts like a diffraction grating at the resolution of the printer.

Substantial improvement has been made since the generation of this sample (2015), and recent results



GRIN solution lens elements, from left to right: ZnS-ZnSe crystalline GRIN, homogeneous AMTIR-1 chalcogenide glass, and IRG4-IRG6 chalcogenide glass GRIN.

published by NanoVox show wavefront errors below ten fringes when measured interferometrically, achieved by allowing some diffusion between adjacent "voxels" of material to smooth out index discontinuities. Next-generation printing technology with simultaneously increased throughput and resolution promises to address these concerns while reducing the cost of 3D-printed optics. The point at which optical quality is sufficient for use in products ultimately depends on the application and spatial frequency range of the errors, but if mid-spatial frequency wavefront irregularity as shown in Figure 10 can be reduced below approximately 0.1 fringes, then commercial applications such as eyepieces become viable.

Further challenges exist in the modelling of GRIN lenses, particularly where the optics must operate over an extended temperature range. The inhomogeneous material no longer expands linearly with temperature due to the potentially inhomogeneous coefficient of thermal expansion. Such effects can be accounted for and compensated in optical design, but require more detailed modelling approaches to form an accurate theoretical prediction of system performance.

Metrology of more advanced GRIN parts is also challenging. In principle, a null test for advanced, freeform GRIN parts can be produced through use of null aspheres and computer-generated holograms, but this adds complexity to the test equipment, and also provides limited diagnostic capability. As such, there is a need for *tomographic* metrology of GRINs that can reconstruct the index distribution of a complex GRIN part and allow the insight required to continuously improve the manufacture process.
Finally, GRIN materials must gain the credibility required to function over a full-operating lifespan and a range of environmental stressors such as temperature cycles and prolonged exposure to high-intensity light. A body of evidence that these materials are sufficiently robust is required to mitigate the risks any organisation takes when incorporating them into a system. Detailed understanding of the failure modes of these materials is needed.

Conclusions

Modern GRIN processes enable new kinds of GRIN distribution with greater variation in refractive index and dispersion. This now enables GRIN media to solve optical problems in unique ways, granting the technology a unique selling point in the optics industry. SWaP-C minimisation of optics is a particularly promising market niche.

Challenges remain for GRIN manufacture, particularly in terms of material quality, but these factors are steadily approaching the level of quality required for commercial imaging optics. Further engineering efforts are required to fully realise the potential of GRIN optics in defence and aerospace applications. These include building evidence for the long-term stability of GRIN materials under environmental stressors such as temperature fluctuations, and developing metrology techniques for complex GRIN parts such as freeform distributions.

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Reduction of wavefront irregularity.
(a) Wavefront error producing a "stripe" effect in a 3D-printed part due to structured scatter, 2015.
(b) Close-up.
(c) Transmitted wavefront error of a transmitted GRIN lens; the wavefront error is much improved as of 2021, but some structure remains.