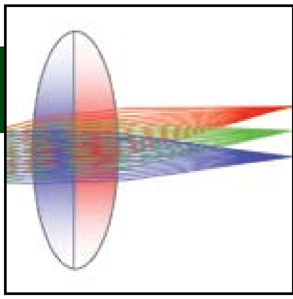

Biomimetic Gradient Index (GRIN) Lenses

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A new class of hierarchically structured polymer optical materials possessing an internal refractive index gradient that mimics biological optical materials is described. The new materials permit the fabrication of gradient refractive index (GRIN) lenses with an unprecedented variety of index gradients. Gradients with different functional forms in both the radial and axial directions have been fabricated. Materials with gradients with a $\Delta n \sim 0.17$ have been made, and larger index ranges are possible. Flat GRIN lenses and shaped lenses with specified internal index gradients have been fabricated from the new materials. The new polymer materials show promise for use in optical systems that have fewer, lighter lenses than traditional lens systems. They encourage the exploration of new paradigms for bio-inspired optical designs that could not be implemented by using homogeneous lens materials.

The fabrication of practical GRIN polymer optical materials involved a series of advances. The first was the recognition that a transparent polymer film with a specified refractive index could be fabricated using nanolayer polymer extrusion technology. The nanolayered films are stacked to create a material with an index gradient defined by the order in which the different nanolayered films are stacked. The stacking order, and thus the gradient, can be defined as desired. These materials are then molded into the GRIN lenses. To take advantage of the ability to construct a specific index gradient in a shaped lens, an optimum index gradient for such lenses had to be designed.

These new materials facilitate the application of GRIN optics to a variety of optical systems and devices. They support the development of bio-inspired lenses and optical systems. The wide range of lens shapes and index profiles that can be fabricated gives an optical designer substantial control over the focal properties of each lens.

INTRODUCTION

Optical systems capture light and use it to produce images with information about the environment. In nature, each set of optics is tailored to fit the specific needs of its owner. Optics inspired by nature's designs have an enormous potential for transforming the process of image collection.[1] A DARPA program, Bio-Optic Synthetic Systems, has the goal of demonstrating the power of such bio-inspired optical concepts.

Eyes for different species are adapted for seeing in the day or night, short or long distances, or with wide or narrow fields of view. Nature tends to optimize these systems to provide the optics required for survival. Eagles have acuity at long distances and the ability to maintain a focus during a rapid descent. The eyes of the prey monitor a wide field of view and permit it to detect an attacker early enough to allow an escape. Human eyes can produce quite high-resolution, relatively aberration-free images with only two optical components, the cornea and the crystalline lens. We perform this imaging feat both close up and at long distances, providing the lenses in question are not over about 40 years old.

Natural optical systems have a feature not usually found in man-made imaging technologies. Bio-optical materials are formed by hierarchical layered protein structures. These give rise to index gradients that can enhance focusing power, correct aberrations, and reduce the number of components needed for an effective optical system. We have developed a new class of nanostructured polymer optical materials that can mimic the layered protein structures found in biological materials. These materials enable the fabrication of a new class of polymer GRIN lenses, lenses that possess a variation in the refractive index within the material.

The new materials enable us to incorporate this important feature of biological vision systems into man-made optical systems. The first examples of the new polymer GRIN optics include single lenses inspired by cephalopod (octopus) eyes and a three-lens, wide field of view, optical system for a surveillance sensor.

GRADIENT REFRACTIVE INDEX OPTICS

Traditional optical materials are homogeneous; the refractive index is uniform throughout the material. In such a lens, a light ray is refracted at the lens surface where there is an abrupt change of the refractive index from air. The imaging properties are determined by the surface shape. GRIN optical materials possess a variation or gradient in the refractive index within the material. The variation of the refractive index within the material causes light rays to be bent within the lens. With a GRIN lens, focusing and imaging depends on how the refractive index varies within the lens material (Fig. 1). GRIN lenses can also be shaped like traditional lenses. Then the focal properties depend both on the surface shape of the lens and on the index gradient within the material.

The theory of gradient index optics is well known.[2] R.W. Wood described a flat radial GRIN lens in 1905.[3] It has been long recognized that GRIN elements add considerable power and flexibility to the design of optical systems. Because GRIN lenses can have flat surfaces, they are useful in optical systems where this geometry allows the simplified assembly of systems of lenses. Varying the thickness of the lens can vary the focal length and working distance. The image plane can be made to lie directly on the exit surface of the lens. Unlike conventional lenses, GRIN lenses can maintain their focusing ability under water.

A traditional lens designer can vary the curvatures, the thickness, and the refractive index of the material. In addition, a GRIN lens designer can also use index gradients to simplify or enhance the optical system. For example, axial gradients, where the index of refraction varies along the optical axis can perform the same functions as an aspheric surface in a traditional lens. A traditional lens design that requires an aspheric surface can be replaced with a spherical surface that is substantially easier to form and polish if an axial gradient is introduced. Even more useful are radial gradient lenses, where the index of refraction is a function of the distance from the center of the lens. Radial gradients can add focusing power and control specific aberrations.

NANOLAYER POLYMER GRIN MATERIALS

Despite the appeal of GRIN optics, actual applications have been limited to fiber optics and small lens systems. This is primarily because the fabrication of materials with a sufficient and controllable refractive index gradient over a 1- to 2-cm diameter lens has not been very practical. In earlier GRIN materials, the index gradient was typically formed by a diffusion process or a copolymerization process in a polymer. The index gradient that can be achieved with such processes is determined by diffusion and is often quite small.

The initial step in the development of the new GRIN materials was the recognition that a transparent polymer film with a specified refractive index could be fabricated using microlayer polymer coextrusion technology. The process, described in the sidebar, has been known for more than 35 years.[4,5] Beginning in 1969, a series of patents and publications describe a coextrusion process using layer-multiplying dies that can produce large sheets of layered polymer materials with hundreds of layers. The process was further developed by Baer and coworkers at Case Western Reserve University.[6] Their recent advances enable the facile production of nanolayer polymer materials with tens of thousands of layers and layer thicknesses as small as 5 nm.[7] This continuous process produces layered polymer materials in the form of flexible sheets and films with large surface areas.

The utility of coextrusion to produce optical materials arises from the variety of polymers and polymer dopants that can be used to make nanolayered polymer materials. Practically, the polymer components are limited to those that mutually adhere and have compatible processing properties. Even with these restrictions, however, it is possible to choose polymer pairs so that the materials in the alternating layers have substantial differences in the index of refraction (n). The resulting layered materials possess a modulation in the index with a period corresponding to the layer thickness.

The layered polymer materials are of particular interest for optics when the layer thickness and thus the period of the modulation in the index is either (A)

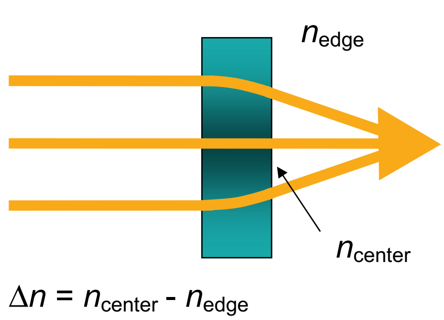

FIGURE 1
Focusing by an index gradient alone.

Microlayer Polymer Processing

The basic ideas of the nanolayer processing are shown in Fig. S1. The two-component coextrusion system consists of two single-screw extruders, each connected by a melt pump to a coextrusion feed block. The feed block combines polymer A and polymer B as two parallel layers. By adjusting the melt pump speed, the relative layer thickness, that is, the ratio of A to B, can be varied. From the feed block, the melt goes through a series of multiplying elements. The multiplying die (Fig. S2) first slices the AB structure vertically, then subsequently spreads the melt horizontally. The illustration shows how the flowing streams recombine, doubling the number of layers. An assembly of n multiplier elements produces an extrudate with the layer sequence $(AB)x$ where x is equal to $(2)^n$. Nanolayered structures with up to 4096 layers have been successfully processed, and more are possible. By altering the relative flow rates or the number of layers while keeping the film or sheet thickness constant, individual layer thickness can be controlled. Nanolayered film or sheet with overall thickness ranging from 0.5 to 60 mils has been processed, and samples with individual layer thickness less than 5 nm have been produced.

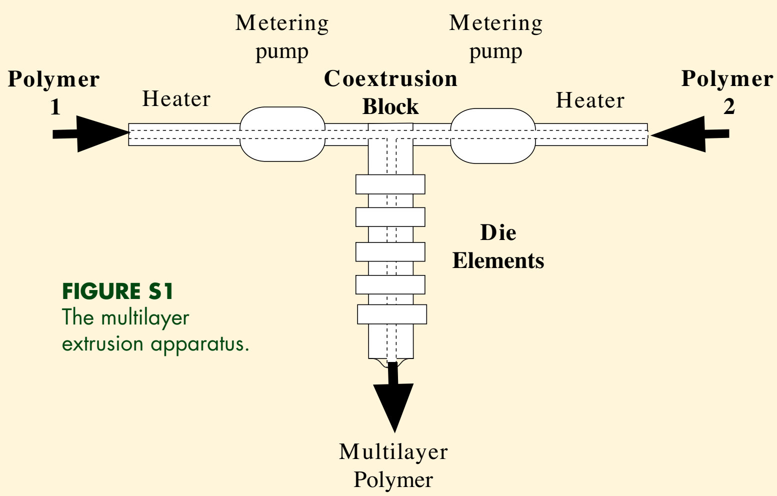

FIGURE S1
The multilayer extrusion apparatus.

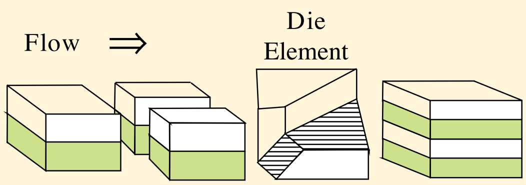

FIGURE S2
Details of a die.

on the order of the wavelength of light or (B) shorter than the wavelength of light of interest. The two cases are illustrated in Fig. 2. In the first case, when the modulation period and layer thickness are $\lambda/4n$, the materials show a high reflectivity at the wavelength λ. They are effective dielectric reflectors or 1-dimensional photonic crystal materials. The reflected wavelength can be selected by varying the layer thickness. In the second case, where the layer thickness is less than $\lambda/4n$, the optical properties are that of an effective medium composite.[8] The refractive index and transmission are an average of those of the component materials.

In case A, when the layer thickness is $\lambda/4$, this technology has been commercialized to make a variety of polymer dielectric reflectors and filters with specific transmission properties and passbands.[9] The extrusion process is well-suited to making large-area reflectors that are difficult to make by using traditional techniques. Layered birefringent polymers yield polarization-selective reflectors that are commonly used to enhance the brightness of laptop computer displays. They also can be used to produce dielectric mirrors that maintain reflectivity over a broad band of incident angles[10] and are useful as light pipes. These layered polymers have also been used to create an iridescent Christmas tinsel.[11]

To fabricate the materials of interest for gradient refractive index materials, the layer thickness is

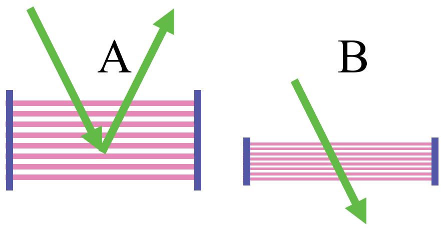

FIGURE 2
Optical function of layered polymer materials. (a) Layer thickness equal to $\lambda/4n$: dielectric filters and mirrors; (b) Layer thickness much less than $\lambda/4n$: effective medium composite.

chosen to be 50 nm or less so that the films do not reflect visible light. In this thickness range, the material properties are described by effective medium theory. The refractive index of the layered film corresponds approximately to a thickness-weighted average of the indices of the component polymers. Figure 3 shows the refractive index of a set of 101 films fabricated by layering polycarbonate (PC) (n = 1.58) and polymethyl methacrylate (PMMA) (n = 1.49) as components. The films were about 50 μm thick overall and had 2048 layers, so that the thickness of an individual layer in the material with equal amounts of PC and PMMA, for example, is about 25 nm. The composition of the polymer film can be varied by adjusting the relative thickness of the different polymer layers. Figure 3 shows that the observed index varies linearly with the composition (relative layer thickness), demonstrating that it is possible to make a polymer film with a refractive index selected to be any value between the indices of the component polymers. The index difference between any two sequential films is small; in this case, the smallest index difference is 0.0009. Such nanolayered composites can be made to be quite transparent; transmissions between 85% and 90% are common. To our knowledge this is the most practical way to fabricate layered composite polymer films with layers thin enough that the material behaves as a transparent effective medium.

A polymer with an index profile is made by stacking a set of such nanolayered polymeric films. The films are stacked in the order that gives the desired index gradient. Figure 4 shows the steps in the process. For example, by sequentially stacking a single film of each of the 101 compositions starting with a pure PMMA film, then one with a 99/1 ratio of PMMA to PC, then a 98/2 ratio, to the 101st layer that is pure PC, a polymer with a linear refractive index gradient varying from 1.49 to 1.58 was made. Notice that this material has a hierarchical structure. It is an ordered array of 50-μm thick composite films; on a finer scale, each of these composite films is made up of 2048 layers of alternating PC and PMMA with a layer thickness of a few nanometers.

More complex index gradients can be made by changing the order in which the nanolayered films are stacked. The final GRIN material typically contains more than 200,000 nanolayers, a number comparable to the number of protein layers found in the biological lenses. The sets of stacked polymer films are consolidated to produce a transparent thick sheet of material with the desired index gradient.

As illustrated in Fig. 4, the gradient is normal to the surface in the consolidated material. Observed from the side, a linear gradient gives a GRIN prism and a parabolic gradient gives a GRIN cylindrical lens. A lens machined from this polymer will have a refractive index gradient in the axial direction. A radial variation in index can be introduced by the molding process illustrated in Fig. 4. A plano-convex lens with both radial and axial gradients can be made by shaping the appropriate preform to the desired curvature, then cutting and polishing the shaped lens.

DESIGNING POLYMER GRIN LENSES

To take advantage of our ability to construct a shaped lens with a specific index gradient, it was necessary to design the lens shape and index gradient. The initial example was a lens designed to demonstrate that a nanolayer polymer GRIN lens, with a proper gradient, can provide both focusing and aberration correction within a single lens. Figure 5 illustrates this strategy.

The starting index profile for the optimization was inspired by that found in many biological eyes, for example an octopus eye. The octopus lives in water, where the refractive index is close to that of the protein on the surface of the eye (Fig. 6). The curvature of a lens is less effective at focusing under water than in air. The octopus solves the problem with an eye that has thousands of layers of protein with different refractive indices. The index gradient gives the octopus the focusing capability and aberration correction needed.

In the octopus, the index gradient was optimized by natural selection. The Navy is not so patient, so an appropriate gradient was designed using the optical ray-tracing program, ZEMAX. The index profile in the first model lenses was designed to provide aberration correction but not underwater operation. As we develop polymer sets with a larger index contrast, it may be possible to extend this design to underwater lenses.

In one lens design, different gradients were used for each half of the lens. The index gradients are shown in Fig. 7. The rationale for the optimized gradient is easy to understand. Spherical aberration is reduced

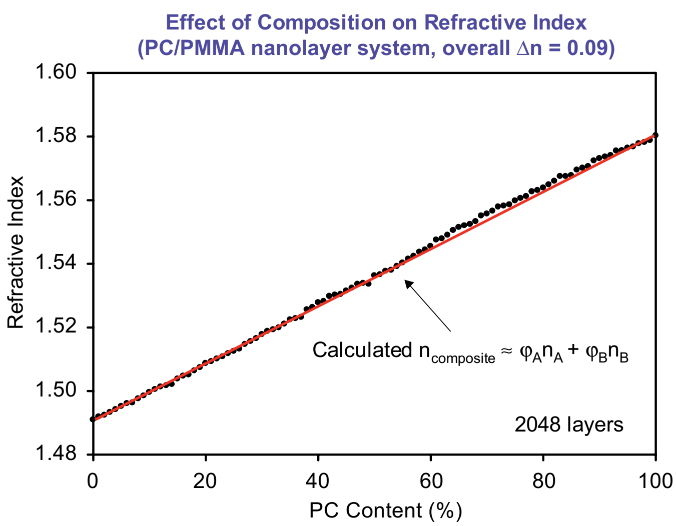

FIGURE 3
Refractive index of a set of films made of layered polycarbonate (PC) poly methylmethacrylate (PMMA) as a function of relative layer thickness/composition.

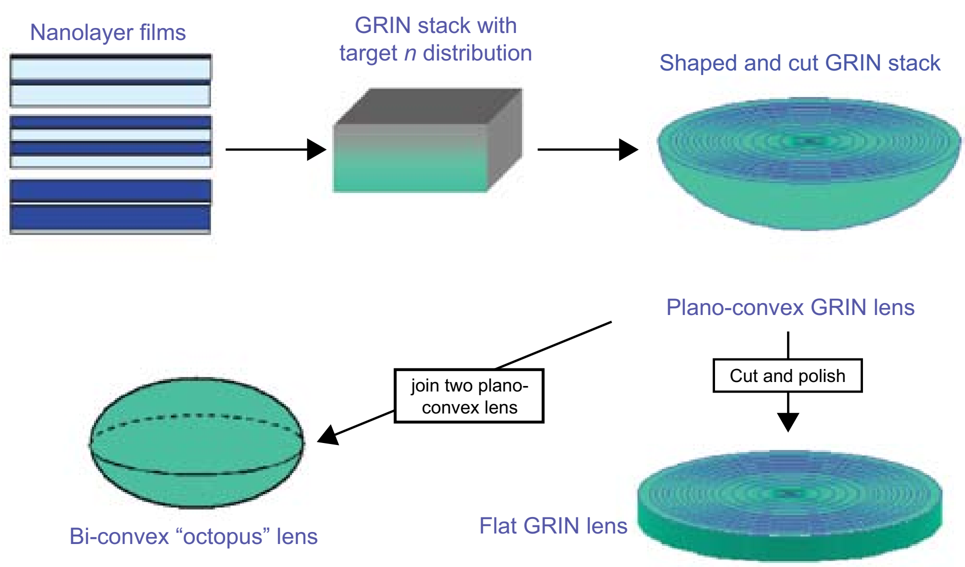

FIGURE 4
Steps to fabricate a polymer GRIN lens.

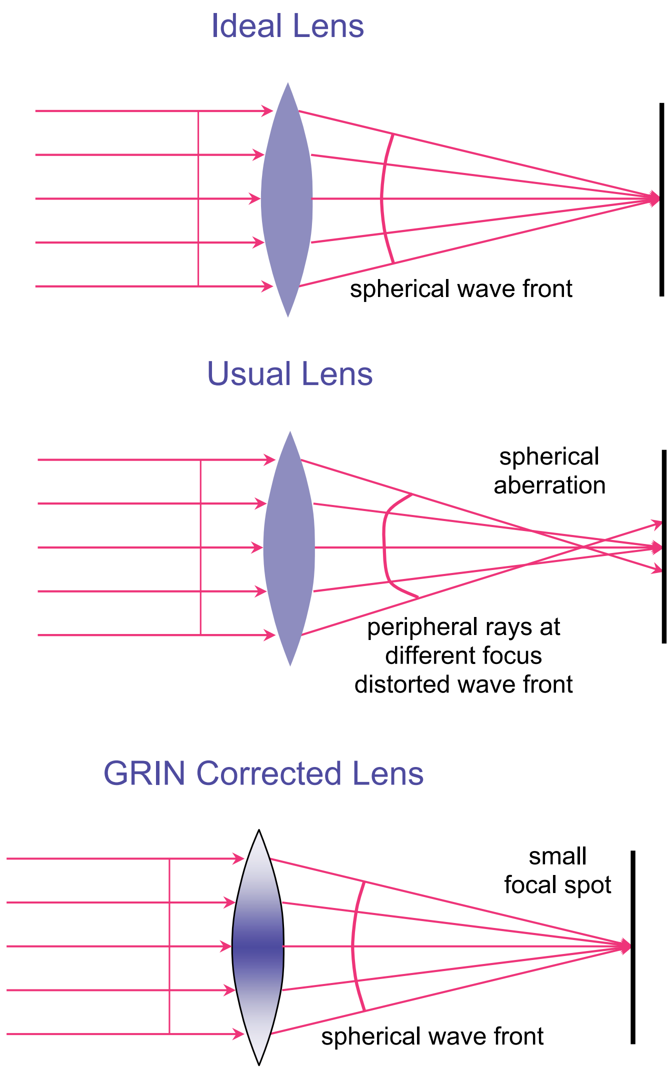

FIGURE 5
Strategy for spherical aberration correction in a convex lens.

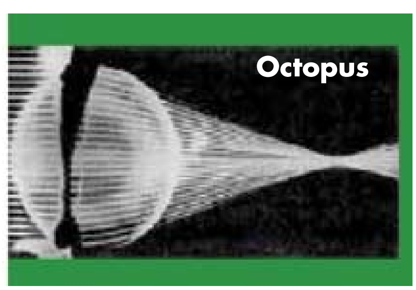

FIGURE 6
Octopus lens with minimal spherical aberrations.

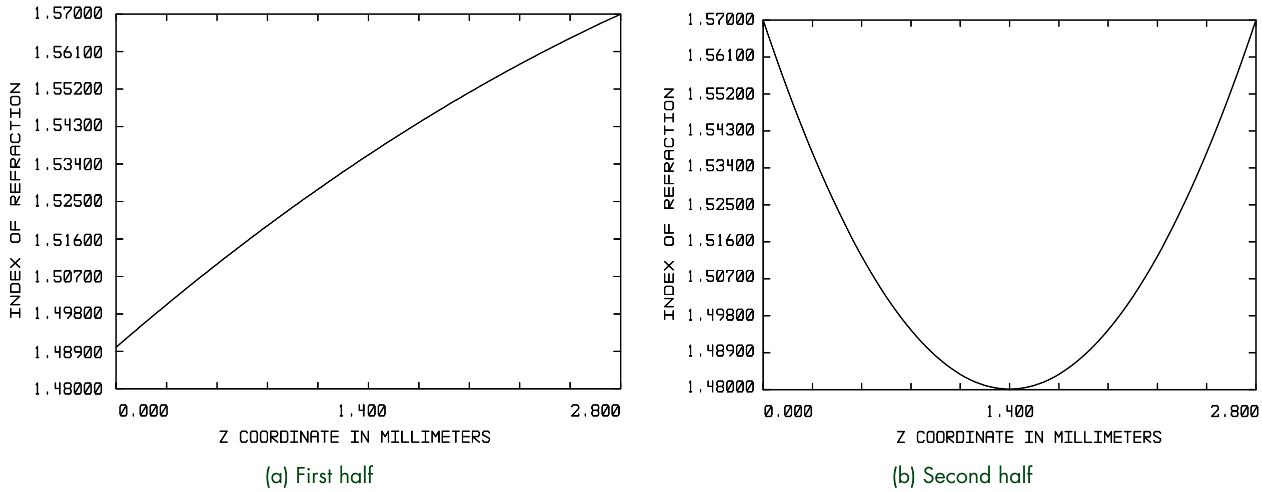

FIGURE 7
Optimized index profiles to correct for spherical aberration in a double convex lens.

with a lower index and hence a shorter optical path near the edges of the lens. The index gradient performs a function similar to that of an aspheric (Schmidt) corrector plate that is sometimes added to telescope designs with homogeneous lenses.

GRIN lenses were produced using the fabrication techniques described above. A Shack-Hartmann wave front analyzer measured the shape of the propagating wave front after the lens. The Zernike polynomial representation of the wave front showed substantially lower spherical aberration in the GRIN lens compared to a similar homogeneous lens. Although the GRIN lens was not free of aberrations, we demonstrated an ability to design and fabricate a GRIN lens with a substantial reduction in a specific aberration.

GRIN OPTICAL SYSTEMS

To explore the potential applications to Navy optical devices, we have begun to design small, lightweight, robust, optical systems that use the polymer GRIN lenses to reduce the complexity and weight of multielement imaging devices. Ray tracing techniques are used to design such systems. Figure 8 shows the initial design of a three-lens system to provide a large field of view for a short wave infrared (SWIR) sensor array.

The optical system was constructed using lenses that were designed with appropriate index gradients. Figure 9 shows an image taken with this lens set imaging onto a SWIR camera. Details are easily resolvable with the polymer lens.

This lens system was installed on an *Evolution* unmanned aerial vehicle (UAV) with a visible sensor, flown to altitudes of up to 1000 ft and used to record video images. The camera provided good image resolution and contrast in the flight test, indicated by the readily identifiable ground vehicles in the images. The flight tests illustrated the ability of this new GRIN lens technology to be transitioned to a lightweight, robust, optical system. We are now extending this technology to develop a small, lightweight zoom lens that uses variable focal length lenses inspired by the structure of the human eye.

SUMMARY

We have introduced a new class of hierarchically structured polymer optical materials where the refractive index can vary in a controllable way within the material. The new GRIN materials permit the fabrication of gradient refractive index lenses with a variety of index gradients. A wide range of lens shapes and index profiles are feasible, giving an optical designer substantial control over the focal properties of these lenses.

The development of these GRIN polymer optical materials began with the recognition that we could make transparent layered composite polymer films with a specified refractive index via a well-known nanolayer polymer extrusion technique. By stacking a set of these films with very small differences in index, we created a polymer with an internal index gradient. The index gradient is defined by the order in which the films are stacked. Molding this material gives a shaped GRIN lens with the desired gradient. Ray tracing techniques allowed us to optimize the index gradients for specific lenses and optical systems. A biconvex lens corrected for spherical aberration and a small, lightweight, robust, multielement lens for a SWIR camera were designed, fabricated, and characterized. The latter lens system was installed in an NRL *Evolution* UAV and used to record video images at a height of up to 1000 ft.

The index gradients in the polymer materials emulate an important feature of optical systems found

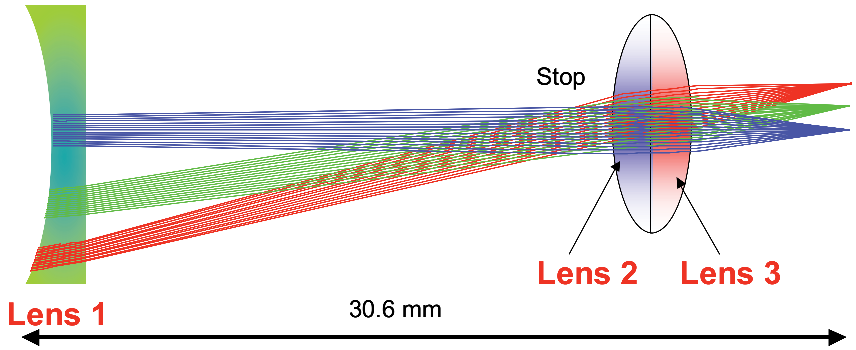

FIGURE 8
Camera lens system designed with a 60° field of view composed of three GRIN lenses with complex refractive index profiles. All the GRIN lenses were made from nanolayered SAN17/PMMA films.

FIGURE 9
Infrared image obtained using the GRIN lens system in Fig. 8 coupled to a SWIR camera.

in nature. The index gradients that enhance focusing power and correct aberrations in nature can perform the same function in man-made optics. An optical designer can look to the intriguing array of optical systems found in nature for inspiration in developing new optical systems using these materials. Such bio-inspired optical systems can be simpler, lighter, and less complicated than traditional glass lens systems.

ACKNOWLEDGMENTS

This was a collaborative project between groups at NRL and Case Western Reserve University. Michael J. Wiggins, who worked at both NRL and Case, was responsible for some of the early optical characterization. Yi Jin and Huwen Tai at Case were responsible for coextruding the nanolayered sheets and fabricating the GRIN lenses.

We also acknowledge useful and stimulating discussions with Dr. Leonard J. Buckley.

[Sponsored by DARPA]

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