New design of two-element aerial camera lens by using axial gradient index

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Aerial camera lenses are often composed of four or more conventional lens elements with spherical surfaces and homogenous refractive indices. Special element such as gradient-index materials can be used to reduce the total number of lenses required to meet the same design specifications. The present work introduces a new design for this four-lens system, using only two lenses put one; of them has an axial-gradient index. Hence, a comparison is set between the conventional four-element system with the proposed design .The results give a better performance of the new design.

الكاميرات التى تستخدم عادة فى التصوير الجوى تحتوى على أربعة عدسات ذات مواصفات خاصة من حيث الأسطح الكروية ومعاملات الانكسار المتجانسة لكل عنصر. التصميم المقترح فى هذا البحث يستفيد من التقنيات الحديثة التى يمكن أن تتمتع فيها العدسة الواحدة بتدرج فى معامل الانكسار لمادة العدسة طبقاً لدالة رياضية معينة. ولقد أدى هذا التصميم المبتكر الى تقليل عدد العناصر التى تحتاجها مثل هذه الكاميرات من أربع عدسات الى استخدام عدستين فقط دون التضحية بأى خصائص ضوئية للنظام بل بالعكس أدى ذلك الى تحسين مواصفات النظام. ويقارن البحث بين مواصفات النظام المقترح بما هو مستخدم حالياً.

Keywords: Gradient-index, Optical design, Lenses

1. Introduction

One way to lower the aerial camera lens's weight is to reduce the number of lens element [1]. New technologies including aspheric element, Diffractive Optical Elements (DOE), and Gradient–Index (GRIN) materials [2-3] aimed at correcting the aberration with fewer elements than many spherical surface elements are used.

For many years, optical designers have been aware of the potential that inhomogeneous refractive index distribution can bring to the precision optical instruments. The groundwork for the analytical treatment and understanding of inhomogeneous glass was developed in the early seventies by Sands [4] in a series of papers. At that time, Sands was conscious of the fact that no means existed to fabricate gradient index lens in a controlled way. This was evident in his statement[4] "In spite of the fact that the routine production of glasses with prescribed and accurate controlled inhomogeneities is still in the future".

Later, a number of papers have been published laying the theoretical foundations of the science of inhomogeneous lens design. The technology is now capable of developing several inhomogeneous glasses, hence producing a lens with axial gradient index distributions [5-7]. In this paper, we demonstrate the use of axial gradient index to reduce the elements of aerial camera lens from four to two-element lens.

The goal of the present design study is to use the gradient-index technology to determine the minimum number of elements needed to meet the same optical performance of the original aerial camera lens. The resulting system is not the same in diameters and weight of the original one.

2. Previous model for four-element lens (aerial camera)

The optical system investigated in this paper is an aerial camera with four-element lens systems [8]. The layout of the aerial camera lens with four-element lens is shown in fig. 1.

The geometrical and optical data of this system is tabulated in table 1.

The specification of this system is given in appendix 1. This system has been studied by

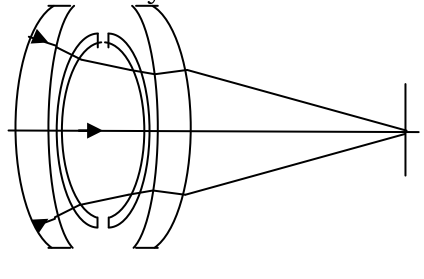

Fig. 1. Four homogeneous lens optical system (aerial camera lens).

Table 1
Prescription of aerial camera lens surface data

Surf	Radius in cm	Thickness in cm	Medium	Diamter in cm
OBJ	*Infinity*	*Infinity*	Air	
STOP	25.01	9.72	1.611	48.77
2	35.00	1.95	Air	48.65
3	19.00	1.05	1.72	37.43
4	16.53	25.28	AIR	33.10
5	-16.53	0.99	1.72	33.99
6	-20.00	3.2	AIR	39.73
7	-40.07	11	1.611	63.64
8	-27.30	121	AIR	54.52
IMG	Infinity			252.8

Stavroudis and Sutton [8]. They looked at the spot diagrams for the prediction of this lens performance from design data. Al-Ahdali, and Shealy optimized the caustic merit function, which constructs of the sagital and the tangential caustic surfaces to improve the image quality [9-10]. Al-Ahdali redesigned the system to improve the image quality by minimizing separately the tangential caustic surfaces and the sagittal caustic surfaces [11]. The results proved that, by reducing the size of caustic surfaces the image quality is greatly improved.

3. The proposed model

In this study, the above system is looked at from a different viewpoint. The present model aims at redesigning the same optical system using axial-Gradient Index (GRIN) so that it would be possible to reduce the total number of the optical system elements lens without affecting the overall performance of the system. This is achieved by removing the two middle elements, and keeping only the front and the back lens of the aerial camera system, as shown in fig. 2.

Table 2
Prescription of axial grin aerial camera lens surface data

Surf	Radius	Thickness	Medium	Diameter
OBJ	Infinity	Infinity	Air	
STO	43.8379	9.72		59.71
2	61.3485	56.1	Air	59.69
3	-70.2353	10.93	1.611	59.86
4	-47.8518	66.43	Air	60.15
IMG	Infinity			59.66

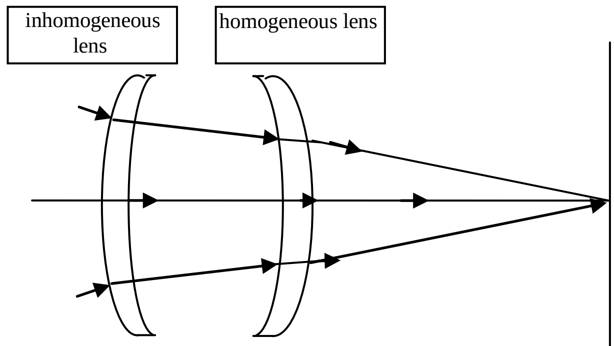

Fig. 2. Proposed Two lens optical system (aerial camera lens).

The front lens has an index of refraction gradient along the axial direction (axial GRIN). The base index, generally defined at the front surface of the glass blank varies as a function of the axial position, z, as:

$$n(z) = n_0 + \alpha z + \beta z^2 + \gamma z^3 . \qquad (1)$$

Where, α, β and γ are constants creating a monotonic index profile with either a positive or a negative slope. Since the index varies along the axis, axial GRINs can be made with a relatively large radial aperture. For most optical designs, glass elements need to be large in radial aperture than in thickness. Axial GRINs are well suited to the aerial camera lens since the gradient can occur over a short distance in the z-direction without limiting the radial size. In this paper, the proposed improvement assumes a linear gradient index, therefore, eq. (1) is reduced to:

$$n(z) = n_0 + \alpha z . \qquad (2)$$

The other lens is kept homogenous with a fixed index

The radii, thickness of gradient and homogenous lens were considered variables, while the effective focal length was fixed at 133.16mm.

GRIN DATA

SURFACE STO:	GRIN SURFACE
n_o:	1.611
Delta t:	0.01753
NZ1:	-0.000751

Ray tracing technique was used to follow optical rays as they travel across several optical media. Each ray obeys faithfully the laws of geometrical optics.

The Zemax Package software [12] is used in obtaining the results in this paper. The focal length and the total power of the system is 133.16 mm. A comparison was set between the conventional homogeneous lens and GRIN lens camera systems. This software is highly efficient in calculating the following parameters were considered

- The RMS spot radius vs field angle,
- The Transverse Ray Aberrations (TSA),
- The Modulation Transfer Function (MTF), and
- The Point Spread Function (PSF) for both lenses.

4. Results and discussions

Fig. 3 presents the rms spot radius vs. the field angle for the aerial camera lens (original lens), and design lens (GRIN lens). It is clear that the improved design proposed in this work gives a better performance than the original lens for all field angles. This demonstrates the effectiveness of the use of a lens that has an axial gradient index.

Fig. 4-a and 4-b, represents the tangential and sagittal fan, Transverse Ray Aberration (TSA) for the present designed lens, and conventional as homogeneous lens for different incident field angles.

It is obvious that the GRIN lens has improved the optical performance of the system; also it is very clear that design lens has different sign aberrations for all incident field angles than the conventional a_1/γ al homogeneous lens. Moreover, the present study shows that for an incident plane wave, the Point-Spread Function (PSF) [13] of the proposed GRIN system offers less Full Width Half-Maximum (FWHAM) than the conventional four-lens system.

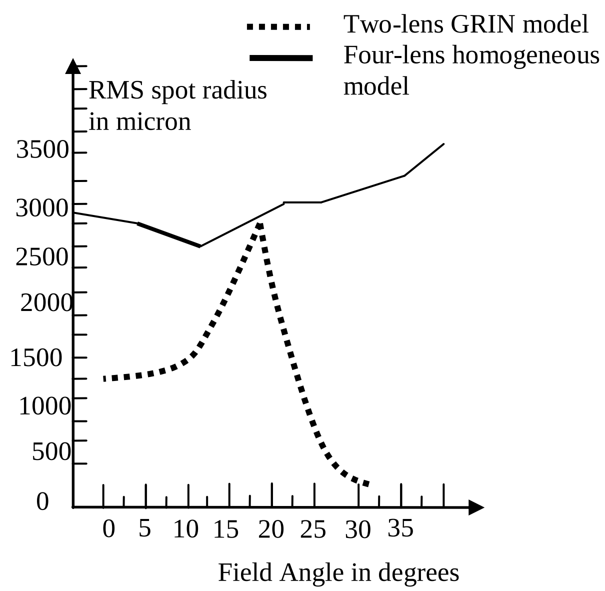

Fig. 3. Comparison of the RMS spot radius vs field angles for the four-lens system and the proposed two-lens GRIN design for aerial camera lens.

The Modulation Transfer function (MTF) has been used to describe how much blurs the image of an object, and to measure how much bright-to-dark contrast is lost (resolution). The tangential and sagittal MTF as a function of the number of lines per millimeter (special frequency)are examined, for different incident field angles fig. 5 compares this effect for the two models under consideration. This figure shows that the present design lens has a better resolution (MTF) than the original lens for all field angles.

5. Conclusions

In this study, we make the first element as an axial-gradient element to produce a drastic reduction of the number of elements of aerial camera lens. The new system has two elements, and in the same time still meeting the original optical performance and specifications.

The optical performance of the conventional aerial camera lens (original lens) was successfully improved by reducing two elements. The total numberof lenses is less. The lens designed, is not easy to manfacture, and mechanical constraints have not been mentioned. But given recent developments in GRIN materials fabrication, this objective can be manufactured with current technology. However, it has been illustrated that new technologies may be used to redesign conventional lens systems to achieve better optical performance with far fewer elements.

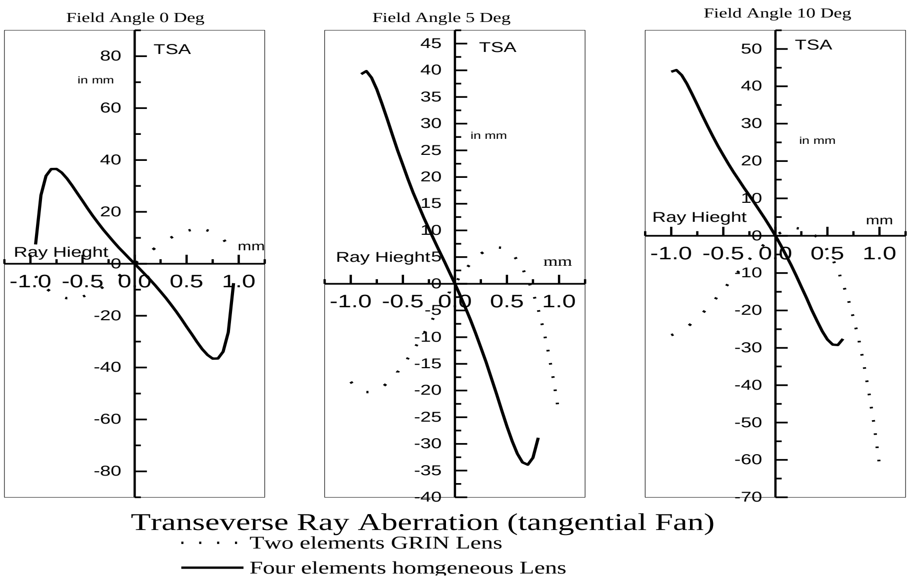

Fig. 4-a. Comparison of the transverse ray aberration curves (TSA for the four-lens system and the proposed two-lens GRIN design for aerial camera lens.

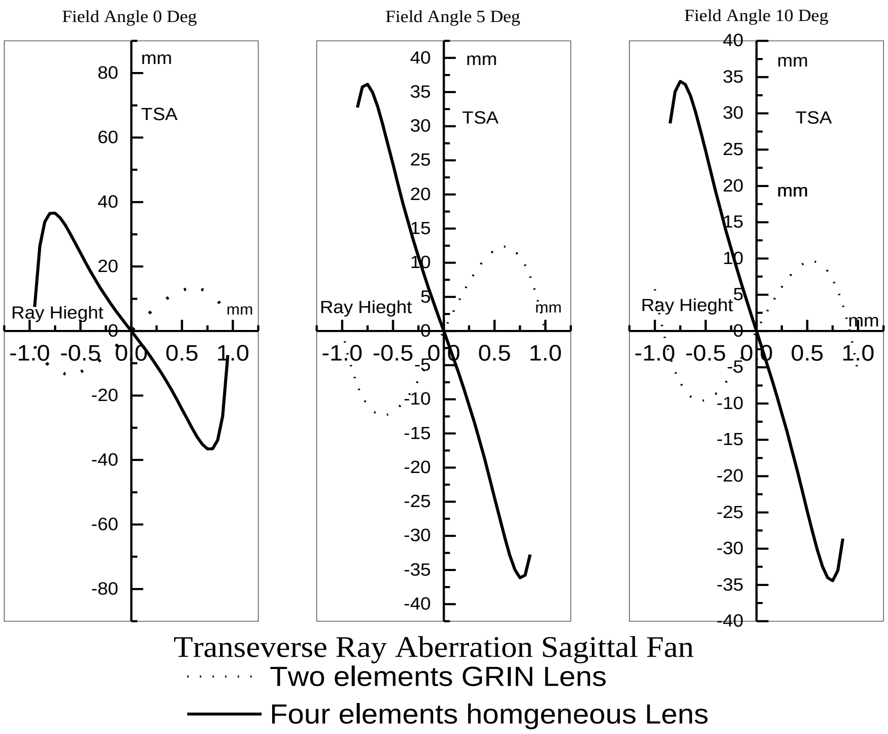

Fig. 4-b. Comparison of the transverse ray aberration curves (TSA) for the four-lens system and the proposed two-lens GRIN design for aerial camera lens.

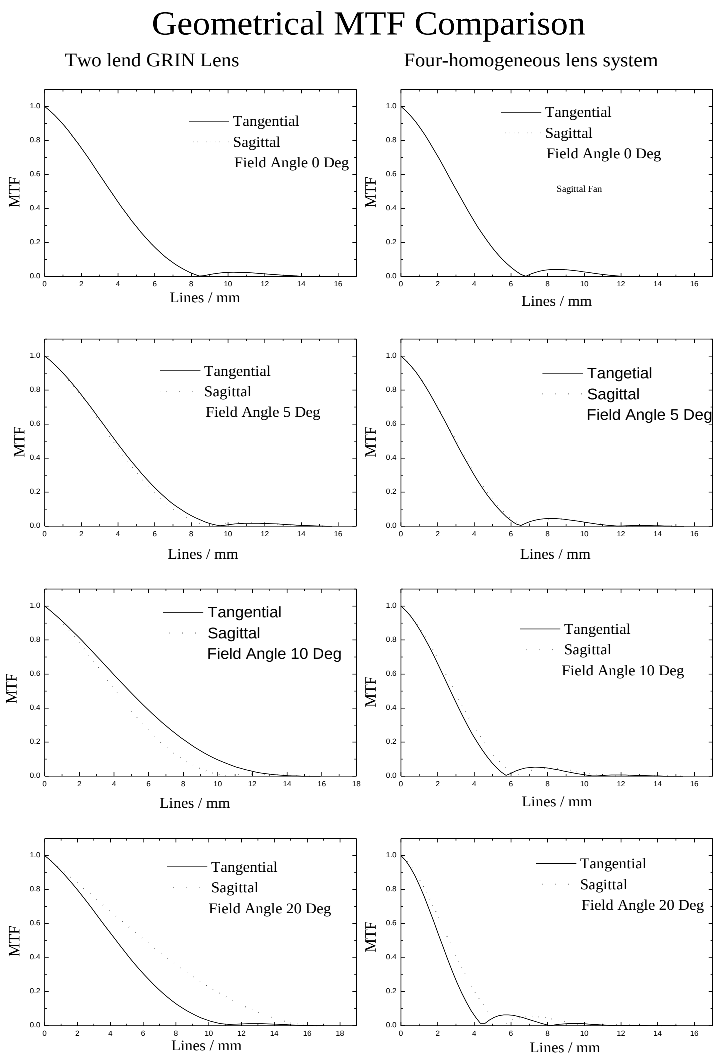

Fig. 5. Comparison of the modulation transverse function (MTF) at different special frequencies for the four-lens system and the proposed two-lens GRIN design for aerial camera lens.

Appendix I

- The f-number equal to 6.3,
- The effective focal length 133.16 mm,
- Back focal length 97mm,
- The total track 145 mm and the ray path is 53 mm,
- Field angle 90°, and
- The spot diagrams show some of the difficulties of obtaining good imagery over such a wide field.
- The central cores of these diagrams are quite small at 0° and 10°, and are still small at 35°.
- The most important part of the field is beyond 35°,

however, it is clear that the density of the points begins to drop off, at 40°, 42°, and 45°.

References

[1] R.N. Pfisterer, "Design of an objective for night vision applications using axial-GRIN materials," in Novel optical

Systems Design and Optimization, J.M. Sasian, ed., Proc. SPIE 2537, pp. 270-278 (1995).
[2] R.J. Pagano, P.K. Mahart, and P.T. Sherman, "Measurement of Refractive Index and Dispersion in Axial Gradient Material Using Prism Refractometry," OSA Gradient index systems topical meeting, Rochester, NY, pp. 7-8 (1994).
[3] M.G. Turner and K.E. Moore, "Optical Design Using Large-Scale Axial Gradient Glass," Proc. SPIE 2863 (1996).
[4] P.J. Sands, "Third-Order Aberration of Inhomogeneous Lenses", JOSA 60 (11), pp. 1436-1443 (1970).
[5] L.G. Atkinson, et al., "Design of a Gradient-Index Photographic Objective", Applied Optics Vol. 21 (6), pp. 993-998 (1982).
[6] R.H. Dueck, J.L. Vaughn, and B.V. Hunter "Optical Design with Inhomogeneous Glass: the Future is Here," Proc. SPIE 3130 (1997).
[7] R.N. Pfisterer, "Design of a 35mm Photographic Objective Using Axial GRIN Materials," Proc. SPIE 2000 (1993).
[8] O.N. Stavroudis, and L.E. Sutton, "Spot Diagrams for the Prediction of Lens Performance from Design Data," J. Res. Nat. Bur. Stand., p. 93 (1965).
[9] I.H. Al-Ahdali, "Optimization of Three and Four-Element Lens Systems by Minimizing the Caustic Merit Function," Ph.D. dissertation, University of Alabama, Birmingham, USA (1989).
[10] I.H. l-Ahdali, D.L., and Shealy, "Optimization of Three and Four-Element Lens Systems by Minimizing the Caustic Surfaces" Appl. Opt.29, pp. 4551-4559 (1990).
[11] I.H. Al-Ahdali, "Optimal correction defects by minimizing the caustic merit function," Nuovo Cimento 17D, (5), pp. 489-479(1995).
[12] ZEMAX,. "Optical design program", version 10, focus software incorporated. Tucson, Az. 85731 U.S.A. (1999).
[13] H.H. Hopkins, Wave Theory of Aberrations, Oxford University Press, New York (1950).

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