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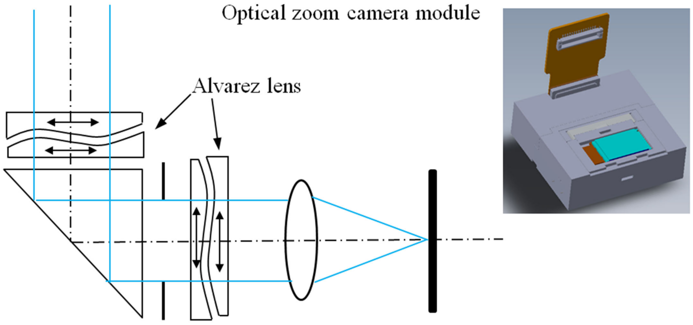

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Ultra Slim Optical Zoom System Using Alvarez Freeform Lenses

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Abstract: In this paper, we proposed an ultra slim optical zoom system with Alvarez freeform lenses. A 3X optical zoom system with two pairs of Alvarez lenses was developed. Alvarez lenses are fabricated by precise injection molding and the movable elements are actuated by voice coil motors. A slim camera module was fabricated with a size of 25 mm(width)×25 mm(length)×6 mm(height). The zooming and imaging capabilities of this Alvarez zoom system are demonstrated experimentally. The prototype exhibits a promising future for space-constrained application such as mobile phone camera module, wearable imaging system and endoscopic system.

Index Terms: Freeform optics, optical zoom system, Alvarez lens, camera module.

1. Introduction

Optical zoom systems were developed a long time age. With the rapid development of optical materials and computers, miniature optical zoom systems have been widely used for many advanced optical systems such as photography for mobile phones, endoscopes and wearable imaging systems [1], [2]. However, it has been very difficult for the module manufacturers to propose an ultra-compact zoom lens unit which can be mass-producible and fit into a small size such as mobile phone or endoscope system. The design of miniature optical zoom system is complicated, not only by the problems of assembling the optical elements and components of a zoom mechanical system, but also because of the complicated design of the mechanical structures. Because of these challenges of conventional way to develop zoom lenses, more attentions are paid on the new principles such as freeform zoom lenses [3], [4] and liquid zoom lenses [2] in the recent decade.

Freeform surfaces are useful for the design of refractive and reflective optical elements. Such surfaces are not rotationally symmetric like conventional spherical or aspheric surfaces. Instead, the surfaces are expressed as non-axis symmetric polynomial equations that enable complex phase variations. The concept of Alvarez lens was first reported and mathematically described by Luis Alvarez and Lohmann [5]–[9]. Alvarez lenses consist of two phase plates that each has a cubic phase profile, one the inverse of the other. The focal length is determined by the steepness of the cubic phase profiles and the lateral displacement of the two phase plates. By varying the

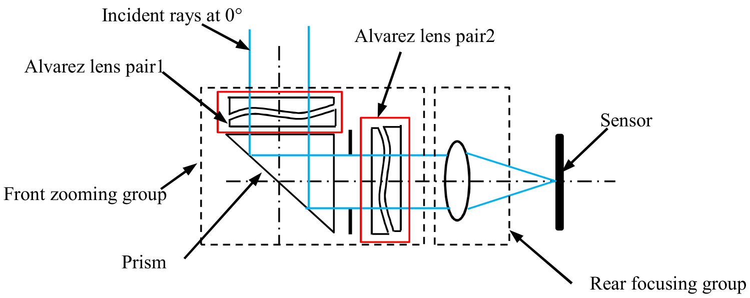


Fig. 1. Schematic diagram of the proposed slim zoom system design utilizing symmetric freeform Alvarez lenses.

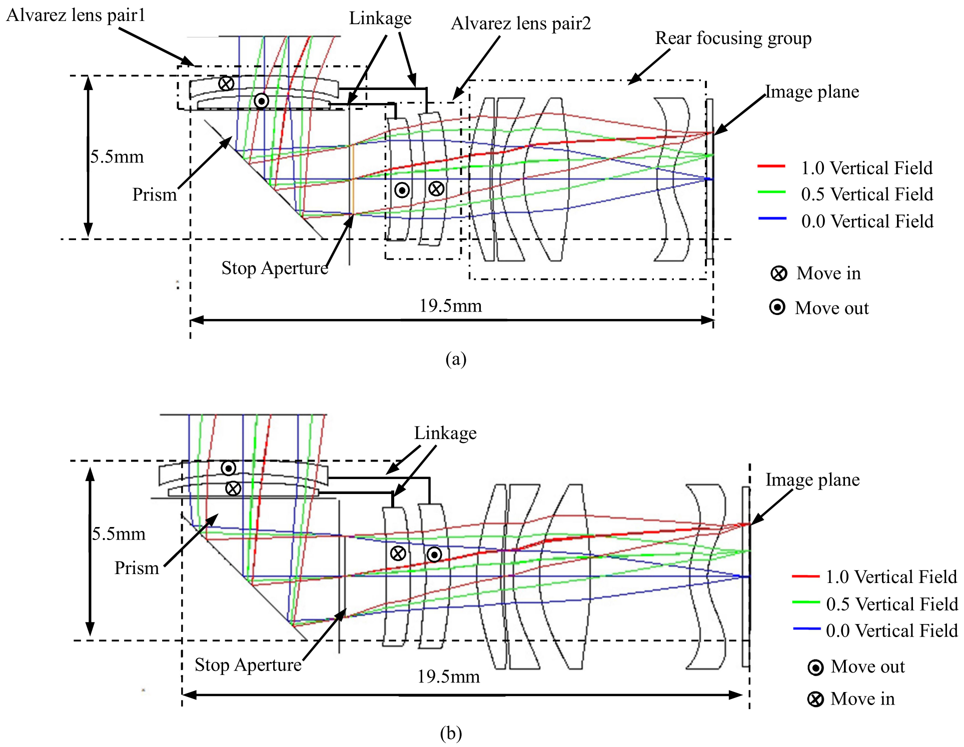
relative displacement of the Alvarez elements in the movement directions which perpendicular to the optical axis, variable focal length can be realized.

Though the Alvarez lens has been proposed for many years, it has not been widely developed until recent years because of the design, fabrication and measurement challenges. The growing interest in these freeform elements has been driven largely due to the rapid development of single point diamond turning and ultra-precision injection molding technology which can produce the required complex surfaces with adequate depth modulation, same surface roughness and productivity as conventional rotational symmetric lenses. In recent years, multiple designs incorporating laterally translated Alvarez freeform elements for improving variable focal systems and for completely different optical functions have been presented [10]–[22]. As prerequisites for successful usage of Alvarez freeform lens, the design method, fabrication and measurement technology for freeform elements were investigated and developed rapidly [10]–[16]. Except the conventional refractive Alvarez freeform lens, the applications of diffractive Alvarez freeform lens were also developed [17], [18]. Guangya Zhou's group demonstrated MEMS-driven miniature adaptive Alvarez lens [3], [4]. Paul J. Smilie and his colleges demonstrated an application of Alvarez lenses for mid-wave and long-wave [19]. S.Petsch and Alesksey N.Simonov demonstrated the usage of Alvarez lenses as intraocular vari-focal lens for human eyes [20], [21]. Recently, Austin Wilson and Hong Hua demonstrated a vari-focal optical see-through head-mounted display system using Alvarez freeform lenses [22].

Based on our previous work [13], [16] that we have done the theoretical analysis on tolerance and feasibility verification of optical zoom with Alvarez lenses, in this paper, a 3X optical zoom built-in camera module which was equivalent to a photographic objective lens with focal length ranging from 34.5 mm to 103.5 mm and field of view ranging from 70 degrees to 25 degrees is developed with two pairs of Alvarez lenses. The size of the module is 25 mm(width)×25 mm(length)×6 mm(height). We described the design of the Alvarez lenses that used, fabricated a zoom lenses prototype and captured the image of the prototype. The plastic Alvarez freeform lenses were fabricated by precise injection molding. The zooming and optical performances of this Alvarez zoom lens system were demonstrated experimentally. Different from traditional zoom system, the zoom system with Alvarez lenses can vary focal length by shifting Alvarez elements perpendicular to the optical axis with a short stroke and can realize fast zooming. The axial separation between the Alvarez elements can be fixed, eliminating the long stroke common in the traditional zoom system.

2. Optical Zoom System Design

Fig. 1 illustrates a schematic diagram of our proposed optical system. In this paper, a periscope configuration was introduced in our optical system. The design can be further divided into two main groups, the front zooming group and rear focusing group. The front zooming group is made up of



(a)

(b)

Fig. 2. Layout of the optical configuration (a) Wide angle end (b) telephoto end (Ray-tracing with ZEMAX).

two pairs of Alvarez lens and a prism. The prism acts as an optical mirror to bend the incident rays 90 degree. The Alvarez lens group boxed in red line in Fig. 1 is composed of two opposing freeform elements that change the optical power of the system with equal and opposite lateral translation.

The rear focusing group is made up of plastic aspheric lenses. There are two basic requirements for optical zoom system: variable focal length and fixed image plane. In order to meet the two basic requirements, two pairs of Alvarez lenses are used in our zoom lenses. As shown in Fig. 2, we developed an optical system by combining two pairs of Alvarez lenses as variable-focal lenses and a fixed focal lens. The two pairs of Alvarez lenses can not only adjust the focal length of the optical system but also compensate the position changes of the image plane during zooming.

The design for the Alvarez lens in this work follows the first-order analytical approach outlined by Alvarez and Humphrey [5]–[8]. In our design, high order terms are also used to minimize the optical aberrations. The freeform surface of each Alvarez element is given by:

$$\begin{aligned} z\,(\mathrm{x},\mathrm{y}) = A\left(\frac{1}{3}x^3 + xy^2\right) + a_{04}x^0y^4 + a_{22}x^2y^2 + a_{40}x^4y^0 + a_{14}x^1y^4 + a_{32}x^3y^2 + a_{50}x^5y^0 \\ + a_{06}x^0y^6 + a_{24}x^2y^4 + a_{42}x^4y^2 + a_{60}x^6y^0 + \cdots \end{aligned} \tag{1}$$

Where the amplitude coefficient A controls the optical power of the surface over a given area, a_{04}, a_{22}, a_{40}, a_{14}, a_{32}, a_{50}, a_{06}, a_{24}, a_{42}, a_{60} are the coefficients of high order terms. The shifting direction of each Alvarez element is parallel to x-axis and the z-axis corresponds to the direction of light propagation. Since the element shifting direction is parallel to x-axis, the freeform surface is symmetric about the x-axis, so the polynomial terms with only even order of y are active.

The freeform surfaces of the Alvarez lens can be oriented and nested with a minimal gap to form a composite plate of constant thickness. However when lateral shift d perpendicular to the optical

TABLE 1

Specifications at Wide Angle end And Telephoto End

Parameter	Specification	
	Wide angle End	Telephoto End
Field of angle(FOV)(degree)	70°	25°
Effective focal length(mm)	4.65	14.1
F# number	2.42	3.4
Maximum distortion (absolute value)	< 3.5%	<3.5%
First pair shifted distance(mm)	1.875	-1.125
Second pair shifted distance(mm)	-1.82	1.18
Image Circle(mm)	6.2	

Note: for shifted distance, positive value means shifting at x direction, negative value means shifting at inverse direction.

axis is introduced, the composite optical component is a lens with variable curvature that depends on the lateral shift. The optical power of the composite lenses in terms of the design parameters results in the following expression:

$$\varphi = 4\mathrm{Ad}\,(\mathrm{n} - 1) \tag{2}$$

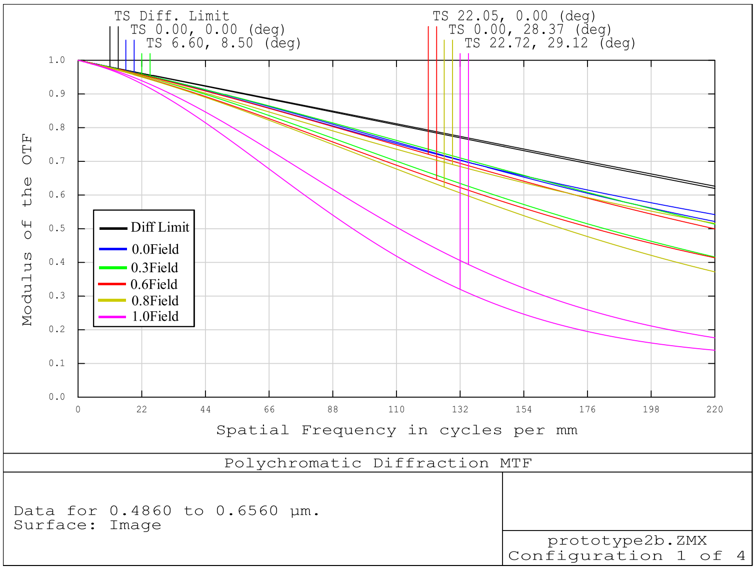
Where n is the refractive index of the material, d is the shifting distance for each element by an equal amount in opposite directions. From equation (2), we can conclude that the optical power of the composite lens is proportional to the lateral shift of the Alvarez elements.

Unlike conventional optical designs where all the surfaces are rotational symmetric like spherical and aspheric surfaces, here polynomial surfaces are introduced to realize optical zoom and reduce the aberrations. Freeform surface has more variables and more degrees to be controlled. The optimization process was carefully controlled and customized micros are used to control the freeform surface shape, for example the slope angle and ray incident angle on surface within active area. To this end, ray-based and wave-based optical optimization was performed using ZEMAX. The specifications of the designed optical zoom system at wide angle end and telephoto end are shown in Table 1.

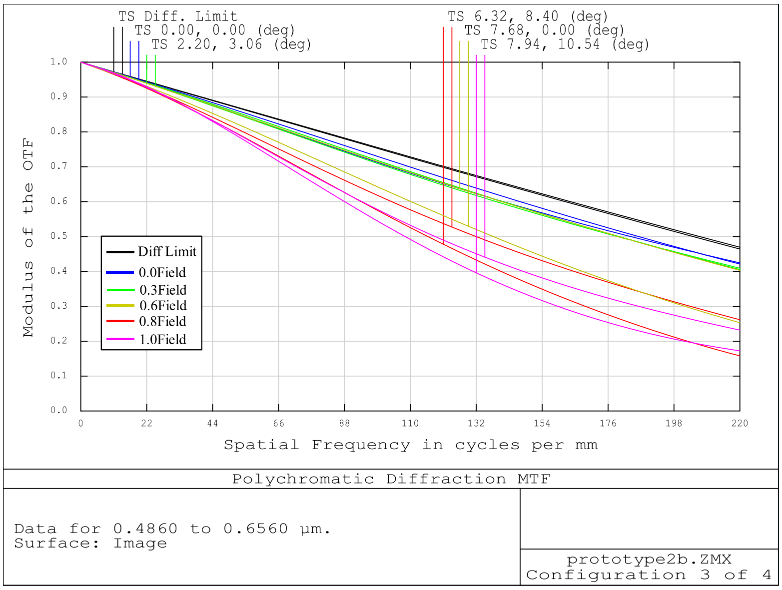
Fig. 2 illustrates the layouts of the zoom system at wide angle end (Fig. 2(a)) and telephoto end (Fig. 2(b)). In order to properly place the actuators, the shifting direction of the Alvarez elements was arranged perpendicular to the paper surface as shown in Fig. 2. The optical system consists of two pairs of Alvarez lenses and four aspheric plastic lenses. The stop aperture is located between the two Alvarez lens pairs. At wide angle end, the first Alvarez lens pair equivalent to a negative lens, the second Alvarez lens pair equivalent to a positive lens; while at telephoto end, the first Alvarez lens pair equivalent to a positive lens, the second Alvarez lens pair equivalent to a negative lens. The total track length (TTL) is 19.5 mm which is smaller than conventional periscope optical zoom system as listed in reference 1 (TTL is 26 mm).

Fig. 3 shows the modulation transfer function (MTF) characteristics of the system at two extreme positions. In general, higher-order freeform terms should be considered to further minimize aberrations. In our design, 12th orders were used to do optimization for each freeform surface. The optimization is realized using the “Damped Least Squares” algorithm proposed by Zemax.

As shown in Fig. 4 is the grid distortion of the zoom system at wide angle end (Fig. 4(a)) and telephoto end (Fig. 4(b)). The active area of the sensor is 3.6 mm×4.8 mm. At wide angle end, the horizontal full field of view is 58.08 degree and the vertical full field of view is 44.0 degree. At telephoto end, the horizontal full field of view is 21.6 degree and the vertical full field of view is 16 degree.



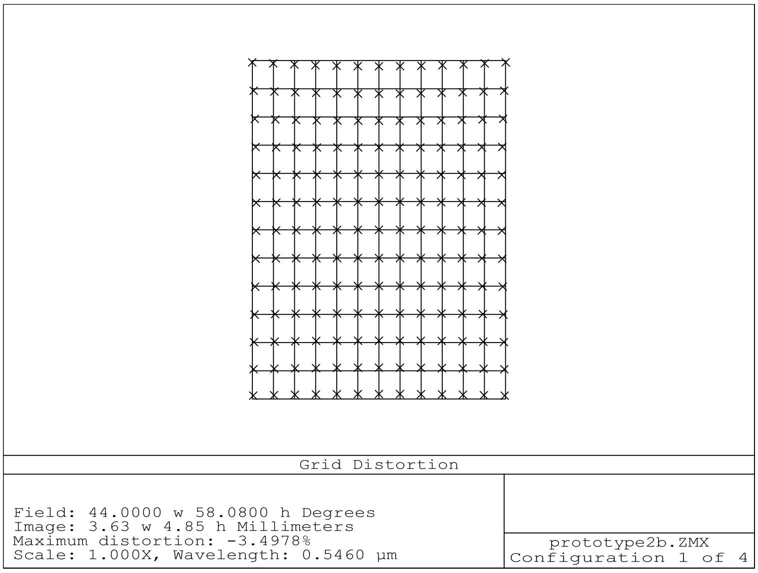
(a) Wide angle end



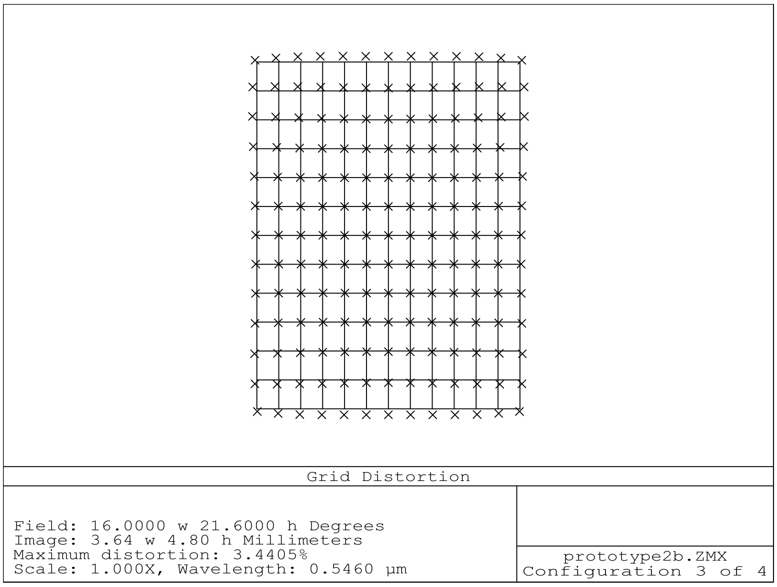
(b) Telephoto end

Fig. 3. MTF plots at (a) Wide angle end (b) telephoto end.

The proposed prototype of the optical zoom module is shown in Fig. 5. Two voice coil actuators were used to control the lateral shift of the Alvarez lenses. The rear focusing lens group can move along the optical axis by another voice coil motor to do auto focusing. Fig. 5(a) shows the integrated zoom camera module. Fig. 5(b) is the exploded view of the optical zoom camera module with front zooming part, rear focusing part and sensor. Fig. 5(c) is the inner structure of the front zooming part. Fig. 5(d) is the exploded view of the rear focusing part with lens barrel, guiding shaft, spring, magnet and cover. The first element of Alvarez lens pair1 and the second element of Alvarez lens pair2 are linked together by the linkage frame (as shown in Fig. 2) and shifted synchronized in same direction by a single actuator. Similarly, the second element of Alvarez lens pair2 and the first



(a) Wide angle end



(b) Telephoto end

Fig. 4. Distortion grid at (a) wide angle end and (b) telephoto end.

element of Alvarez lens pair2 are also linked and shifted synchronized by another actuator. Two voice coil motors were placed at left and right side of the freeform lenses.

3. Experiment Results

Fig. 6 illustrates the plastic lenses fabricated by precise injection molding. The material of all the Alvarez elements, the first aspheric lens and the third aspheric lens in rear focusing group is E48R with refractive index 1.531 and Abbe number 50.04. The material of the second aspheric lens and the fourth aspheric lens in rear focusing group is OKP4HT with refractive index 1.633 and Abbe number 23.36. The Alvarez freeform lenses and aspheric lenses were fabricated by

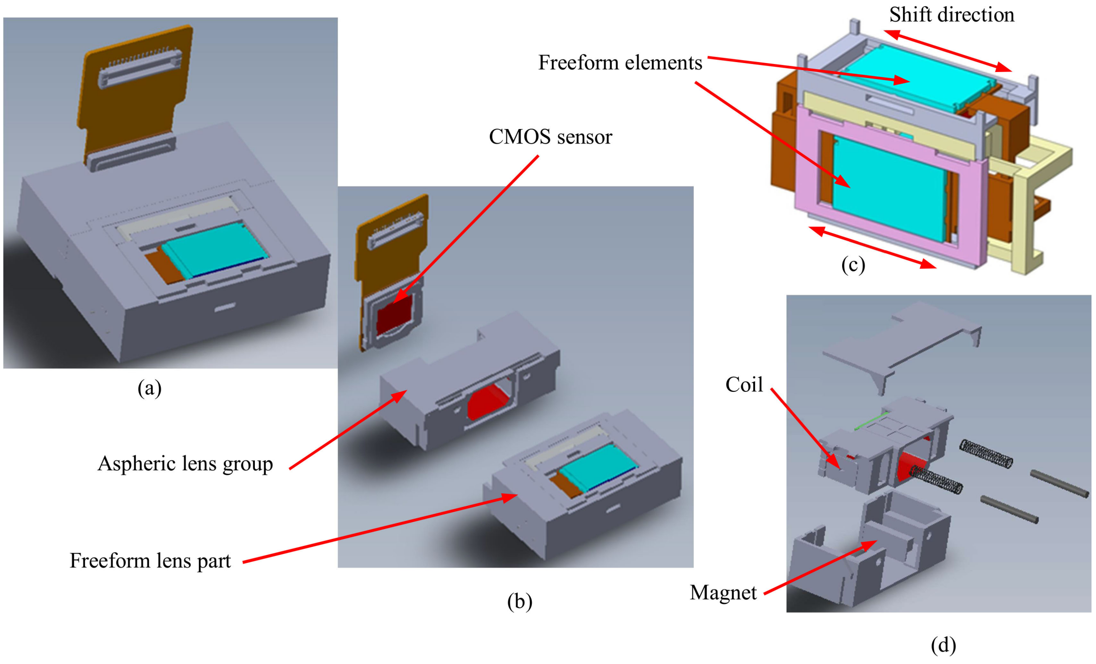


Fig. 5. Opto-mechanical model. (a) Integrated zoom camera module. (b) Exploded view of the zoom camera module. (c) Inner structure of the front zooming part. (d) Exploded view of the rear focusing part.

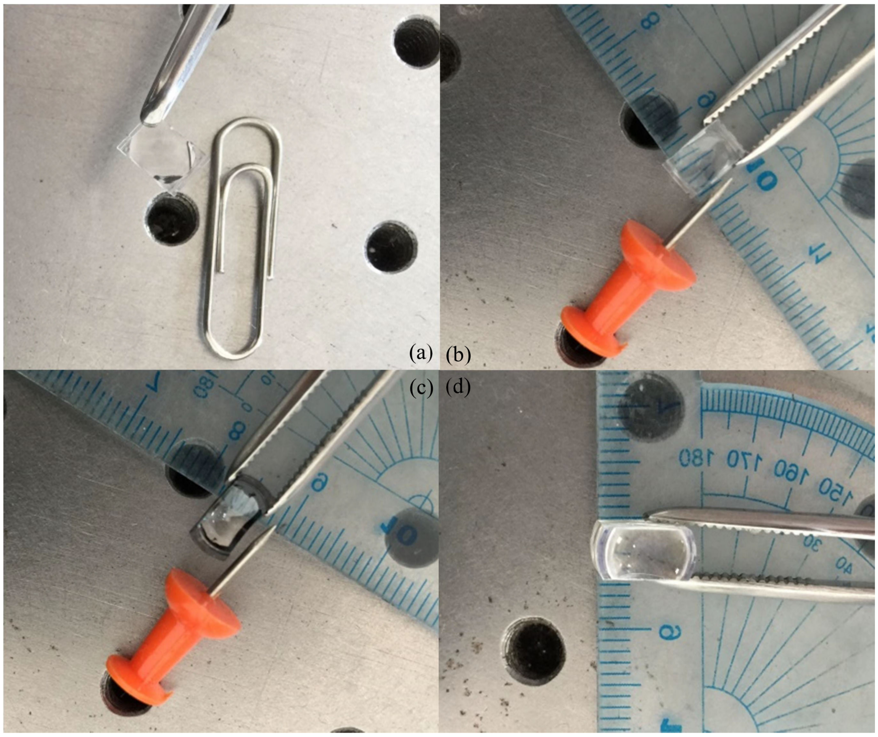


Fig. 6. Lenses fabricated by precise injection molding. (a) Alvarez freeform element1. (b) Alvarez freeform element2. (c) Aspheric lens with top and bottom non-active area cropped. (d) Stacked aspheric lens group.

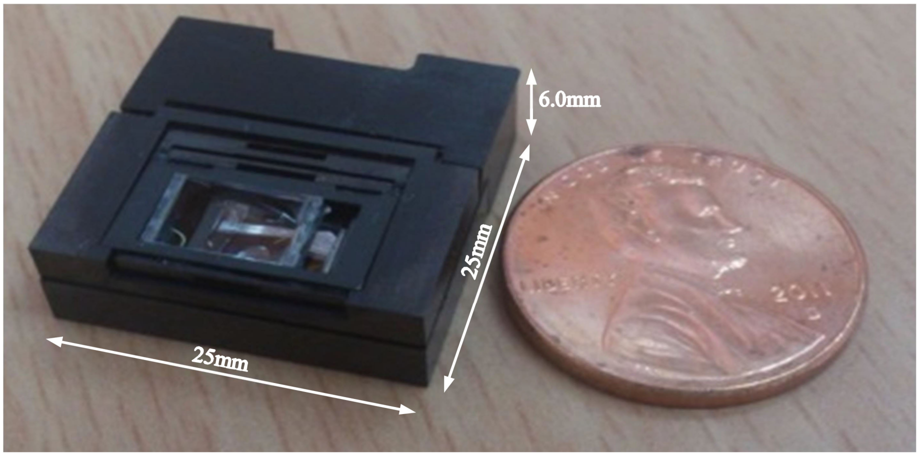


Fig. 7. Prototype of Alvarez optical zoom module (with cover removed).

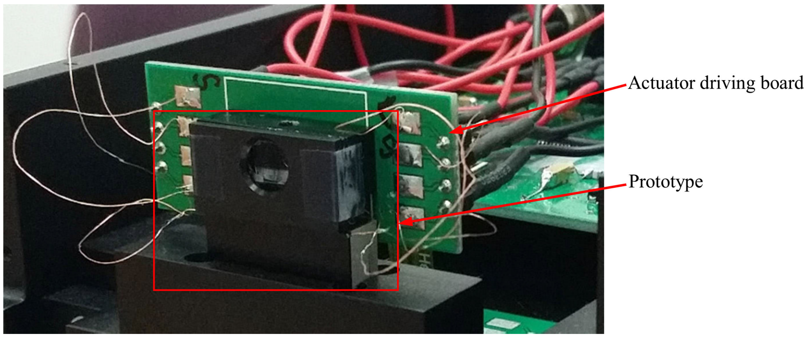


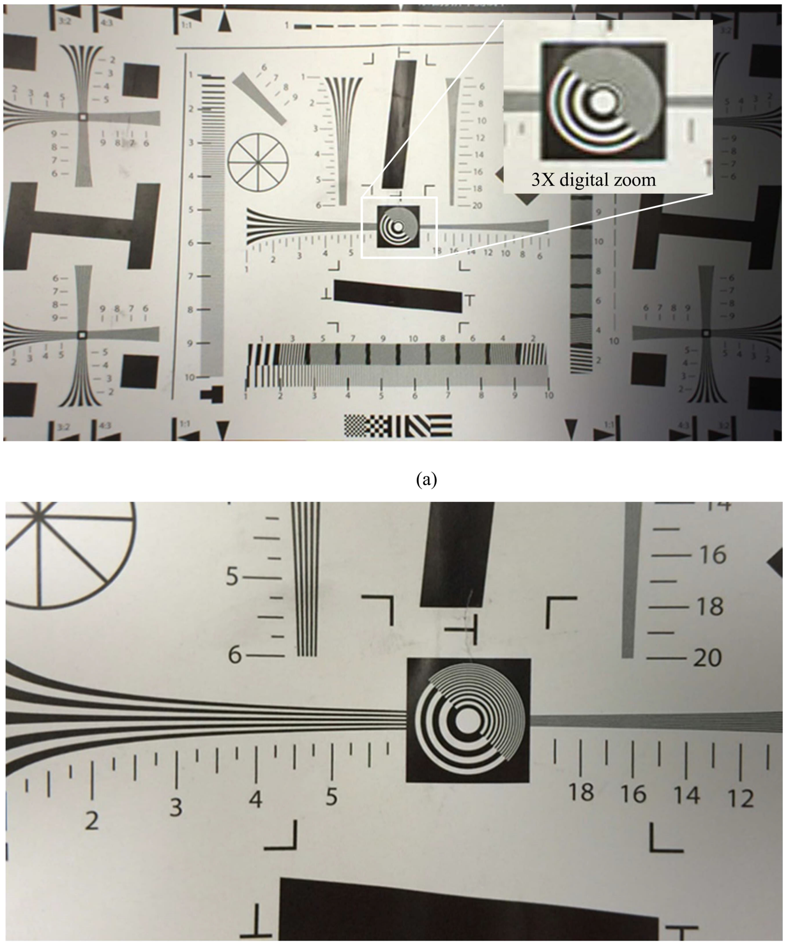
Fig. 8. Experimental setup of the prototype.

precise injection molding by Delta Pte Ltd. The freeform surfaces were measured on high precision profiler (profiler model: UA3P, made by Panasonic) by Dr. Wang Shihua from Agency for Science, Technology and Research (A*STAR) in Singapore. The PV values of all the surfaces are controlled less than 2 um and the surface roughness (Ra) less than 10 nm. The positioning and mounting tolerances of the Alvarez freeform elements in axial and lateral directions are ±2 um. In order to reduce the module height, all the aspheric lenses were cropped at top non-active area and bottom non-active area (as shown in Fig. 6(c) and Fig. 6(d)).

Fig. 7. Shows a prototype of the optical zoom module. The overall width of the module is 25 mm, with a length of 25.0 mm and a height of 6.0 mm.

As shown in Fig. 8 is the experimental setup to capture image with the prototype.

Fig. 9 shows the captured images at wide angle end (1X) and telephoto end (3X) by the prototype (CMOS sensor: OV4688 made by OmniVision). The size of the standard ISO12233 chart is 1.0 meter in width and 0.6 meter in height. The distance between the prototype and the chart is 800 millimeters. By laterally shifting the freeform lenses of the two Alvarez lens pairs with respect to each other by 3 mm, the focal length of the zoom system can be varied correspondingly from 4.65 mm to 14.10 mm. Fig. 9(a) shows the captured image of the prototype at wide angle end (1X). Fig. 9(b) shows the captured image of the prototype at telephoto end (3X). Because of the lens fabrication error (Introduced by mold inserts and injection molding process) and lenses assembly error (especially the decenter of Alvarez elements at the direction perpendicular to the shifting direction and optical axis as reported in reference 13), the image is blurry. The image quality at



(a)

(b)

Fig. 9. Captured Image. (a) Wide angle end. (b) Telephoto end).

center area is only around 350LW/PH. From the image by 3 times digital zoom at wide angle end and 3 times optical zoom at the telephoto end, we can see the quality of the image captured by optical zooming is much better.

4. Conclusion

In this paper, we demonstrated a slim optical zoom module based on two pairs of Alvarez freeform elements. We have successfully demonstrated and characterized a 3X optical zoom system with focal length ranging from 4.65 mm to 14.1 mm and field of view ranging from 70° to 25° while the moveable parts only shifted 3 mm. Compared with conventional optical zoom system in which the moveable parts are shifted along the optical axis, the volume is compact and the shifted distance of the moveable part is greatly decreased. Such zoom lens system may be suitable for miniature cameras for autofocus and fast zooming. Simulation and experiment results are presented to show that the described zoom lens system is a highly viable and promising alternative to the conventional zoom lens system in some space constraint applications such as cell phone camera module, wearable imaging system and endoscopy system.

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