Optics Communications 354 (2015) 132–139

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Centroid shift analysis of microlens array detector in interference imaging system

Zhu Zhao, Mei Hui*, Ming Liu, Liquan Dong, Xiaohua Liu, Yuejin Zhao

Beijing Key Laboratory for Precision Optoelectronic Measurement Instrument and Technology, School of Optoelectronics, Beijing Institute of Technology, Beijing 100081, China

A R T I C L E I N F O

Article history:
Received 23 January 2015
Received in revised form
15 May 2015
Accepted 21 May 2015
Available online 28 May 2015

Keywords:
Microlens array
Low order aberration
Geometric Ensquared Energy
Interference imaging system
Centroid shift

A B S T R A C T

Most CCD imaging detectors integrated microlens arrays (MLAs) to increase fill factor and sensitivity. However, they also introduce spot calibration issues with the inconsistency of spot geometry center and intensity distribution center. We setup theoretical and experimental models to research the problem of centroid shifting. According to the Seidel and Zernike coefficients of the optical model, we analyze main aberrations of microlens. In “Chief Ray” and “Centroid” reference frames, centroid shift numerical value is calculated with Geometric Ensquared Energy (GEE). Based on pentaprism test for 8.4 m mirror segment, we conduct spot imaging experiment in interference system. Spots images are obtained, and two-dimensional centroid algorithm processing is performed on them to get the analog experiment values of centroid movements. The results show that the MLA placed in KAI-16000 imaging detector causes the spot centroid to move. When there is a 14° (or −14°) angle of incident ray, the shifting values are about 1.46 μm in simulation and 2.18 μm in experiment. Our research makes a contribution to the compensation of calibrated error in metrology technology. We also prove that a significant portion of the shift comes from the low order aberration of microlens.

1. Introduction

CCD detector pixels present a trend of decrease in size to improve the resolution [1]. But smaller pixels cause less light rays to be directed to photo sensitive area, which reduce availability ratio of light and enhance potential noise. By integrating a microlens array (MLA) on top of CCD detector, the light that would normally be lost on metal light shield is collected on photoreceptive cell. The main advantage is that the design has higher light collection efficiency and better sensitivity than conventional imaging systems. MLAs have wide application in the areas of infrared focal plane arrays imaging, digital projectors, micro-optics scanner, and CCD imaging detector [2–5].

However, the smaller size of lenses arises unwanted effects. For example, when outer portions of incident beam projected onto the adjacent photodiode, MLAs will result in spot centroid offset in the image [6–8]. It causes an error for optical measurements which are based on spot centroid calibration, such as the scanning pentaprism test.

Scanning pentaprism test was implemented by the University of Arizona as a verification of principal test to guide the fabrication of the off-axis mirror segments for the Giant Magellan Telescope (GMT) [9–11]. 8.4 m segment of GMT is a near paraboloidal surface, the aspherical constant is −0.9983, and the 18-meter primary mirror focal length gives an $f/2.1$ focal ratio for the segment. [12,13]. In this system, a collimated beam scans across the parabolic mirror surface with a pentaprism. Since the scanning beam is parallel to the axis of parabolic profile, it comes to strikes a detector at the focus. Here, displacement of the spot is proportional to the slope error. Since the detector is integrated MLA, centroid point and geometrical center of the spot may be misaligned, which play a significant role in test precision. Thus it is important to analyze and calibrate the MLAs' spot centroid shift.

The occurrence of centroid movement in spot's imaging process may be due to the distortion of the MLA. This paper has dealt with the following respects to verify this assumption: (1) we setup an optical model based on structural features of plano-convex refractive microlens integrated in Kodak KAI-16000 imaging detector, and then analyzed Seidel aberrations and wave aberrations; (2) we proposed the methods of centroid shift numerical calculation based on GEE; (3) we conducted an experiment of spot imaging, and processed the images captured in detector and validated the centroid shift value of this MLA system. At the end of this paper, we discussed the conclusions and expatiated on the applied value of the model.

---

* Corresponding author.
E-mail address: huim@bit.edu.cn (M. Hui).

http://dx.doi.org/10.1016/j.optcom.2015.05.049
0030-4018/© 2015 Elsevier B.V. All rights reserved.

2. Model simulation and aberration analysis

A typical microlens placement scheme is illustrated in Fig. 1(a). Tiny optical lens is placed over the metal light shield of a photodiode. It serves to concentrate light onto photodiode surface instead of allowing it to fall on non-photosensitive areas. Our optical model is built based on the analysis of MLA in KAI 16000 imaging detector. This microlens is a single element with one plane surface and one spherical convex surface to refract the light.

2.1. MLA structure and optical model

Kodak KAI-16000 image detector is an array of 4728(H) × 3248(V) with 7.4 μm square pixels. Fig. 1(b) shows micrograph of MLA provided by Eastman Kodak Company. Each microlens is a plano-convex lens with former spherical surface, and the main parameters are illustrated in Fig. 1(c).

Height at the vertex h_L is about 2.6 μm as measured by a microscope, and $r=D/2=3.7$ μm. Then, the radius of curvature at the vertex can be given by:

$$R = \frac{h_L}{2} + \frac{r^2}{2h_L} \tag{1}$$

The vertex focal length f of the plano-spherical refractive lens is:

$$f = \frac{R}{n(\lambda) - 1} = \frac{h_L + r^2/h_L}{2(n(\lambda) - 1)} \tag{2}$$

The focal length f is a function of the wavelength λ due to material dispersion. Refractive index of fused silica microlens is $n(\lambda=632.8\ \text{nm}) \approx 1.46$. The lens profile $h(r)$ is a function of the R, r and aspherical constant K. As $h(r)$ is spherical here, $K=0$, the lens profile is generally described by:

$$h(r) = \frac{1}{R}\cdot\frac{r^2}{1 + \sqrt{1 - r^2/R^2}} \tag{3}$$

We developed a single microlens model of Kodak KAI- 16,000 image detector based on Fig. 1. Wavelength of light is set to 632.8 nm in Zemax, and incident angles are set to +14°, 0° and −14° as the GMT has an $f/2.1$ focal ratio for 8.4 m segmented mirror. Aperture type of MLA is “Entrance Pupil Diameter” and its value is 7.4 μm. According to Kodak KAI- 16,000 CCD product description [14], results of Eq. (1–3) and photomicrograph, the parameters of MLA are determined. Key parameters are listed in Table 1. Non-sequential model is shown in Fig. 2(a).

Table 1
Key parameters of microlens model.

Parameters	Value
Lens diameter (D)	7.4 μm
Height at the vertex (h_L)	2.6 μm
Radius of curvature at the vertex (R)	3.9 μm
Vertex focal length (f)	≈ 8.5 μm
Aspherical constant (K)	0
Refractive index, $n(\lambda=632.8\ \text{nm})$	1.46

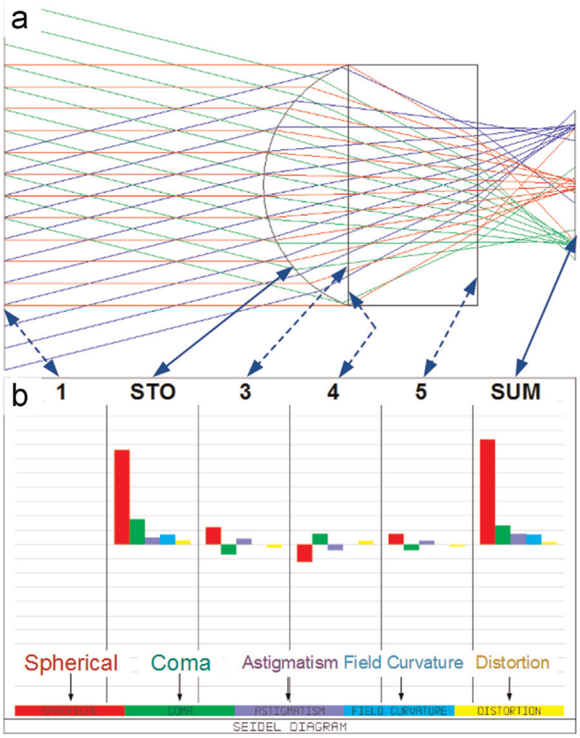

Fig. 2. KAI-16000 microlens optical system. Plane 1 represents the incident light source, STO is the aperture stop, planes 3–5 respectively represent the rear surface of spherical lens, front and rear surface of substrate, and SUM is the image plane. (a) Non-sequential model. (b) Seidel diagram.

2.2. Aberration analysis

We analyze the MLA aberration with Zemax software. This effort aims to explore the connection between MLA aberrations and spot centroid movement.

2.2.1. Seidel aberrations of MLA

Microlens aberration can be expressed in various forms. Seidel aberration is researched, as it breaks down the microlens aberrations into five quantities and they can be manipulated arithmetically. If we neglect the higher order terms, the approximate function of microlens aberration can be expressed in terms of Seidel coefficients as [15]:

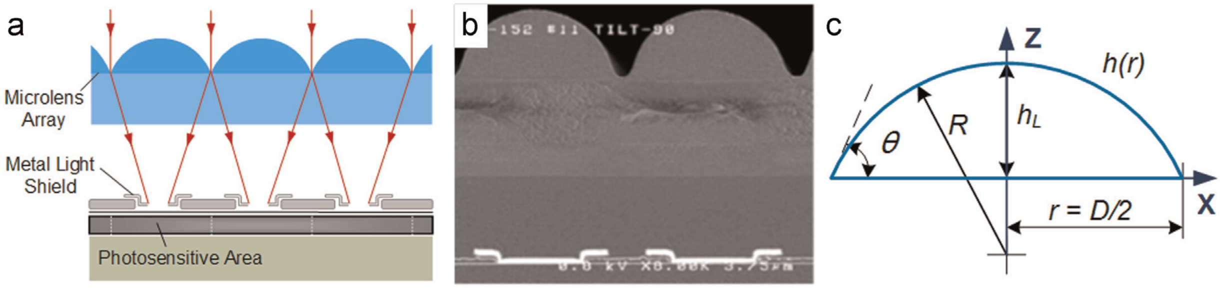

Fig. 1. (a) Typical microlens placement scheme. (b) Micrograph of microlens array, each microlens unit is plano-convex lens with former spherical surface and corresponds to one pixel. (c) A plano-convex microlens is described by the lens diameter D, the height at the vertex h_L, the radius of curvature R, the refractive index n and the contact angle θ.