# Development of ZnS Lenses for FIR Cameras

Tomoyuki UENO*, Masato HASEGAWA, Masashi YOSHIMURA, Hiroshi OKADA,
Takao NISHIOKA, Kanji TERAOKA, Akihito FUJII and Shigeru NAKAYAMA

Recently, demand for far infrared ray (FIR) cameras, which visualize objects without any light source, has been increasing for security purposes and other applications such as night vision devices installed in vehicles. For such reasons, the development of affordable lenses is demanded and Zinc sulfide (ZnS) lens will be one of the solutions. The authors have currently realized a low-price ZnS lens by a newly developed precise mold-forming process utilizing powder metallurgical technology, in which ZnS powder is molded and sintered directly into a perfect lens shape at the same time. The ZnS lens has excellent characteristics such as high-purity FIR transmission from 8 to 12μm in wavelength (equivalent to conventional, expensive chemical vapor deposition (CVD) products), optical surface roughness of less than 0.020 μm on average and profile errors within 3 μm. In addition, a ZnS lens has remarkable modulation transfer function (MTF) performance to make images clearer in detail. To conclude, a ZnS lens is suitable for FIR optics.

Keywords: far-infrared ray camera, zinc sulfide lens, net-shape molding process, low cost, MTF

## 1. Introduction

Far-infrared ray (FIR; wavelength 8 to 12 μm) cameras can detect the surface temperature of objects without any light source. Therefore, they are widely used for night vision systems and other industrial or consumer electronic applications [(1), (2)]. Demand for FIR cameras is expected to increase by 10% or more [(3)] every year.

The prices of such FIR cameras are still very expensive, but to promote their broad use in the future, affordable FIR cameras are in need. For this reason, the development of economical lenses is strongly demanded. Currently, a germanium lens, which has advantages of high refractive index and transmission, is mainly used for the FIR. However, it is very expensive due to the finishing process of the lens surface shape, such as machining, grinding and ultra precision cutting, as well as the scarcity of germanium metal. Recently, chalcogenide glass [(4), (5)] is suggested as a solution for price reduction, but its cost cutting effect seems to be insufficient because chalcogenide glass contains germanium as its element.

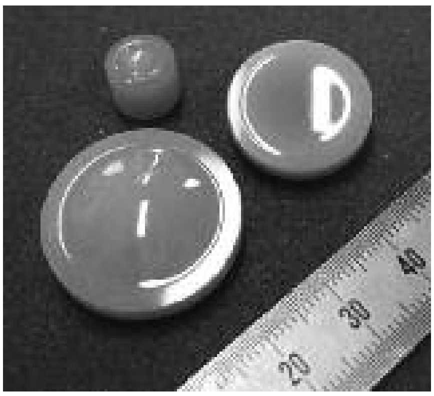

**Photo 1.** Developed ZnS lens

The authors successfully developed a zinc sulfide (ZnS) lens, shown in **photo 1**. It has a remarkable economical advantage and good optical performance, and will be a possible replacement of a germanium lens. In this paper, the fabricating process, physical and geometric characteristics, and optical performance of the ZnS lens are reported in detail.

## 2. Development of ZnS lens using powder metallurgy process

Generally, highly purified and dense ZnS material has been fabricated by a chemical vapor deposition (CVD) process. However, CVD-ZnS is not suitable for commercial use due to the expensive costs of its raw materials and production equipment. Therefore, the authors started the development of a powder metallurgy process by using ZnS raw powder to make more economical lens compared to CVD-ZnS. The developed process consists of a sintering process with highly purified and dense ZnS material and a net-shape molding process in which optical surfaces are formed without finishing. A schematic process diagram and detail process diagram of the most important molding process are shown in **Fig.1 and 2**, respectively. In this process, ZnS powder is sintered and molded directly into a lens shape at the same time, using the developed precise molding die. Thus, the authors succeeded in shortening sintering time, which usually takes more than ten hours, and making a dense body with a relative density of 99.8% or more. The authors solved the above problem by rigidly controlling a sintering temperature and pressure as well as managing the grain size and purity of ZnS powder to shorten the sintering time. **Photo 2** shows a scanning electron microscope (SEM) image of the developed ZnS lens surface. It shows closely-packed crystal structures without

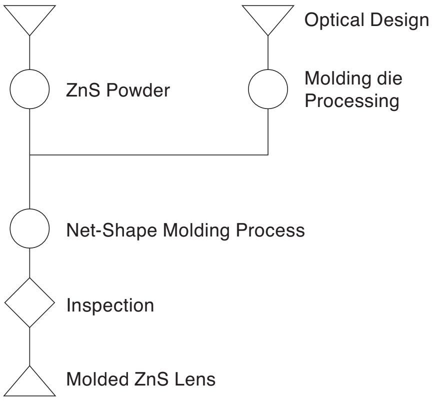


**Fig. 1.** Fabrication Process of Molded ZnS Lens

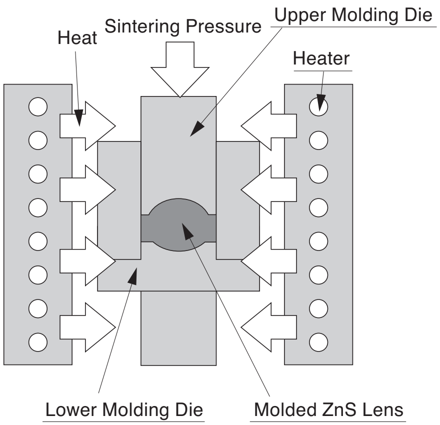


**Fig. 2.** Diagram of Net-Shape Molding Process

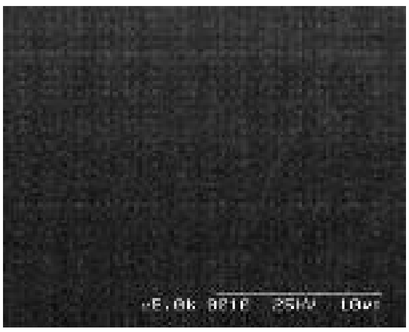

**Photo 2.** Structure of ZnS Lens Surface

any pores and impurities which can cause FIR scattering.

**Table 1** shows the mechanical and thermal properties of the developed ZnS lens. It has the same properties with CVD-ZnS [(6)].

**Figure 3** shows the surface roughness of the developed ZnS lens and molding die with a 3D surface profiler (ZYGO Corporation; New View), respectively. The surface roughness of the molding die shows Ry: 0.025 µm and Ra: 0.003 µm, while that of ZnS lens shows Ry: 0.036 µm and Ra: 0.003 µm. This result describes that the surface roughness of the molding die is excellently transcribed to the ZnS lens and the developed ZnS lens has a sufficient optical surface level of Ra≦0.020µm.

**Table 1.** Mechanical Characteristic

| Item | Unit | Molded ZnS | CVD-ZnS |
|---|---|---|---|
| Bending Strength | MPa | 86 | 98 |
| Knoop Hardness | | 231 | 230 |
| Young's Modulus | GPa | 86 | 75 |
| Thermal Expansion Coefficient | $\times10^{-6}$/K | 6.7 | 6.7 |
| Thermal Conductivity Index | W/(m·K) | 17 | 17 |

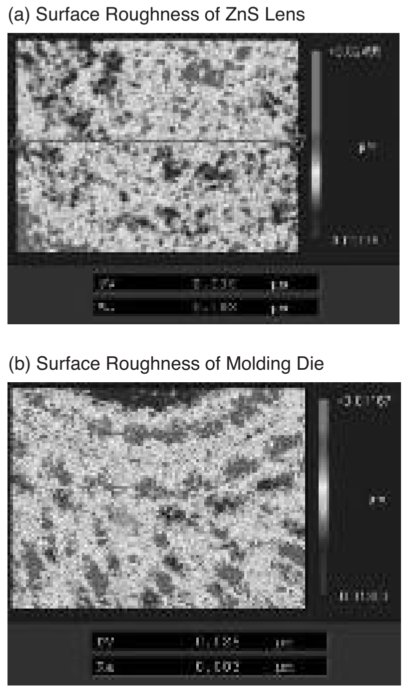


**Fig. 3.** Surface Roughness of ZnS Lens and Molding Die

## 3. Optical characteristics of ZnS material

**Table 2 (a)** shows the FIR transmittance of the developed ZnS lens and CVD-ZnS (thickness: 3 mm). It was measured by Fourier transform infrared spectrometer (JASCO Corporation: FT/IR-6100). In the result, the average transmittance of the developed ZnS lens in the wavelength range between 8 and 12 µm (an important characteristic as the FIR camera lens) is 71%, almost equal to 72% of the CVD-ZnS. Thus, the authors conclude that the developed molding process is suitable as a mass-production process of the ZnS lens and that the developed ZnS lens has excellent FIR transmittance for practical use. In addition, **Table 2 (b)** shows the transmittance data of the ZnS lens coated with anti-reflection (AR). In the wavelength range between 8 to 12 μm, the average transmittance of ZnS material coated with AR is improved to 91%.

The refractive index of the ZnS lens measured by FT/IR-6100 is shown in **Fig. 4**. The refractive index of ZnS is the same as CVD-ZnS's. In addition, Abbe's number ※1 of ZnS in the wavelength range between 8 and 12 μm is also the same as CVD-ZnS's.

**Table 2 (a).** FIR Transmission of ZnS Lens

| Wavelength (μm) | FIR Transmission (%) | |
|---|---|---|
| | Molded ZnS | CVD-ZnS |
| 4 | 63 | 64 |
| 5 | 68 | 67 |
| 6 | 71 | 58 |
| 7 | 72 | 71 |
| 8 | 73 | 73 |
| 9 | 74 | 74 |
| 10 | 74 | 74 |
| 11 | 67 | 67 |
| 12 | 65 | 68 |
| 13 | 54 | 54 |
| 14 | 35 | 36 |

(thickness: 3 mm)

**Table 2 (b).** FIR Transmission of ZnS Lens with AR Coating

| Wavelength (μm) | FIR Transmission (%) | Wavelength (μm) | FIR Transmission (%) |
|---|---|---|---|
| | With AR coating | | With AR coating |
| 4 | 76 | 10 | 95 |
| 5 | 78 | 11 | 85 |
| 6 | 92 | 12 | 79 |
| 7 | 94 | 13 | 60 |
| 8 | 94 | 14 | 35 |
| 9 | 95 | | |

(thickness: 3 mm)

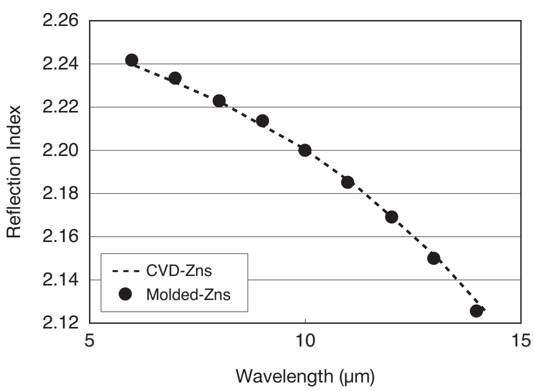


**Fig. 4.** Refractive Index of FIR

## 4. Precision of the ZnS lens

**4-1 Development of ZnS lens with highly precise shape**

Using the developed process, the ZnS lens can be molded into spherical, aspherical and diffractive optical element ※2 (DOE) shapes. In such cases, it is necessary to develop a design technique to make those shapes with perfect precision. This is because the ZnS lens needs to be molded under high pressure and high temperature compared with a normal glass lens made by a conventional molding process.

A major problem in the molding process of ZnS lens is a profile error of micron order. This is happen because the shape of the ZnS lens is affected by the elastic deformation caused by the thermal expansion difference between ZnS and the molding die under the sintering pressures. It is necessary to calculate an acceptable error margin for the designed lens shape using the allowance analysis method of an optical simulation. **Figure 5** shows the relation of the MTF ※3 value and profile error of the ZnS lens designed to be 21 degrees in field of view (FOV) and 19 mm in focal length. The value of MTF decreases with an increase in the value of the profile error. Therefore, the authors set the target value of the ZnS lens form accuracy to below 3 μm to keep practical MTF performance. The MTF performance of ZnS lens made by the molding process can reach the equivalent value to that of lens made by a machining method when the reduction of MTF is within 10% of the designed value.

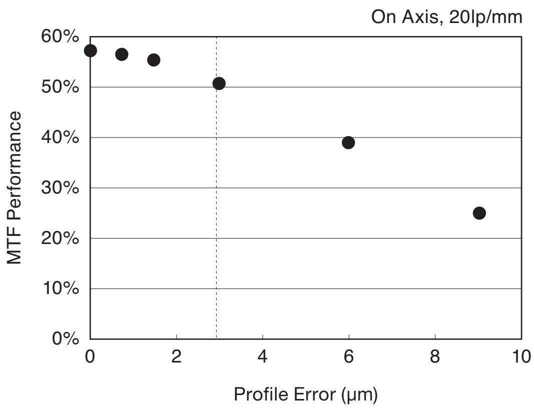


**Fig. 5.** Relationship of MTF Performance and Profile Error

The adjusting technique of the profile error between a lens and its original design was already reported (7). However, with the method the molding die needs to be modified more than twice to make a highly precise lens, resulting in the cost increase. The authors tried to reduce the costs and keep high precision in the lens form simultaneously by using pre-designed molding die. The molding die adjusts the profile error caused by thermal expansion difference between the molding die and lens as well as their elastic deformation. This principle is shown as follows. The formula (1) shows the shape of an aspherical lens. The formula (2) shows an aspherical lens shape to decrease the influence of the profile error caused by thermal expansion difference.

$$Z = \frac{C \cdot r^2}{\left(1+\sqrt{1-(1+K)C^2 \cdot r^2}\right)} + \sum A_i \cdot r^i \quad \cdots\cdots\cdots\cdots \ (1)$$

$$Z = \frac{C \cdot r^2}{\left(1+\sqrt{1-(1+K)C^2 \cdot r^2}\right)} + \sum A_i \cdot r^i + \sum B_i \cdot r^i \quad \cdots\cdots \ (2)$$

$$C = \frac{1}{R} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \ (3)$$

$Z$ : Ordinate of aspherical lens shape
$r$ : Abscissa of aspherical lens shape
$R$ : Radius of curvature
$K$ : Conic number
$A_i$ : Aspheric coefficient
$B_i$ : Coefficient of invalidate thermal expansion difference

On the other hand, it is necessary to invalidate the influence of elasticity deformation by molding pressure. Therefore, the authors considered various factors including Young's modules, Poisson ratio, molding pressure and so on under the molding temperature. The authors also needed to calculate the amount of elasticity deformation by computer-aid engineering (CAE) analysis. Formula (4) shows an aspherical lens shape to decrease the influence of the profile error caused by the elasticity deformation.

$$Z = \frac{C \cdot r^2}{\left(1+\sqrt{1-(1+K)C^2 \cdot r^2}\right)} + \sum A_i \cdot r^i + \sum B_i \cdot r^i + \sum C_i \cdot r^i \quad \cdots\cdots \ (4)$$

$C_i$ : Coefficient of invalidated elasticity deformation

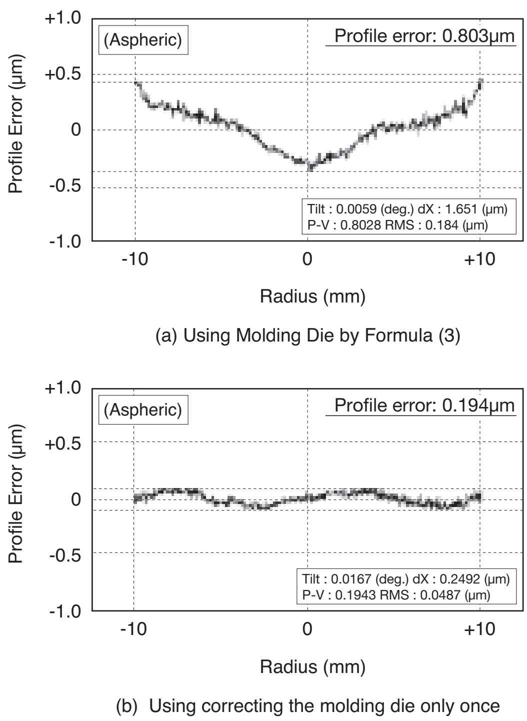


**Fig. 6.** Profile Error of Aspherical ZnS Lens

The profile error of the developed asperical ZnS lens whose effective diameter is ø20 mm is shown in **Fig. 6 (a)**, in which the molding die calculated by the formula (4) was used. The lens shape was measured by laser probe 3D measuring equipment (Mitaka Kohki co., Ltd.). As a result, the profile error of the ZnS lens was improved to 0.803 µm, achieving our target figure of under 3µm. In addition, the authors succeeded in fabricating a precisely-shaped asperical lens with profile error 0.194 µm, which is equivalent to a result by the machining method. This result was obtained by correcting the molding die only once.

**4-2 Development of DOE shaped ZnS lens**

**Table 3** shows the optical characteristic of ZnS and germanium [(8)] lens. Compared with germanium, ZnS has advantages such as less FIR reflectance loss and less temperature dependence of the refractive index (dn/dT). On the other hand, it is necessary to decrease chromatic aberrations using diffraction effects to use ZnS lens for high resolution imaging cameras. This is because Abbe's number ※4 of ZnS is lower than that of germanium. The performance of a DOE-shaped ZnS lens is shown in **Table 4** by the comparison with an aspherical ZnS lens. The MTF performance of a DOE-shaped ZnS lens is better than that of a singlet ZnS lens in an aspherical shape designed to be 18 degrees in FOV and 12.6 mm in focal length.

**Table 3.** Characteristic of FIR Materials

| Item | Zinc Sulfide (ZnS) | Germanium |
|---|---|---|
| Refractive Index@10µm | 2.200 | 4.003 |
| Abbe's Number (8 to 12µm) | 22.7 | 942 |
| dn/dt [$K^{-1}$] | $4.1\times10^{-5}$ | $40.0\times10^{-5}$ |

**Table 4.** Designed MTF Performance of ZnS Lens

| Item | MTF Performance (10lp/mm) | | |
|---|---|---|---|
| | FOV: 0° | FOV: 6.8° | FOV: 9° |
| Aspherical Shaped | 24% | 26% | 20% |
| DOE Shaped | 70% | 71% | 66% |

The DOE configuration of a ZnS lens can be calculated from the refractive index in wavelength of 10 µm, as shown in formula (4). The DOE configuration shows a minute difference of about 8.3 µm in the height of lens surfaces.

$$D_h = \frac{\lambda_{10\mu m}}{(n_{10\mu m}-1)} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \ (5)$$

$D_h$ : Height of DOE difference
$\lambda_{10\mu m}$ : Wavelength
$n_{10\mu m}$ : Refractive index at wavelength 10 µm of ZnS material

Generally, in the case of the DOE shape, a sharp DOE edge whose width is only 1 to 3 µm is processed on the lens surface by a machining method using a single crystalline diamond byte with a sharp edge [9]. However, when the authors fabricated the ZnS lens by the molding process, it was necessary to manage the reaction of ZnS powder, fill the minute differences of DOE, and prevent edge chipping. To this end, the authors developed the molding die with great potential for imprinting and high durability by adjusting the DOE sharp edge to the minute curvature that doesn't influence the optical characteristic. The surface image of the DOE shape and the cross-section image in detail are shown in **Photo 3**. There is no chipping in the DOE edge. The width of the DOE shape is less than 5 µm, which is the same as the machining.

Next, the profile error of the DOE ZnS lens shaped by the developed molding process is shown in **Fig. 7**. The profile error of an aspherical ZnS lens removed the DOE difference is shown in **Fig. 8**. The DOE shape is processed uniformly and sharply within the optical effective diameter. Furthermore, the DOE shaped ZnS lens has a highly precise shape with a profile error of 0.239 µm, as shown in **Fig. 8**.

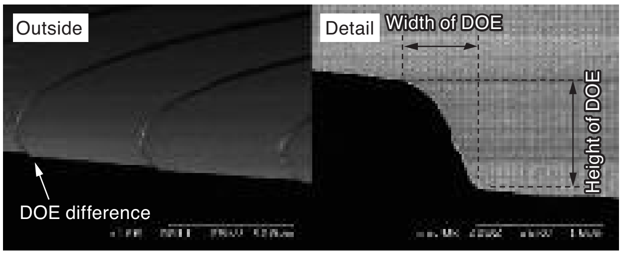


**Photo 3.** DOE Shaped ZnS Lens

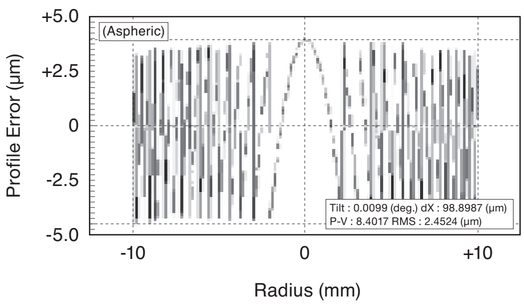


**Fig. 7.** Profile Error of DOE Shaped ZnS Lens

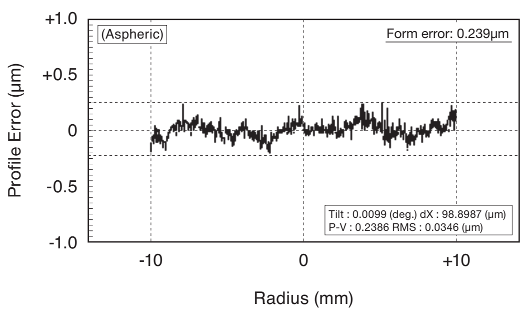


**Fig. 8.** Profile Error of Removed DOE Difference

## 5. FIR camera performance with ZnS lens

### 5-1 MTF performance

Generally, the MTF performance shows the resolution of the image through a lens. The decrease in MTF value is mainly caused by errors in lens shape, thickness and the decentering. The MTF shows the overall optical performance of a lens and is measured by OPT-IR (Optikos corporation, LWIR OpTest lens MTF system).

**Figure 9** shows the designed MTF value of the optical system designed to be 21 degrees in FOV and 19 mm in focal length. **Table 5** shows the MTF measurement results of the developed ZnS lens unit by the molding process and a machined lens unit in each angle with the designed value. The MTF performance of the developed ZnS lens unit is the same as the designed value and the machined one.

### 5-2 Image of FIR camera

**Photo 4 (a)** shows the FIR camera image through the developed ZnS lens unit by the molding process, while **photo 4 (b)** shows the FIR camera image through the machined ZnS lens unit. Both images have almost the same quality of the definition in detail and brightness. Especially, an FIR camera with a ZnS lens can produce a clear image of a thermal source corresponding body tempera-

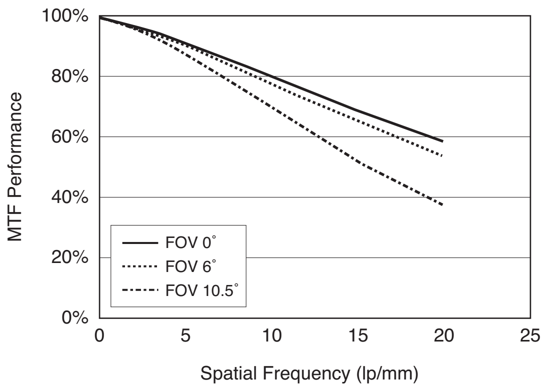


**Fig. 9.** Designed MTF Performance

**Table 5.** MTF Measurement Results

| Item | MTF Performance (20lp/mm) | | |
|---|---|---|---|
| | FOV: 0° | FOV: 6° | FOV: 10.5° |
| Designed | 58% | 54% | 38% |
| Machined ZnS lens Unit | 58% | 53% | 37% |
| Developed ZnS lens Unit (Molding process) | 54% | 51% | 36% |

ture. As a result, the developed ZnS lens is suitable for FIR optical devices which require high resolution.

(a) Using Developed ZnS Lens (Molding process)  (b) Using Machined ZnS Lens

**Photo 4.** Image of FIR Camera with ZnS Lens

## 6. Conclusion

The authors have currently realized an economical ZnS lens for FIR cameras by a newly developed precise net-shape molding process, utilizing powder metallurgical technology. It enables to mold a ZnS lens into spherical, aspherical and DOE lens shapes. The ZnS lens also has an optical surface of Ra≦0.020μm and a highly precise lens shape with a profile error under 3μm.

The developed ZnS lens has excellent optical characteristics such as the FIR transmittance between 8 and 12 μm in wavelength (equivalent to CVD-ZnS) and remarkable MTF performance which enables to produce clear images in every detail as much as a machined ZnS lens.

In conclusion, the developed ZnS lens has an economical advantage and suitability for FIR optics instead of germanium and chalcogenide glass lenses.

* ZYGO and New View are trademarks or registered trademarks of Zygo Corporation.

**Technical Term**

※1 Abbe's number: The inverse of dispersion index. A largeer Abbe's number indicates less dispersion.

※2 DOE: An optical element to control the reaction of beams in this paper. DOE is used to decrease the chromatic aberration.

※3 MTF performance: An indicator of optical lens resolution.

※4 Chromatic aberration: Dispersion caused by the differences in the refractive indexes of wavelength.

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**Contributors** (The lead author is indicated by an asterisk (*)).

T. UENO*

- Advanced materials R&D Department, Electronics & Materials R&D Laboratories
  Development of Fundamental Ceramics Materials & Processes at Work

M. HASEGAWA

- Assistant Manager, Advanced materials R&D Department, Electronics & Materials R&D Laboratories

M. YOSHIMURA

- Doctor of Engineering, Assistant General Manager, Advanced materials R&D Department, Electronics & Materials R&D Laboratories

H. OKADA

- Assistant General Manager, Advanced materials R&D Department, Electronics & Materials R&D Laboratories

T. NISHIOKA

- Doctor of Engineering, General Manager, Advanced materials R&D Department, Electronics & Materials R&D Laboratories

K. TERAOKA

- Assistant Manager, Engineering Department, Hybrid Products Division

A. FUJII

- Assistant General Manager, Engineering Department, Hybrid Products Division

S. NAKAYAMA

- Manager, Engineering Department, Hybrid Products Division