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Design of Far-infrared Optical System for Night Object Recognition for Safe Driving of Intelligent Automobile

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Abstract*: *This paper deals with the design of an optical system for a far-infrared camera for night object recognition for driver's safe driving assistance of an intelligent vehicle. It was designed by considering the specification and mass production required for night vision of automobile. We designed the far-infrared optical system applying germanium optical system with 3 spherical configuration by using OSLO which is a special program for optical design. An optical system for a far-infrared ray camera with a wavelength band of 8~13[μm] was designed by applying germanium, which is a high-refractive index special material, so that the image can be realized by sensing radiant energy emitted by the subject. The designed optical system showed a total track length(TTL) of 35[㎜], a focal length of 15.93[㎜] and a horizontal angle of view of 26°. We have designed optical system for far-infrared ray camera with 3 spherical surfaces using germanium. We made optical design considering the mass production and miniaturization when manufacturing optical system. In addition to night vision systems for automobiles, it can spread to various fields such as crime prevention, fault diagnosis of high-voltage electric wires, body heat analysis and building insulation measurement.

Index Terms: Thermal infrared, Far-infrared, Automotive night vision, Optical system design, High-refractive index, Spherical optics

I. INTRODUCTION

Far-infrared optical system is applied to the automotive night vision system to assist view and safe driving for drivers at night. Night vision is a technology that combines infrared and thermal imaging technology to reproduce radiant heat emitted by a subject. Night vision has effect ensuring 5 times of vision for low beam or 3 times of vision for high beam. In general, in the event an object out of vision of a driver appears at night such as a person replacing tires at roadside, or an animal or a person on the road, most cases result in unavoidable accidents. Night vision is a system to duplicate safety of a car so as to allow the driver to sense dangerous situation by providing visual information much exceeding human sight in the dark[1]. Figure 1 shows a night vision to sense cars on the opposite lane and persons and an image on the automotive display during driving at night[2].

Far-infrared camera senses radiant heat of long wavelength in 3~5[μm] or 8~13[μm] emitted by the subject to implement images under no light source. When an optical system composing the far-infrared camera uses crown base or flint base optical glass that is usually used, it cannot react with long wavelength light nor play optical performance. Therefore, the optical system of the far-infrared camera uses high refractive special material to react to the long wavelength such as Ge, Si, ZnS, ZnSe, etc. Since these high refractive materials are sensitive to thickness of lenses, light transmittance becomes extremely low depending on lens thickness and have characteristics of metals with very difficult manufacturing feasibility, they require a lot of cutting and grinding fluids[3].

Accordingly, optical system of far-infrared cameras mainly uses spherical lenses that are relatively easy to be manufactured. When the optical system consists of spherical lenses only, it becomes larger and heavier and restricts on size, shape, etc. of lenses. Although spherical shape restricts degree of surface freedom and optical performances, spherical lens design allow easy machining and reduces manufacturing cost of the optical system upon design methods comparing to non-spherical lens design[4].

Fig. 1. Configuration of automotive night vision system (Audi A8)

This paper describes design of an optical system for subminiature far-infrared cameras applicable to the automotive night vision system with detection of far-infrared ray in order to increase optical

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performances by improving shape and array of lenses using spherical surface and contribute to stable optical performance and correct detection of far-infrared ray. In addition, it describes study on design of a subminiature far-infrared optical system using spherical surface to allow miniaturization of the system by implementing improvements of resolution and F-number.

An optical system to sense or detect heat from subjects by detecting far-infrared ray has been designed with convex surface of positive refractive power at object side and concave surface of negative refractive power at image side so that the entire optical system can have positive magnification. Visible distance of the far-infrared optical system to be applied to the automotive night vision system shall be generally 150m or longer with narrower angle of view than that of the optical system to be applied to normal digital products[5].

Accordingly, this paper has designed an optical system for a far-infrared camera with 26° of horizontal angle of view, TTL 35[㎜] and 15.93[㎜] of focal distance.

II. Materials and Methods

The far-infrared optical system must sense radiant energy emitted by a subject under no external light source and reproduce it as images to allow easy recognition of objects. Though an imaging equipment with the existing optical system observes objects with existence of visible light and intensity difference of reflective light, the far-infrared optical system makes images from difference of radiant energy emitted per unit area of an object and per unite time to allow observation without light at night[6]. Although it was impossible to implement images in real time at an early stage of developing the far-infrared camera with far-infrared optical system due to delayed response time of the detector, devices having short time constant had been manufactured due to development of detection materials and introduction of cooling method early 1950s and they have been regularly used for military night observation or fire control devices since middle of 1970s[7].

For far-infrared detection sensors, various shapes of the 1st generation detection sensors started from parallel injection method in USA since middle of 1970s, serial injection method at the end of 1970s and serial/parallel injection method in UK and France since middle of 1980s. Researches on the 2nd and 3rd generation detection sensors with excellent resolution and detection performance and increased reliability have started since middle of 1980s[8]. For the 1st generation devices, the number of devices has been limited to 10~200 due to difficult manufacture of them and it was difficult to have sufficient resolution. The 3rd generation sensors with Infrared Focal Plane Array have excellent heat resolution and increased optical resolution due to increased number of pixels up to several hundred thousand[9].

For cameras with far-infrared optical system and detection device, there is constant increase of demand in industrial areas such as security monitoring, disaster rescue firefighting helmet, high voltage cable maintenance, building insulation test, etc., but they are all imported and high price of difficult distribution. In addition, there is remarkable growth of body heat diagnosis system as medical imaging equipment and also rapid growth of demand due to development of inspection equipment for PCB test using far-infrared camera with a trend of thin and compact for electronic parts[10]. This far-infrared camera has been used for driving cars at night. This study has proceeded design of an optical system for automotive night vision cameras with subminiature high resolution pixels to detect radiant heat and obtain real time images using far-infrared detection sensor in order to meet constantly increasing demand. Figure 2 shows images for areas where the far-infrared camera is utilized such as body heat image diagnosis, semiconductor test, automotive night vision, security camera, etc.

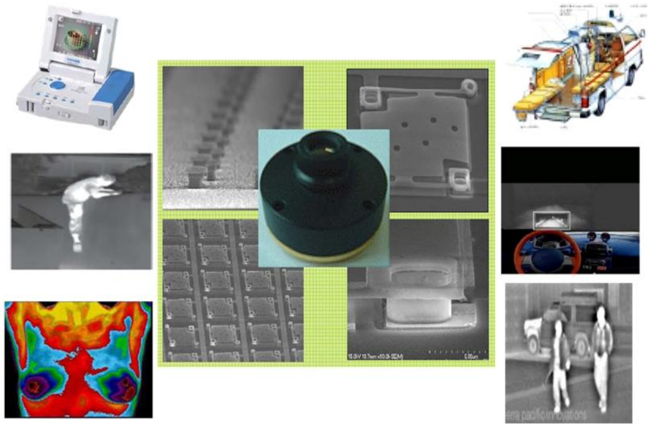

Fig. 2. Utilizations of far-infrared camera

Infrared ray is electromagnetic wave of 0.77~1,000[μm] wavelength bandwidth existing between visible light and radar communication wavelength. Infrared ray is usually classified into short wave infra-red(SWIR) up to 0.77~3[μm], mid wave infra-red(MWIR) up to 3~6[μm], long wave infra-red(LWIR) up to 6~15[μm] and extreme infra-red up to 15~1,000[μm][11]. Infrared bandwidth is partially utilized including wavelength of energy emitted by military targets, short wave infrared around 1[μm] due to characteristics of detectors and penetration characteristics of air, mid wave infrared of 3~5[μm], long wave infrared of 8~13[μm], etc.

Especially, thermal imaging to make images with energy difference uses mid and long wave infrared. Thermal imaging easily obtains images at night without light as well as on daytime and penetrates smokescreen in visible light bandwidth, so it is much utilized as monitoring equipment. Wavelength used for far-infrared cameras is 8~13[μm] bandwidth to allow reception of radiant heat to sense subjects without light[12]. Figure 3 shows categories of optical sensors per wavelength of light.

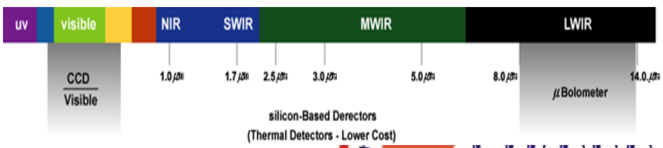

Fig. 3. Optical sensor per wavelength of light

The optical system for far-infrared cameras with usually crown base and flint base optical glasses does not react to long wavelength of light, so it cannot play optical performance. Accordingly, it uses high refractive special materials such as Ge, Si, ZnS, ZnSe, etc. These materials are sensitive to thickness to extremely decrease light transmittance upon thickness of a lens and have metal characteristics that are difficult to be cut and uses a lot of cutting and grinding fluid[13]. Figure 4 shows glass map indicating classification of usual optical glasses upon refractive index and Abbe's number.

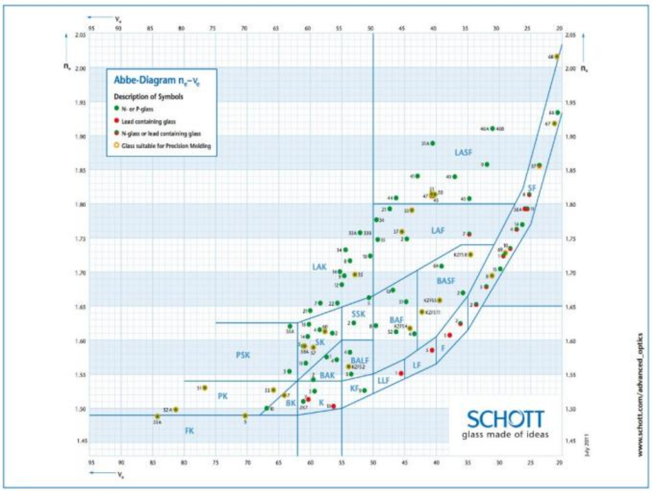

Fig. 4. Glass map (SCHOTT)

Table 1 shows mechanical, thermal and optical characteristics of a high refractive special material, germanium.

Table 1: Germanium properties sheet

		Unit	Germanium
Mechanical properties	Density(298K)	10^3 [kg/m³]	5.32
	Young's modulus(298K)	GPa	103
	Poisson's ratio		0.28
Thermal properties	Thermal expansion coefficient(298K)	10^{-6} [K^{-1}]	5.9
	Specific heat(298K)	J/g.k	0.31
	Thermal conductivity(298K)	W/m.k	60
	Melting point/ Glass temperature	K(℃)	1,210 (940℃)
Optical properties	Refractive index (at 10.6[μm])		4.0
	Index homogeneity	$\times 10^{-6}$	10~100
	Temperature coefficient(dn/dt)	10^{-6} [K^{-1}]	400
	Spectral range	μm	2.0-15
	Absorption coefficient	10^{-3} [cm^{-1}]	27

The optical system for far-infrared cameras mainly uses spherical lenses to allow relatively easy manufacturing. When an optical system is fabricated with spherical lenses only with grinding method, it becomes large and heavy with large restriction on shape, degree of surface freedom size and optical performance as well[14]. This paper describes design of an optical system for subminiature far-infrared cameras applicable to the automotive night vision system with detection of far-infrared ray in order to increase optical performances by improving shape and array of lenses using spherical surface and contribute to stable optical performance and correct detection of far-infrared ray. In addition, it describes study on design of a subminiature far-infrared optical system using spherical surface to allow miniaturization of the system by implementing improvements of resolution and F-number.

A far-infrared optical system to react to wavelength of far-infrared to sense/detect radiant heat has been designed with convex surface of positive refractive power at object side and concave surface of negative refractive power at image side so that the entire optical system can have positive magnification. The designed optical system has been adjusted to be applied to the automotive night vision cameras. Generally detection distance of the automotive night vision system is 150[m] or longer, so its optical system shall have narrow angle of view. Therefore this study has designed an optical system for far-infrared cameras with horizontal angle of view 26° and TTL 35[mm].

III. Results and Discussion

This study has used a dedicated optical design program, OSLO in order to design an optical system for far-infrared cameras. The optical system for far-infrared cameras has 3 spherical lenses. Since general detection distance of the far-infrared cameras for automotive night vision is 150m, this optical system design has applied the same number. In addition, since the angle of view to detect objects in long distance should be narrower than that of an optical system for usual digital equipment, this design has horizontal angle of view 26°. Material of the optical system uses Germanium, TTL that is distance from its first surface to receive radiant heat to surface of the detecting sensor is 35[mm] and focal length is 15.93[mm]. Table 2 shows specifications of the optical system for far-infrared cameras for automotive night vision.

Table 2: Far-infrared camera optical system specifications

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Description	Specifications
Source wavelength	8~ 13[μm]
Focal length	15.93[mm]
Total track length(TTL)	35[mm]
F-number	1.0
Image height	26˚
Lens construction	3SG

Figure 5 shows 2D design of the optical system for far-infrared cameras for automotive night vision. As shown on the figure, the optical system has 3 spherical lenses and aperture stop is located before the lens #2.

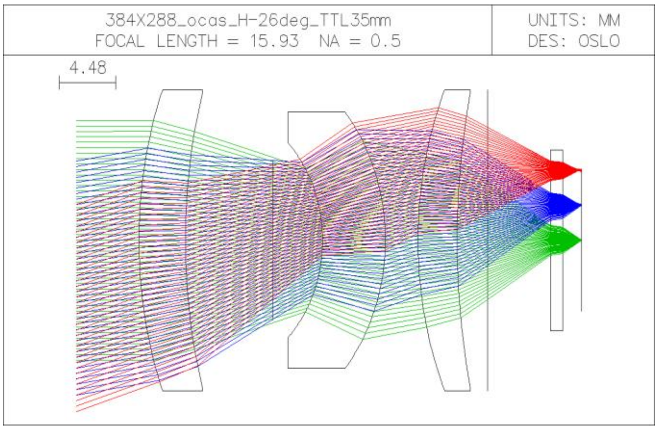

Fig. 5. Optical system design drawing (2D)

Figure 6 shows 3D design of the optical system to check sectional shape of the designed lenses. From the left to the right, there are Lenses #1, #2 and #3. We can see that Lenses #1 and #2 have opposite shapes each other.

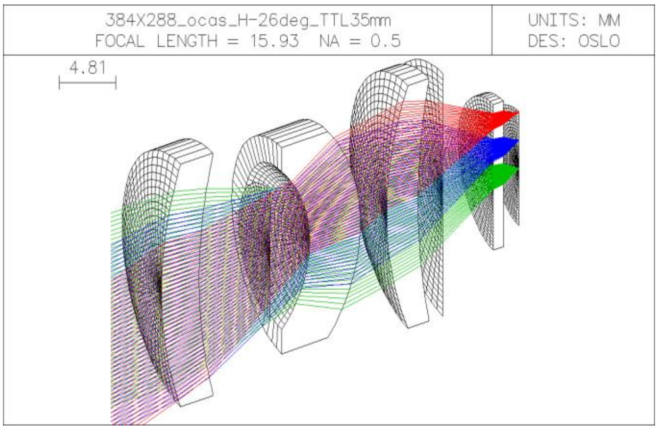

Fig. 6. Optical system design drawing (3D)

Figure 7 shows ray trace indicating various aberrations arising from optical system design. Ray trace analysis allows analysis of various aberrations, distortion, etc. arising from optical system design. As shown on the figure, coma of each field much increases, astigmatism also shows large number. Optical axis spherical aberration and chromatic aberration do not have large difference and comprehensive design evaluations shows that they have no problem. So we can see that this design stably transfers images.

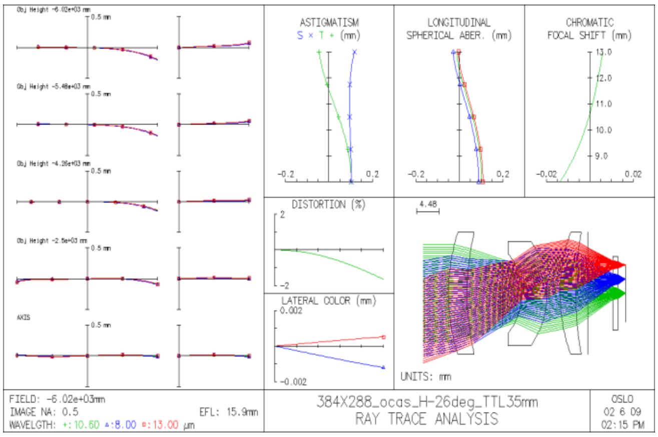

Fig. 7. Optical system ray trace analysis

Figure 8 shows modulation transfer functions(MTF) graph to indicate resolution of images at horizontal angle of view 26°. Resolution is indicated for 0.25, 0.5, 0.75 and 1.0 of image screen from 12[mm] to 60[mm] around the light axis. We can see that the best resolution of image around the light axis is 1.0 and resolution becomes lower as it goes away from the light axis. We can see that average resolution at 40[mm] from the light axis is 26% and the lens has good resolutions. Declined lines on MTF graph are resulted from difficult correction of off-axis aberrations for spherical optical systems.

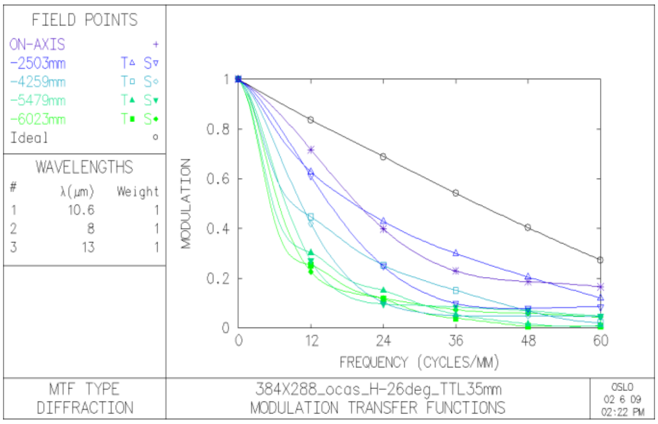

Fig. 8. Optical system MTF graph

Figure 9 shows MTF weighted graph of each field for the designed optical system. Optical design should consider MTF weight of each field. We can see that MTF weight keeps a little regular distribution at the center but a little irregular distribution at ± displacement of focus on X axis based on field. Therefore, we can see that MTF dispersion of horizontal angle of view 26° is wide and resolution becomes lower at surroundings versus at the center.

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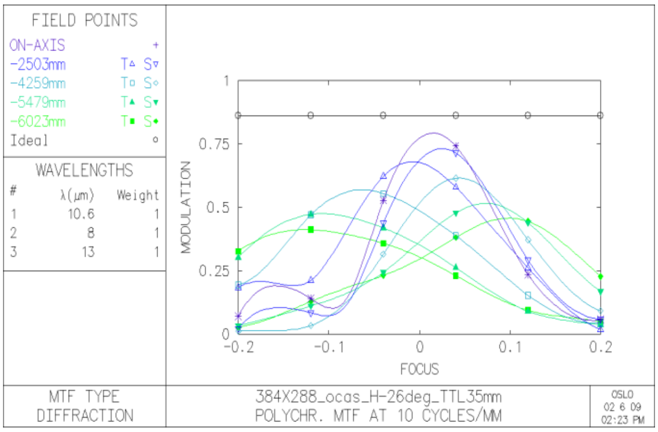

Fig. 9. Optical system MTF weight graph

Figure 10 shows point spread function(PSF) graph. We can see from a graph analyzed by PSF that energy accumulation density of each field becomes lower as it goes away from X axis center and X axis and light axis distribution of MTF is dispersed.

Figures 11 and 12 show wavefront analysis graphs used for optical design. Table 3 shows data of each designed optics lens.

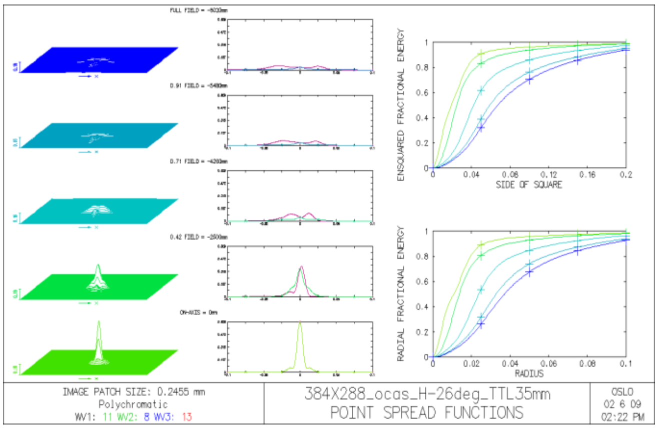

Fig. 10 Optical system point spread function graph

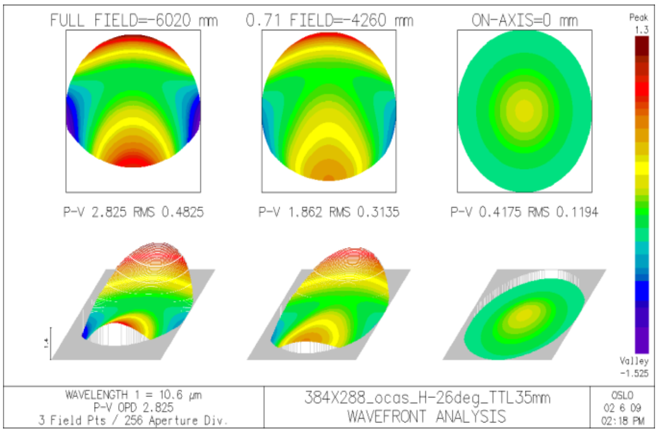

Fig. 11 Optical system wavefront analysis graph (1)

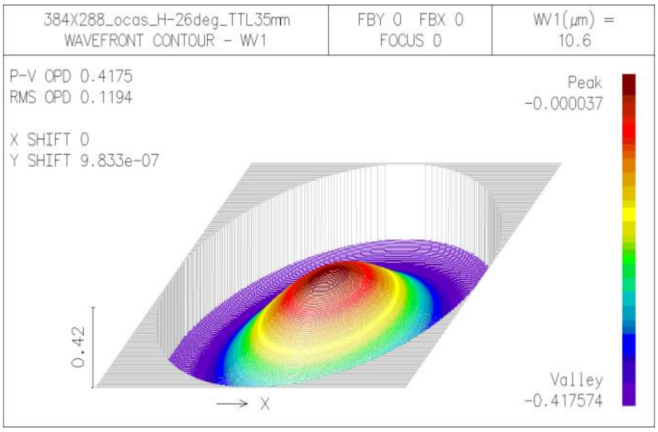

Fig. 12. Optical system wavefront analysis graph (2)

Table 3: Far-infrared camera optical lenses data specifications

Description	Lens Data (Unit: ㎜)				
	Radius 1	Radius 2	Aperture 1	Aperture 2	Thickness
SG1	27.55	35.70	20	20	3.7
SG2	-8.98	-12.90	12	17	5.0
SG3	24.80	45.40	20	20	3.1

IV. Conclusion

This study has intended to design an optical system for far-infrared cameras to be applied to automotive night vision using spherical lenses and increase optical performance of the lenses with improvement of their shapes and array. It has intended that the system can play stable optical performance and correctly sense radiant energy of the subject, i.e. heat detection comparing to the existing optical system for far-infrared cameras. In addition, it has focused on design of a subminiature optical system for far-infrared cameras using spherical lenses in order to increase image quality and brightness and reduce the entire length of the optical system for microminiaturization.

The optical system for far-infrared cameras for automotive night vision has been designed by applying high refractive Ge material. For improvement of performance and functions of the optical system for far-infrared cameras, high refractive special material lenses are much applied. However, the optical system having high refractive material lenses are expensive, require a lot of cutting and grinding fluids for manufacturing and have a problem with high manufacturing price from long time machining. In addition, increased manufacturing cost of the optical system may extremely restrict scope of use for the far-infrared cameras and mass production becomes impossible.

Therefore, this study has applied shape of the optical system for far-infrared cameras as spherical surface and designed thickness and shape of lenses to be easily machined for each grinding process. The designed optical system for far-infrared cameras has 3 spherical lenses, its material is Ge. Its horizontal angle of view is 26°, its focal length is 15.93[mm], TTL is 35[mm], F-number is 1.0. Max outer diameter of the lenses is Φ20 and their center thickness is within max 5.0[mm].

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