Development of F-Theta Lens for Printed Wiring Board Processing

Takashi ARAKI

For compact and advanced electronic devices, such as cellular phones and notebook PCs, there is an increasing demand for the size and weight reduction of printed wiring boards (PWBs). PWBs are processed by laser drilling in which small holes are created at high speed. The laser beam used in this process must be focused on each fine spot scattered across the PWB, while entering the focal plane perpendicularly. These requirements are met with the use of f-theta lens, a compound lens which has an optical design to suppress the aberration to the diffraction-limited level, and a precise aspheric surface. In this paper, the author outlines the engineering of the f-theta lens and its applications.

Keywords: f-theta lens, laser drilling, PWB, CO_2 gas laser, ZnSe

1. Introduction

Digital products, such as cellular phones and notebook PCs, have become increasingly compact, lightweight and sophisticated. This advance has been made possible by miniaturized, high-density printed wiring boards (PWBs) contained in digital products. Substantially contributing to this progress is advanced PWB mounting technology, one driving factor in Japan's competitive advantage.

One such key technology is the build-up PWB, which has been in widespread use since the 1990s.[(1)-(3)] This multilayer PWB is produced through a process involving repeated layering, drilling and wiring. The board is characterized in having non-penetrating holes, known as interstitial via holes (IVH) (**Fig. 1**), which must be drilled without damage to the next conductor layer. Moreover, IVH requires micromachining to meet high-density mounting requirements. A laser drilling machine incorporating a CO_2 gas laser drills holes 50 to 400 µm in diameter at the high frequency of 2 kHz or more. Furthermore, such a system achieves precision-stop drilling by principle, as the CO_2 gas laser beam is reflected by a copper conductor layer. Consequently, use of the CO_2 gas laser drilling machine is a *de facto* standard in the IVH drilling process.[(4),(5)]

Figure 2 outlines a laser drilling machine. The oscillator emits a laser beam, which is directed toward a target spot on a PWB via scan mirrors, high-speed controlled by a two-axis galvano-scanner, and via an f-theta lens that converges the beam for processing. An actual laser drilling machine is designed as a system that places a PWB on an X-Y stage so that a wide, fast processing area is produced in conjunction with galvano-scanner motion.

The drilling process using a laser drilling machine was first applied to electronic circuit boards contained in cellular phones and digital cameras. Nowadays, the process is used on semiconductor package boards that require smaller holes of high circularity. Some companies are seeking cost reduction through use of a laser drill instead of a mechanical drill for through-hole drilling. Laser drilling has also been a focus of attention from the perspective of board material, since the technology achieves drilling into hard-to-process materials comprising plastic and fiberglass. Moreover, laser drilling has been put to practical use in green sheet processing to manufacture multi-layer ceramic

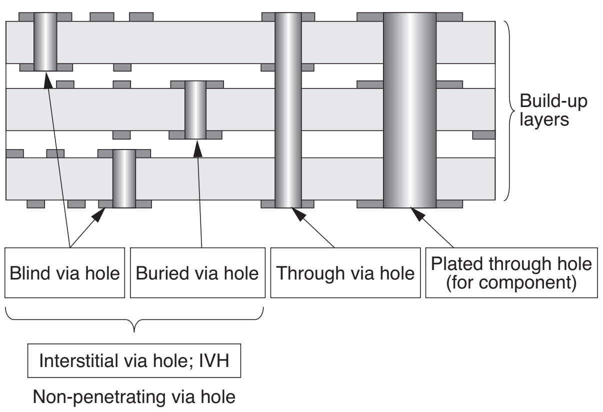

Fig. 1. Build-up board with via holes

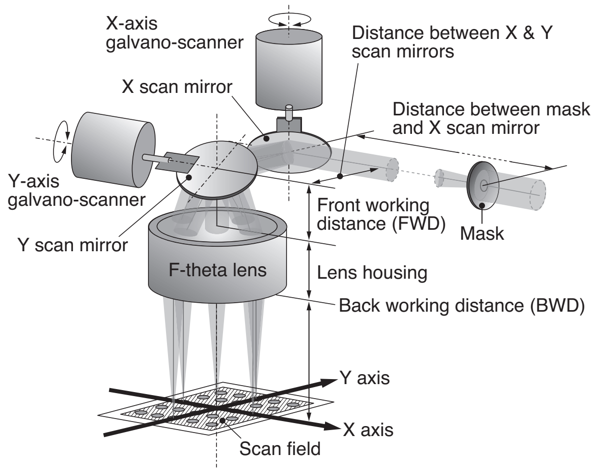

Fig. 2. Laser drilling

capacitor chips and other electronic components.

To respond to the growing demand in these applications, we have developed f-theta lenses for drilling small-diameter holes, for drilling in a large area, and many other types of f-theta lens suited to specific applications. This paper outlines f-theta lenses designed for PWB processing, presents an overview of our design and production, principally of f-theta lenses for CO_2 gas laser, and lastly reports examples of performance improvements pursued through combinations with other components.

2. Features of PWB-Processing F-Theta Lens

In this section, three types of laser processing lens are compared to identify the features of the PWB-processing f-theta lens.

Figure 3 (a) shows laser beams converged by common lenses used for steel sheet cutting and welding. When the laser beam enters the lens parallel to the lens axis, the lens focuses the laser beam to a small spot on the workpiece surface at a fixed distance from the lens. When the intention is to converge the laser beam at a different position by tilting the laser beam at angle θ (rad), the laser beam, having passed through the lens, travels toward a position (f × tanθ) away from the center (where f denotes the focal length of the lens). Since, as compared with normal incidence, the focus shifts toward the lens as shown in the figure, the convergence spot becomes extremely larger in diameter. In the lower section of **Fig. 3**, point spread function (PSF) contours represent the intensity distributions of spots. Isointensity lines are drawn at 9% intervals, the peak intensity at the center being 100%. In the figure, convergence spots differing in size and shape are evident.

Single-optical-element f-theta lenses are commonly used for laser marking. Characteristics of such lenses are shown in **Fig. 3 (b)**. A laser beam entering the lens at an angle is converged at a position (f × θ) away from the center, with (f × θ) being linear to incident angle θ. Hence, the lens was named the f-theta lens. Meanwhile, the beam does not enter the focal plane perpendicularly (telecentric error), and the lens has optical distortion (aberration). The resultant convergence spot becomes elliptical.

Figure 3 (c) shows laser beams converged by a PWB-processing f-theta lens. This f-theta lens enables the beam to enter the focal plane almost perpendicularly, thereby achieving roughly uniform small spot size on the same surface even when the laser beam entering the lens is tilted with respect to the lens axis. To achieve that high a performance level, the PWB-processing f-theta lens must be a compound lens consisting of multiple large-diameter lens elements. Furthermore, to converge the laser beam to the tiniest spot possible, as a means of aberration control each lens element is often of a shape that is not a portion of a sphere.

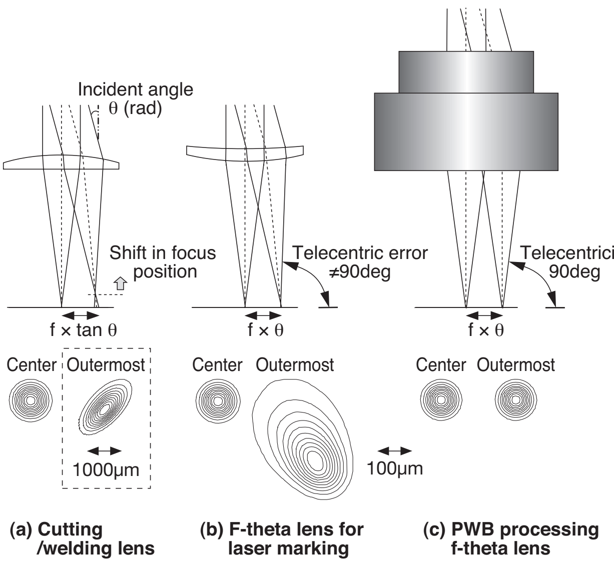

Fig. 3. Comparison of laser processing lens characteristics
(Entry of 13 mm diameter Gaussian beam, with 9.4 μm wavelength and 100 mm focal length)
Upper section: optical paths
Lower section: PSF contours at different incident angles

3. Design

3-1 Optical design of f-theta lens

First of all, hole diameter, hole uniformity, scan field and other PWB processing requirements are translated into optical specifications. Next, the required lens structure is determined, including tolerances, to accord with those optical specifications.[6]

F-theta lens requirements include a wide scan field, small spot size and minimum telecentric error, as shown in the left section of **Fig. 4**. To meet these requirements, it is necessary to provide convergence characteristics at a diffraction-limited level throughout the scan field. A wider scan field, however, generally results in increased variation in spot size. Many of these characteristics are in a trade-off relationship. Moreover, in many cases lens design solutions

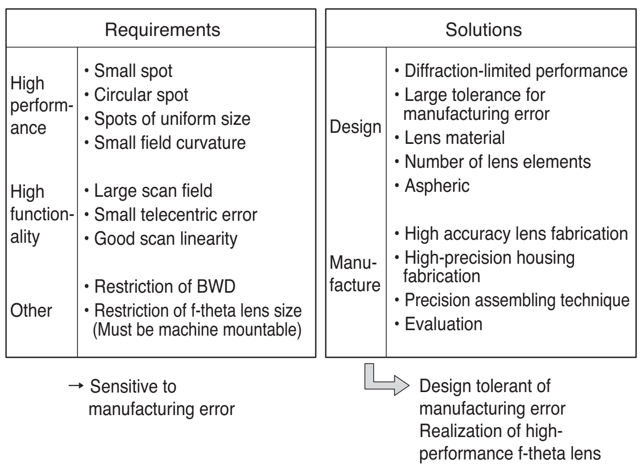

Fig. 4. Solutions

meeting high-performance requirements are sensitive to manufacturing error. As a result, a prototype f-theta lens that apparently works fine can in fact be practically useless, due to substantial characteristic variation in the volume production phase.

It therefore becomes important to fully ascertain the actual manufacturing capacity and take that into consideration when establishing optical design conditions. Sumitomo Electric Hardmetal Corporation selects materials and determines the number of lens elements, even making use of aspheric surfaces when necessary, and develops optical designs(7) with the aim of producing a solution with wide tolerances, as shown in "Solutions" in the right section of **Fig. 4**. Combining high-precision lens processing and assembly, explained later, we produce f-theta lenses featuring high precision and robustness with regard to manufacturing error.

CO_2 gas lasers emit a beam in the infrared wavelength region from 9.3 to 10.6 µm, in which region the usable materials are generally limited to ZnSe and Ge. The beam paths shown in **Fig. 5** present typical examples of optical design results for an f-theta lens using these materials and incorporating aspheric surfaces. **Tables 1 and 2** show design results, including mechanical design, and characteristic analysis results. **Figure 6** shows image analysis results for key spots in the scan field, where a 2 mm diameter mask image was scaled down and transferred via the f-theta lens. (The contours represent 30%, 13.5% and 5% intensities, spot size calculations being 76 µm, 93 µm and 110 µm, respectively.) The lens is expected to exhibit drilling with high circularity throughout the scan field.

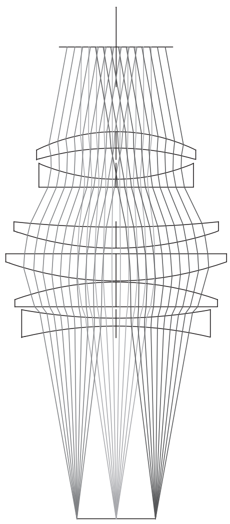

Fig. 5. Beam paths

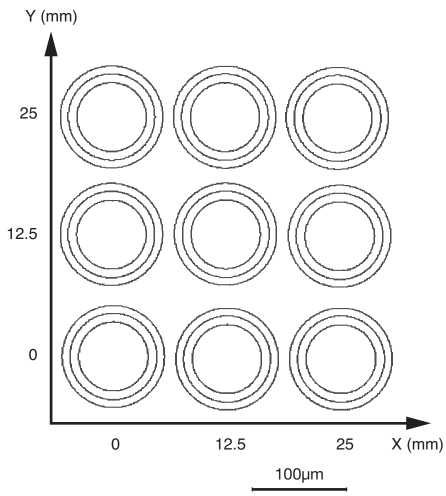

Fig. 6. Image analysis

Table 1. Typical f-theta lens design results

No.	Item	Specifications	Note
1	Wavelength	9.4 µm	
2	Incident beam diameter	ø26 mm	Entrance pupil diameter
3	Distance between mask and X scan mirror	2,000 mm	
4	Distance between X & Y scan mirrors	37 mm	
5	Front working distance (FWD)	32 mm	Distance between mirror and lens housing end face
6	Effective focal length	100 mm	
7	Scan field	52 mm × 52 mm	
8	Lens housing geometry	ø140 mm L80 mm	Size including window cell
9	Cover window	included	Removable window cell

Table 2. Characteristics determined by transferring 2 mm diameter mask image

No.	Item	Characteristics	Note
10	Back working distance (BWD)	95.9 mm	
11	Spot size	ø93 µm	@ 13.5% peak intensity
12	Spot size variation	±0.10%	(max-min)/min × 100 ÷ 2 (%) @ 13.5% peak intensity
13	Spot circularity	99%	@ 13.5% peak intensity
14	Max. telecentric error	4.0 deg	

3-2 Mechanical design of f-theta lens

Optical design solutions provided in the preceding section are quality characteristic values and tolerances, such as the radius of curvature and lens thickness of each lens element, lens distance, decentering and tilt. These parameters generally number in dozens and must be controlled on the basis of optical axis (virtual axis of reference), which is difficult to mechanically establish. Mechanical design involves alignment to high accuracy, using a lens housing, while establishing the shapes of individual lens elements as shown in **Fig. 7**. In assembling, precision requirements are on the order of microns for decentering, tilt and distance between lens elements. An adjustable lens housing is used in some cases.

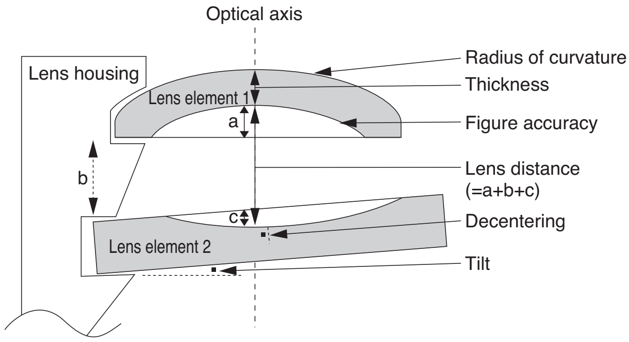

Fig. 7. Mechanical design

4. Fabrication

4-1 Fabrication flow

Sumitomo Electric Hardmetal Corporation began its optics business by manufacturing and marketing CO_2 gas laser cutting/welding lenses. We operate a continuous production process, from ZnSe material synthesis, polishing and thin-film optical coating to inspection. Since an f-theta lens is a compound lens, (1) the fabrication of individual lens elements is followed by (2) the lens housing fabrication process, then by (3) assembly process. **Figure 8** shows the fabrication flow.

An essential part of PWB-processing f-theta lens development is the fabrication of large-diameter high-precision aspheric lens elements. Sumitomo Electric Hardmetal Corporation commercialized aspheric single ZnSe lenses early on, having developed seed technology.[8] While advancing these elemental technologies, we responded in a timely manner to lens size and precision improvement needs, and were able to enter the business area in the early stage of laser drilling machine development. An example f-theta lens fabricated in accordance with the flow in **Fig. 8** is shown in **Photo 1**. The following sections present key points in f-theta lens fabrication: high-precision processing technology and performance evaluation.

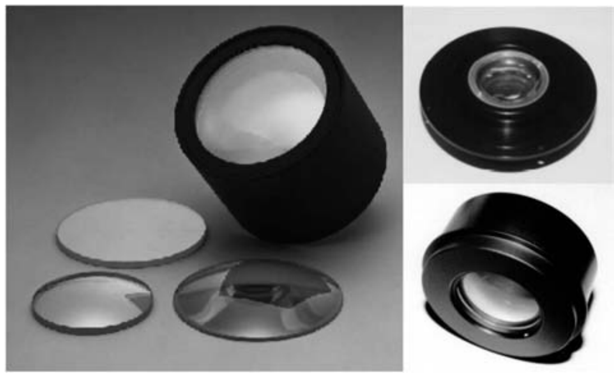

Photo 1. F-theta lenses

4-2 High-precision machining technology

This section explains SPDT (single point diamond turning) technology, which is especially important in meeting rigorous precision requirements.[9],[10] The ultraprecision lathe used for that purpose consists of an air spindle, hydrostatic slide and other components, and achieves numerically controlled position resolution of 0.03 mm. **Figure 9** shows lens machining. Lens material is set on the spindle and turned. In turning, two axes are numerically controlled so that the tool edge traces the intended lens shape (spherical, aspheric etc.). Requirements for producing the

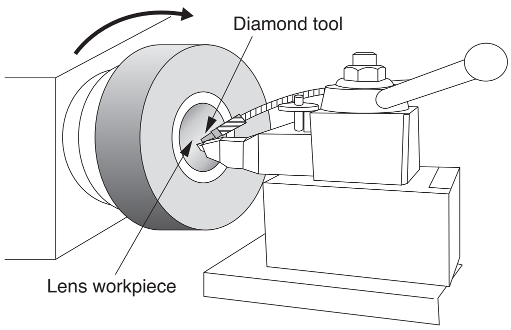

Fig. 9. Lens machining with ultraprecision lathe

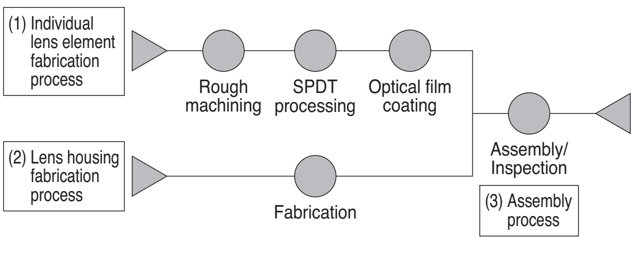

Fig. 8. F-theta lens fabrication flow

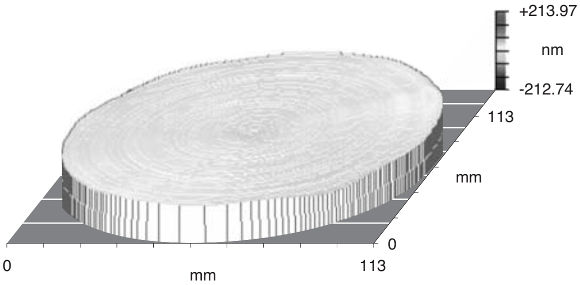

Fig. 10. Figure accuracy of ZnSe aspheric lens

high-precision lens elements that comprise an f-theta lens include machining environment variation control (temperature control during machining, floor vibration etc.), optimization of workpiece material machining conditions (depth of cut, feed rate, cutting rate and tool edge shape), and a highly rigid air spindle, as well as the machine's increased geometric accuracy of motion.

Figure 10 shows representative examples of aspheric form measurement results for lenses produced through the SPDT process. This is an extremely high-precision machining process, its accuracy of form being 0.076 μm, which is the deviation from designed aspheric surfaces.

4-3 Performance evaluation

Using an f-theta lens made to the specifications shown in **Table 1**, holes were drilled in a polyimide film covered with copper foil. **Figure 11** shows images of holes drilled at the center and outermost area of the scan field. The holes are approximately 100 μm in diameter, with excellent circularity. Using the intensity distributions represented by contours shown in **Fig. 6**, it is possible to calculate spot sizes and diameters of drilled holes, comparison of which shows that the ablation threshold of this material is substantially low.

In addition to this evaluation of actual application, the following methods are used for f-theta lens evaluation.

(1) Characteristics simulation based on actual fabrication data acquired from the manufacturing process. Actual fabrication data include thickness, radius of curvature and other measurements of lens elements, as well as decentering, lens element distances and other measurements collected during the assembly process.

(2) Purely optical testing of f-theta lens

Method (2) differs from the aforementioned evaluation of actual application in that the actual f-theta lens alone is evaluated, without being affected by laser system or workpiece. In general, optical measurement is extremely difficult in the infrared wavelength region. Sumitomo Electric Hardmetal Corporation is actively working on developing such relevant measurement techniques.

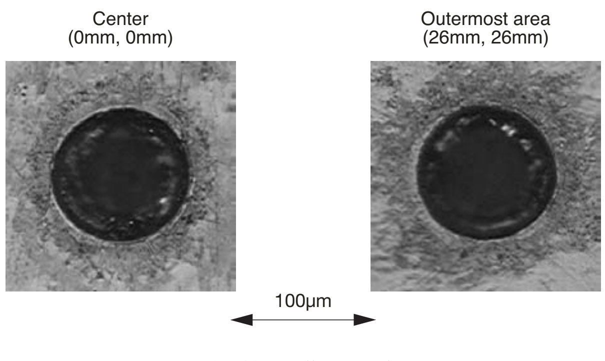

Fig. 11. Drilling results

5. Various F-Theta Lenses for CO_2 Gas Laser

5-1 Basic line of f-theta lenses

Since PWB requirements include drilling with excellent circularity, f-theta lenses must be provided with convergence characteristics of diffraction-limited level throughout the scan field. Achieving small spots under the restrictions necessitates shortening the focal length or providing a large incident beam diameter. In either case, the galvano-mirror system increases in size and telecentric errors increase, resulting in a narrowed scan field. Thus, many of these characteristics are in a trade-off relationship. Naturally, even if priority is placed on basic performance, many types of f-theta lenses are produced, as shown in **Table 3**. They can cover hole diameters ranging from 50 to 400 μm, depending largely on machining methodology and PWB material. A variety of application-specific f-theta lenses derived from the basic types are currently in use, including lenses suited to low ablation threshold materials, lenses adapted to specific wavelengths (10.6/9.6/9.4 μm), lenses designed to pass He-Ne laser beams and lenses for high-power transmission.

Table 3. Basic line of f-theta lenses for CO_2 gas laser

	Wide scan field type	Standard type 1	Standard type 2	Fine type	VA type 1	VA type 2
Incident beam diameter	ø30 mm	ø30 mm	ø30 mm	ø30 mm	ø20 mm	ø20 mm
Scan field	100 mm × 100 mm	50 mm × 50 mm	40 mm × 40 mm	30 mm × 30 mm	50 mm × 50 mm	40 mm × 40 mm
Focal length	170 mm	100 mm	80 mm	65 mm	100 mm	80 mm

5-2 Measures against spatters

Laser drilling a PWB causes spattering of board components, a portion of which spatter reaches and deposits on the f-theta lens as debris. As a result, f-theta lens transmittance decreases to the extent that drilling becomes no longer possible. This is often particularly problematic during direct drilling of copper on a PWB. One solution is to increase the distance between f-theta lens and PWB (back working distance: BWD) or, when necessary, to clean the exit surface of the cover window mounted as a standard accessory on the f-theta lens. The former lens, with a large BWD, is known in optics as the retrofocus type, with which it is usually difficult to extend the scan field. It also requires a large lens diameter and is therefore expensive. An example of the retrofocus type is shown in **Table 4**.

Regarding the latter, or the cover window, a diamond-

Table 4. Example f-theta lenses with large back working distance (BWD)

	Standard type 1	Retrofocus type
Incident beam diameter	ø30 mm	ø30 mm
Scan field	50 mm × 50 mm	45 mm × 45 mm
Focal length	100 mm	100 mm
Back working distance (BWD)	96 mm	125 mm
Lens housing geometry	ø140 mm L80 mm	ø170 mm L92 mm

ISO 9211-3 & 4 compliant

Test item	Method
Density	Affix tape, then peel it quickly in perpendicular direction.
High temp./humidity	16 h or more at 55°C and 90% humidity
Abrasion	50 strokes with cheese cloth
	20 strokes with eraser
Solvent stability	24 h immersion in salt water
	4 h immersion in water

Photo 2. DLC-coated window

like carbon (DLC)-coated window (**Photo 2**) was developed[11] to resist abrasion during cleaning. Since that development, the retrofocus f-theta lens has been in limited use.

5-3 Reduced temperature/wavelength dependence

The ambient conditions of an f-theta lens in operation are subject to constant changes due to: heat generated by laser beam passage or by peripheral parts; laser oscillation wavelength fluctuation; and other factors. Although the causes can be most effectively eliminated by rearranging the other parts of the laser drilling machine, it is also effective to use an f-theta lens that is robust against environmental changes. Many f-theta lenses use highly refractive Ge, whose refractive index, however, is highly temperature dependent. To reduce temperature dependence, one option is to not use Ge (**Table 5**). To reduce wavelength dependence, it is important to make use of the material property differences between ZnSe and Ge, shown in **Table 5**. **Table 6** shows a design example of an f-theta lens with reduced temperature dependence. The example illustrates controlled variation in back working distance (BWD) and beam converging position.

Table 5. Refractive index and related characteristics comparison between ZnSe and Ge

	Property of ZnSe	Property of Ge	Ge characteristic (Relationship to ZnSe)
Refractive index, n	2.41	4.006	Approx. × 2 [Note: relation in difference between Ge/ZnSe's refractive index and that of air (n - 1)]
Temperature dependence of refractive index dn/dT	5.7×10^{-5}	4.2×10^{-4}	Approx. × 7.3
Wavelength dependence of refractive index dn/dλ	-5.4×10^{-3}	-1.1×10^{-3}	Approx. × 1/5

Table 6. Example of f-theta lens with reduced temperature dependence (Specs: 100 mm focal length, 50 mm × 50 mm scan field)

	Standard type 1	With reduced temperature dependence
Change in back working distance (BWD)	23.6 μm/°C	6.5 μm/°C
Change in outermost converging position (25 mm, 25 mm)	-7.7 μm/°C	-1.8 μm/°C

Incidentally, there has been a report on the development of an f-theta lens that incorporates a hybrid system, combining refracting and diffracting types, to improve temperature stability and reduce dependence on incident laser wavelength.[12]

6. Pursuit for Performance and Future Development

The f-theta lens, combined with other optical components in an optimum design, will deliver improved performance.

Figure 12 outlines a taperless hole drilling optical system.[13] To achieve uniform intensity, it uses an aspheric beam homogenizer for leveling a laser beam with Gaussian intensity distribution. The system then scales down and transfers the mask image of the beam through the f-theta lens. This optical system is already widely used in processing build-up boards.

A multi-hole drilling optical system is outlined in **Fig. 13**.

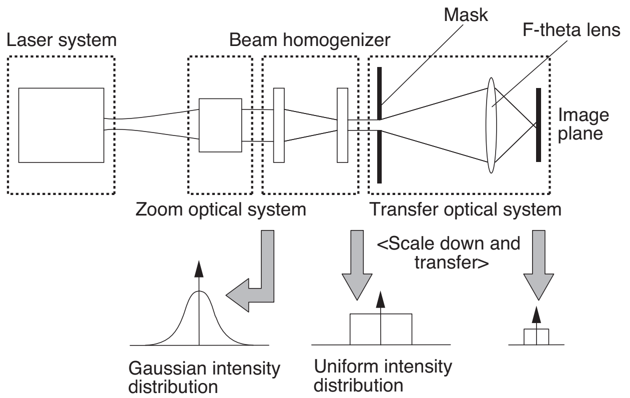

Fig. 12. Taperless hole drilling optical system

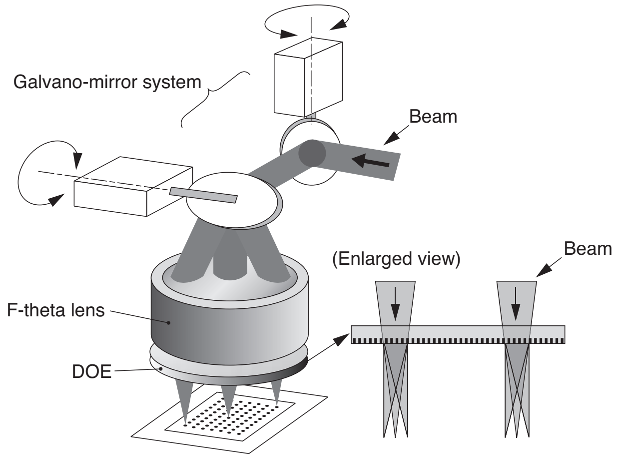

Fig. 13. Multi-hole drilling optical system

Photo 3. Promising UV laser f-theta lens

This system enables a drilling rate several times faster than otherwise possible, by dividing the beam with diffractive optical elements (DOE) at the subsequent stage of the f-theta lens.

The trend toward smaller PWB hole sizes is accelerating at an increasing rate. Sumitomo Electric Hardmetal Corporation feels that current hole diameter has not yet reached the limit of CO_2 gas laser drilling, so the Corporation is promoting the development of higher-performance f-theta lenses, considering that further hole diameter reduction is technically possible. One promising option is to use a UV laser (wavelength: 0.355 μm) as the light source instead of CO_2 gas laser (wavelength: 9.3 to 10.6 μm). Accordingly, we have made efforts to develop UV laser f-theta lenses, as reported previously (**Photo 3**).[14] Other anticipated applications of this UV laser f-theta lens include drilling through-holes in silicon wafers (through-silicon via: TSV).[15]

7. Conclusion

This report explained Sumitomo Electric Hardmetal Corporation's design and manufacture of CO_2 gas laser f-theta lenses for PWB drilling applications, and various other types of f-theta lenses. We believe that optical evaluation of f-theta lens performance, and subsequent correlation of the optical evaluation data and processing results, enable the supplying of high-processing performance f-theta lenses to the market, though this topic was not discussed owing to page number limitations.

There is often a gap between specification requirements and feasible product level as determined in accordance with the actual designing and manufacturing capability. However, in several years it may be possible to come up with a novel f-theta lens by meeting difficult improvement and development challenges. I am deeply moved by the advances we achieve when design and manufacturing staff, while employing new technologies and through frank discussions, manage to produce the best possible production design acceptable to both sides. Furthermore, when I see an f-theta lens completed through actual production processes, I feel the beauty of its pure functionality. The next task is to reduce cost and popularize the lens as an industrial product.

We intend to continue proposing novel forms of product, as reported above, and to contribute to the development of digital products in the field of laser processing.

Technical Term

Retrofocus : Denotes the condition in which the back focal distance (BWD in this report) is longer than the focal length.

References

(1) Japan Jisso Technology Roadmap 2007, Japan Electronics & Information Technology Industries Association, pp. 130-284, 2007
(2) H. Utsunomiya, JPCA NEWS October 2009, pp. 16?25
(3) Y. Kenmochi, Design Wave Magazine, June 2007, pp. 79?80
(4) I. Nakai et al., Journal of Japan Laser Materials Processing Conference, 35th, Vol. 2, No. 2, pp. 199?206, 1995
(5) Y. Kita et al., "Trends of CO_2 Gas Laser Direct Copper Drilling Technology," Proceedings of 23rd Japan Institute of Electronics Packaging, 2009
(6) T. Araki et al., "Development of F-Theta Lens for Laser Drilling," Sumitomo Electric Technical Review, No. 154, pp. 89?95, 1999
(7) K. Fuse, Japanese Patent No. 3006611, 1999
(8) K. Ebata et al., "Characteristics of ZnSe Aspheric Lens," Sumitomo Electric Technical Review, No. 148, pp. 106?112, 1996
(9) T. Kyotani et al., "Molybdenum-Coated Paraboloidal Mirror for CO_2 Laser," Sumitomo Electric Technical Review, No. 138, pp. 162-167, 1991
(10) T. Hirai et al., Proceedings of 71st Laser Material Processing Conference, pp. 127-130, 2008
(11) Sumitomo Electric Technical Review, No. 175, p. 145, 2009
(12) K. Fuse et al., "Diffractive/Refractive Hybrid $f\theta$ Lens for Laser Drilling," Sumitomo Electric Technical Review, No. 159, pp. 66-71, 2001
(13) T. Hirai et al., "Characteristics of ZnSe Aspheric Beam Homogenizer for CO_2 Laser," Sumitomo Electric Technical Review, No. 161, pp. 91-97, 2002
(14) T. Araki et al., "Development of UV Laser F-Theta Lens," Sumitomo Electric Technical Review, No. 175, pp. 62?67, 2009
(15) T. Narita, "Laser Drilling for TSVs & Thin Wafer Dicing," Proceedings xm-07-043.0 STS Japan, 2007

Contributor

T. ARAKI

• Senior Specialist
Senior Assistant Manager
Laser Optics Department
Sumitomo Electric Hardmetal Corp.
He is engaged in the development and production of optical components for laser processing.