Development of F-Theta Lens for UV Lasers

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In order to improve the performance of electronic equipment and reduce its size and weight, UV laser drill machines are highly required, with which small holes within 50 μm in diameter can be provided during printed wiring board (PWB) processing. To meet such demand, Sumitomo Electric Hardmetal Corp. has developed f-theta lenses for UV lasers with diffraction-limited performance over a scan field of 50 mm × 50 mm.
Test results by transmission wavefront measurements have confirmed that the f-theta lenses have excellent properties in accordance with designs. According to our laser drilling experiments, the holes were 23 μm in diameter and showed uniformity throughout the 50 mm× 50 mm scan field.

Keywords: f-theta lens, UV laser, laser drilling, PWB, transmission wavefront

1. Introduction

Advanced electronic products such as cellular phones and notebook PCs have become increasingly compact, lightweight, sophisticated and fast. Driving these trends are the advancing integration and speed of semiconductor devices, in addition to increasingly higher density, multi-layer configuration and diversity of PWBs, on which semiconductor devices are mounted. In keeping with these trends, demand requires that PWB hole diameter be reduced and their circularity be improved. Additionally, boring technique should be applicable to various types of board material.

In this respect, microdrills are used to bore relatively large holes, while laser drills are used to bore relatively small holes and to process build-up PWBs. In general, the laser drill is used for 50 to 200 μm diameter processing, depending on board materials and processing conditions.[(1)-(3)]

Figure 1 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 processing area is produced in conjunction with galvano-scanner motion.

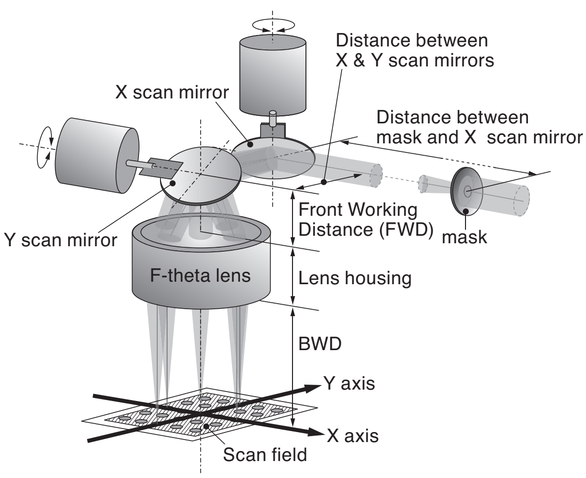

Fig. 1. Laser drilling

The currently predominant laser drilling machine incorporates a carbon-dioxide laser because of the speed and processing cost advantages. In the advanced technology area, however, there is increasing demand for hole diameter reduction to 50 μm or less. That necessitates reducing the focal length (more accurately, the f-number) of the f-theta lens for carbon-dioxide laser. This focal length reduction is under development at Sumitomo Electric Hardmetal Corp. Strict requirements concerning hole shape precision throughout the scan field necessitate minimal f-theta lens aberrations (optical deformations). This in turn necessitates an increased number of lens elements and higher accuracy production than ever before.

Another method for reducing hole diameter is to use a short-wavelength laser. For example, a UV laser wavelength is 0.355 μm, which is approximately 1/30 the wavelength of carbon-dioxide laser light (9.4 or 10.6 μm). Accordingly, in principle, the use of a UV laser is favorable for achieving a smaller spot. Furthermore, in contrast to carbon-dioxide laser drilling, in which heat plays a dominant role in processing, UV laser drilling, principally involving non-thermal processing, can be applied to various board and composite materials. It has been used even in processing for solar cell production, as well as for PWBs. For this reason, UV laser drill research and development is actively under way.

This paper reports on the present development status of the f-theta lens for UV lasers; its design, fabrication and performance evaluation are also reviewed.

2. Optical Design

Optical design concept and method were detailed in our preceding paper. [(4)] This paper clarifies the features of the f-theta lens for UV lasers and reviews its important design points in comparison with the f-theta lens for carbon-dioxide lasers.

2-1 Specifications for F-Theta Lens

Table 1 shows the f-theta lens requirements for carbon-dioxide lasers and UV lasers. A general case is shown for the f-theta lens requirements for carbon-dioxide lasers. The f-theta lens requirements for UV lasers represent typical values, which are receiving attention highly in the market. UV lasers, which use a short wavelength, achieve a small spot size without the need for a large incident beam diameter or for short focal length. In practice, the f-theta lens for UV lasers has a longer focal length and a smaller entrance pupil diameter, as shown in **Table 1**. However, its spot size, 7.2 to 25 μm in diameter, is substantially smaller than the 88 μm diameter spot size of the f-theta lens for carbon-dioxide lasers. (Note: Here, "spot size" refers to a calculated Airy disk diameter, which differs from the actual processing hole diameter.)

Table 1. Requirements

No.	Item	Required		Note
		for carbon dioxide laser	for UV laser	
1	Wavelength	9.4μm	0.355μm	
2	Entrance pupil diameter	ø 26mm	ø 7~12mm	
3	Distance between mask and X scan mirror	2000mm	1500~4000mm	
4	Distance between X & Y scan mirror	37mm	23.7mm	
5	Front Working Distance (FWD)	≧37.8mm	≧19.4mm	Distance from Y scan mirror to lens housing input side
6	Effective focal length	100mm	100~200mm	
7	Scan field	50mm × 50mm	50mm × 50mm	
8	Cover window	included	included	

Consequently, in many UV laser optical systems, it is possible to reduce the entrance pupil diameter and make the galvano mirror system compact. This in general brings about the following effects.

· Telecentric errors (beam entry angles with respect to a focal plane) are reduced.
· Because the mirror is scanned close to the f-theta lens, given the same mirror swing angle, it is possible to reduce the lens element diameters.
· Small and lightweight, the mirror can be driven fast for an increased drilling rate.

Similarly, a somewhat longer focal length implies an extended working distance. This is useful for maintaining f-theta lens transmittance, which can decrease as the lens is soiled by dust spattering from the workpiece during processing.

2-2 Optical Design of F-Theta Lens

"Optical design" refers to the process of determining a lens structure to accord with given specifications, as shown in **Table 1**, including tolerances.

F-theta lens requirements include a wide scan field, small spot size and truly circular and uniform spot shapes throughout the scan field. Consequently, one optical requirement is diffraction-limited performance throughout the scan field. Furthermore, such functionalities as reduced telecentric errors and favorable scan linearity are also required. A wider scan field, however, results in an increased spot size in general. Many of these characteristics are in a trade-off relationship. For this reason, producing an optical design solution requires expertise. Moreover, in many cases the produced solution is 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.

Therefore, it becomes important to fully ascertain the actual manufacturing capacity and take that into consideration when establishing optical design conditions. Sumitomo Electric Hardmetal Corp. develops optical designs [5] with the aim of producing a solution with wide tolerances, selects materials and a number of lens elements, and even makes use of aspheric surfaces when necessary - as shown in **Fig. 2** - in order to process and assemble high-precision lenses. The result is an f-theta lens that features high precision and robustness with regard to manufacturing error.

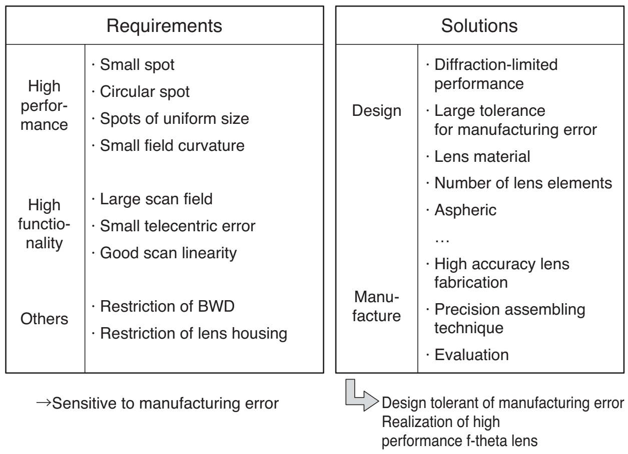

Fig. 2. Solutions

Comparisons of f-theta lenses for carbon-dioxide lasers and for UV lasers show that, with the f-theta lens for UV lasers it is possible to reduce entrance pupil diameter and extend focal length; a favorable result for achieving required characteristics. On the other hand, the materials that can be used for the two types of lenses comprise ZnSe and Ge for the former, but only S_iO_2 for the latter. The material used for the latter has a far smaller refractive index, as shown in **Table 2**. Moreover, in the production of high-precision aspheric surfaces, single-point diamond turning (SPDT) [6], [7] can be used for ZnSe and Ge, whereas it is difficult to process S_iO_2. Accordingly, the f-theta lens for UV lasers comprises a larger number of lens elements. Further-

Table 2. Comparison of lens materials

	for carbon-dioxide laser		for UV laser
	ZnSe	Ge	S_iO_2
Index	2.410	4.006	1.457
Aspheric fabrication	○	○	△
Figure accuracy @λ/20 <example>	0.47μm	←	0.018μm

more, if the surface must be processed to a precision of 1/20 the wavelength used, the f-theta lens for UV lasers requires close tolerances due to the shorter wavelength.

2-3 Optical Design Results and Verification

Table 3 shows design results for an f-theta lens for UV lasers. Its characteristics are shown in **Table 4**. Both spot size uniformity and circularity are favorable, the field curvature is small, and the telecentricity is excellent. This f-theta lens was designed for a parallel incident beam, as shown in **Fig. 3 (a)**, in order for it to be of general-purpose type. **Figure 4** shows a contour plot of the point spread function (PSF) of the f-theta lens. The contour plot represents calculated intensity distributions of a beam converged by the f-theta lens at representative points within the scan field. Concentric circles at each point in the scan field represent intensity in 9.09% decrements, intensity at the center being 100%. Because in actual processing, processing thresholds are considered to be quite low, the sizes and shapes of outer circles of the contour plot become of importance. The plot reveals that substantially favorable characteristics were achieved throughout the scan field.

Table 3. Specifications

No.	Item	Specifications	Note
1	Wavelength	0.355μm	
2	Entrance pupil diameter	ø13mm	
3	Full-angle beam divergence	0mrad	
4	Distance between X & Y scan mirrors	23.7mm	
5	Front Working Distance (FWD)	29mm	
6	Effective focal length	160mm	
7	Scan field	50mm x 50mm	
8	Lens housing	ø120mm	
		110mm L	
9	Cover window	included	

Table 4. Characteristics (focusing)

No.	Item	Characteristics	Note
10	Beam diameter	ø 8.7mm	$1/e^2$ beam diameter, Gaussian-beam
11	Field not shaded	53mm × 53mm	Beam shaded above following Field
12	Back working distance (BWD)	213.1mm	
13	Spot size	ø 8.9 μm	$1/e^2$ spot size
14	Spot size variation	± 0.38 %	
15	Spot circularity	99%	Shortest/longest width
16	Scan linearity	＜0.3%	
17	Field curvature	± 2.6 μm	
18	Telecentric error	1.6deg	

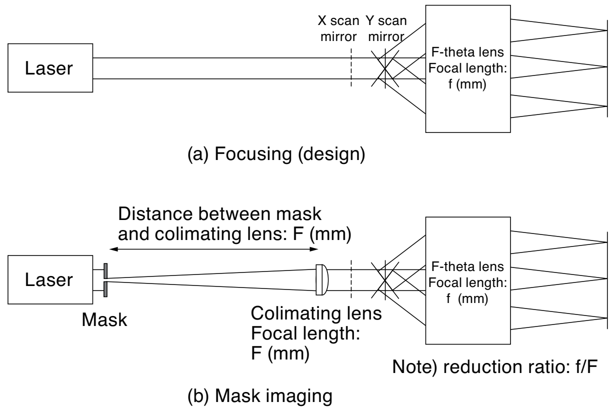

Fig. 3. Optical systems of typical laser drilling machine

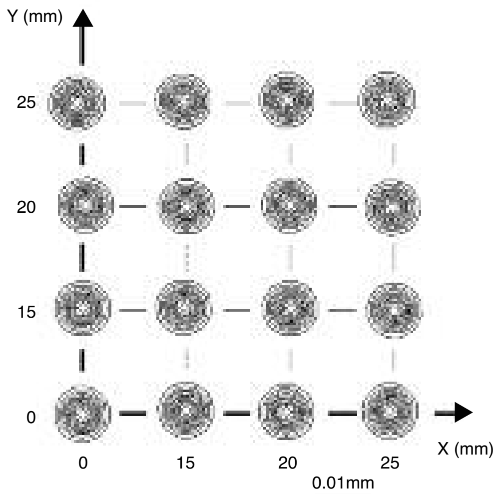

Fig. 4. Point spread function shown as contour

When this f-theta lens is used to transfer a mask image, a collimating lens is additionally used, as shown in **Fig. 3 (b)**. **Table 5** shows characteristics observed in an instance using a 0.6 mm diameter mask and a collimating lens with a focal length of 2000 mm. **Figure 5 (a)** shows image analysis results of that instance (13.5, 30 and 60% intensities only are shown in this contour plot, to avoid dense concentric rings). The results revealed that favor-

Table 5. Characteristics (ø 0.6mm mask imaging)

No.	Item	Characteristics	Note
19	Distance between mask and colimating lens	2000mm	
20	Focal length of colimating lens	2000mm	
21	Spot size	ø48.3μm	1/e² spot size
22	Spot size variation	± 0.10%	
23	Spot Circularity	99%	Shortest/longest width

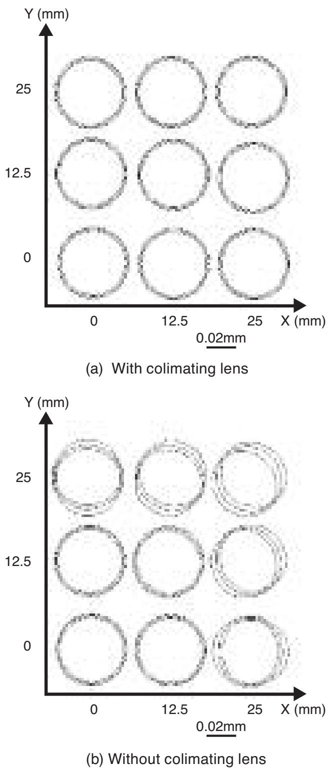

Fig. 5. Image analysis

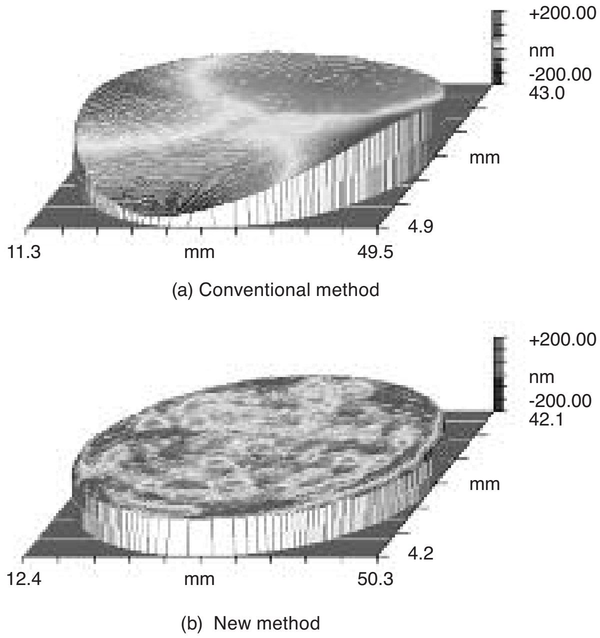

Fig. 6. Figure accuracy of polished surfaces

Photo 1. F-theta lens for UV lasers

able characteristics were gained throughout the scan field. Without a collimating lens, field curvature increases and elliptic spots are produced, as shown in **Fig. 5 (b)**.

3. Fabrication of F-Theta Lens

One manufacturing quality that affects the performance of f-theta lenses for UV lasers is the geometric accuracy of the lens elements. Polishing quartz (SiO_2) lenses is not a novel technique. However, unlike usual single lenses, the f-theta lens requires extremely close tolerances for quality parameters such as radius of curvature, thickness and figure accuracy. With a lens having small thickness-to-diameter ratio, it is particularly difficult to control figure accuracy. In many cases, the result is a shape as shown in **Fig. 6 (a)**. A new polishing technique with optimized processing and affixing conditions, which we are using, has enabled improvement of figure accuracy (PV value) by 40 to 60% from the conventional value, and reduction of geometric distribution, as shown in **Fig 6 (b)**.

Photo 1 shows f-theta lenses for UV lasers fabricated for this study. Each lens element is fitted in an aluminum-alloy housing to high accuracy.

4. Performance Evaluation

Three methods can be used to evaluate fabricated f-theta lens performance.

(1) Optical testing of f-theta lens (transmission wavefront test, MTF test etc.)

(2) Characteristics simulation based on actual manufacturing data acquired from manufacturing process

(3) Evaluation of actual processing performance using fabricated f-theta lens on a laser drilling machine

Three f-theta lenses (A, B and C) were fabricated for this study. Evaluation results are shown below.

4-1 Transmission Wavefront Measurements and Characteristics Simulation

Transmission wavefront aberration (optical deformation) was measured as an evaluation indicator of f-theta lens optical characteristics. Employing the optical system used in the Fizeau interferometer (shown in **Fig. 7**), we measured the deformation of interference fringes produced by laser light incident on the f-theta lens, and laser light reflected by a reference spherical standard after passing through the f-theta lens. [8]

Using the three fabricated f-theta lenses (A, B and C), measurements were conducted at several points within a 50 mm × 50 mm scan field created by swinging the scan mirror. Measurement results are shown in **Fig. 8**. Measurement results and design results of the three f-theta lenses (A, B and C) match each other well, indicating that desired optical characteristics were achieved. Transmission wavefront aberration measurements within a 50 mm × 50 mm scan field revealed that variation among the three f-theta lenses was 4.6%, which is considered sufficiently small.

The dotted line in **Fig. 8** represents a calculated characteristics simulation using the actual manufacturing data of lens C. The actual manufacturing data comprise measured thickness, radius of curvature and other values of lens elements, and decentered lens intervals and other values sampled during assembly. For figure accuracy, coefficients of Zernike polynomials were determined and entered. The simulation data of lens C favorably match design values, proof that manufacturing was carried out well under control.

To ensure trouble-free use in actual processing, an acceptable level of deviation from design values depends on workpiece materials, processing conditions and optical conditions such as of laser oscillators and beam transmission systems. The acceptable level should therefore be determined on a case-by-case basis, taking individual laser drilling machines and processing conditions into consideration. Regarding the three f-theta lenses fabricated for this study, the maximum deviation of measured values from design values was 7.0%. These lenses all worked well in the processing evaluation, which will be explained in the following section, without any significant differences.

4-2 Processing Evaluation

Figures 9 (a) and (b) show processing results for two f-theta lenses (A and B). Processing conditions were for converging, not for mask imaging, as shown below.

Laser Power: 1.5 W
Frequency: 120 KHz
Irradiation Duration: 1 ms
Workpiece: aluminum-deposited glass plate (1.82 mm thick)

The data were acquired at the center, middle and outermost point of a 50 mm × 50 mm scan field, defocus (DF) level being +0.05, 0 or −0.05 mm. Truly circular holes were not achieved, even at the center of the scan field. One reason for this is surmised to be the influences of the laser beam characteristics. Slight variations in hole shape were observed while the effects of defocus level and mirror

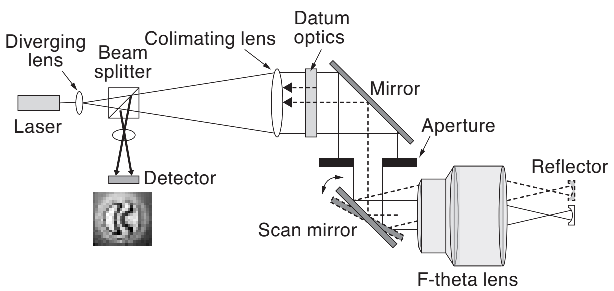

Fig. 7. Transmission wavefront measurement

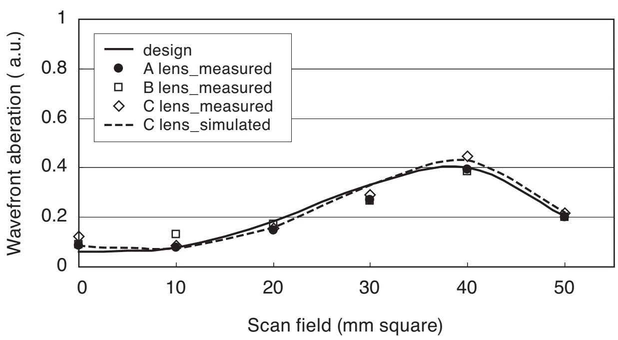

Fig. 8. Transmission wavefront measurement results

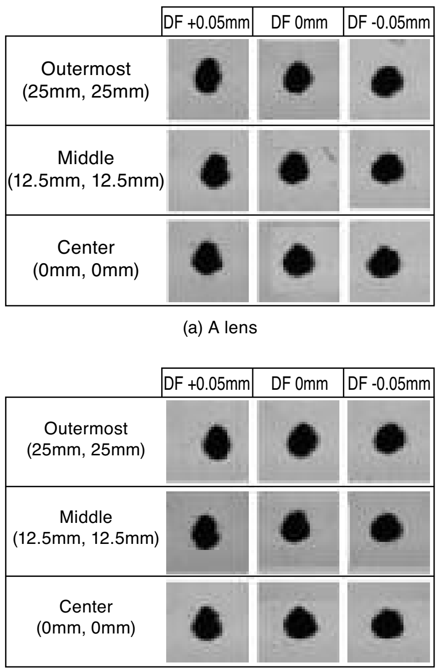

Fig. 9. Processing results

scanning were present. This is considered to result from the characteristics of the f-theta lenses and galvano mirror system. No significant differences were observed between the drilling results of the two f-theta lenses, substantiating the transmission wavefront aberration measurement results presented in the previous section. Incidentally, hole diameter was 23 µm at the center of the scan field. In comparison, **Fig. 10** shows processing results obtained using a conventional lens (representing the level of conventional design and manufacture by Sumitomo Electric Hardmetal Corp.). The produced hole quality was poor in the outermost zone of the scan field. These results suggest that, when using this f-theta lens, to ensure hole quality it is necessary to narrow the scan field to, for example, 30 mm × 30 mm, depending on the type of processing.

Lastly, using hole positions and defocus levels shown in **Figs. 9 and 10**, telecentric errors were determined for the outermost zone in a 50 mm × 50 mm scan field. The results are shown in **Table 6**. Lenses A and B, fabricated for this study, are better in telecentricity than the conventional lens, as revealed in **Table 6**. Design values for telecentric errors are 0.46 deg. in the X-direction and 1.71 deg. in the Y direction, which are thought to match the measurement results well, taking measurement errors into account.

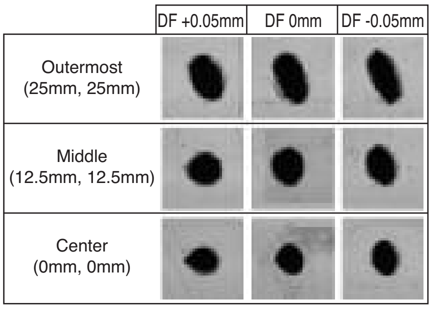

Fig. 10. Processing results (conventional lens)

Table 6. Telecentric errors obtained from processing tests

		X direction	Y direction
New lens	A lens	0.80deg	1.40deg
	B lens	0.75deg	1.46deg
Conventional lens		0.32deg	2.83deg

5. Conclusion

High-precision f-theta lenses for UV lasers were fabricated. Their performance was verified by transmission wavefront aberration measurements and processing test results. The correlation of optical evaluation data and processing results enables the supplying of high-processing performance f-theta lenses to the market.

We are also studying performance improvements such as expanded scan fields and shorter focal lengths. The design section receives feedback on transmission wavefront aberration measurement results, to facilitate development.

In addition to PWB processing, UV laser drills have found increasingly wider applications including: [9], [10]

· Green sheet processing
· Silicon boring
· Transparent electrode scribing
· Plastic sheet cutting

Moreover, it is similarly possible to develop and fabricate f-theta lenses for longer wavelengths than that used in UV lasers, such as f-theta lenses for the fundamental (1.064 µm) and second harmonic (0.532 µm) wavelengths of YAG lasers. We intend to explore this area.

F-theta lenses for short wavelength lasers enable small-diameter processing and are increasingly finding wider applications. We will continue contributing to the development of such f-theta lenses.

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