Development of Rectangular Core Optical Fiber Cable for High Power Laser

Kazuhisa KONISHI*, Tomohiko KANIE, Kenichirou TAKAHASHI, Osamu SHIMAKAWA, Yuuichi MITOSE, Takashi SASAKI, Toshiki TARU, Takuji NAGASHIMA, Keiji FUSE, and Akira INOUE

Laser scribing is a commonly used process for manufacturing thin film solar cells. The quality and efficiency of the scribing process can be improved by the use of rectangular flat-top beams. The beams are formed easily by rectangular core optical fiber. The authors have developed a rectangular core optical fiber and examined its characteristics in this study. The results demonstrate that the developed optical fiber is capable of forming rectangular flat-top beams that have sufficient uniform intensity distribution. This paper also includes some investigations on factors that affect the uniform intensity distribution profiles.

Keywords: rectangular core optical fiber cable, flat-top beam, laser scribe, thin film solar cell

1. Introduction

In recent years, efforts for CO_2 emission reduction have been actively made in various fields as countermeasures against global warming. At the same time, the use of solar cells has spread rapidly as a source of recyclable energy. In particular, there are plans for substantially increased production of silicon thin film solar cells for use in large-scale photovoltaic systems in the world(1).

A silicon thin film solar cell has a laminated structure comprised of a transparent electrode (TCO film), a power generation layer (silicon film), and a back surface electrode (metal film) on a base glass substrate as shown in **Fig. 1**. This laminated panel is further segmented into several cells that are connected in series. To form this structure, it is necessary to cut (scribe) each layer selectively. Laser processing is used in this scribing process, and selective scribing is made possible by using lasers at the wavelengths absorbed in each layer.

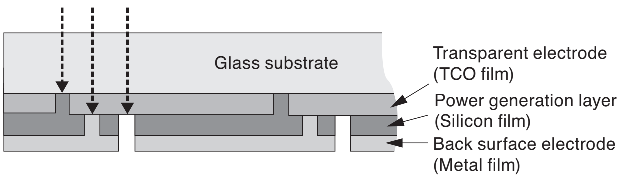


Fig. 1. Cross section structure of silicon thin film solar cell

In the scribing process, when normal laser beams are focused by a lens, the energy density is increased in the spot center (Gaussian beam) as shown in **Fig. 2**, which results in damage to the other layers. In the scribing process, a line profile is formed by scanning pulsed beams at high speed. The processing speed is higher in the rectangular spot profile than in the circular spot profile because the overlap of beams can be reduced in the former profile. Thus, using rectangular flat-top beams realizes an effective scribing process.

Various homogenized optical systems have been suggested for the formation of rectangular flat-top beams(2),(3). Among them, rectangular core optical fibers are capable of forming rectangular flat-top beams easily, and the flexible transmission is effective in a system where it is necessary to move the working head at high speed such as in large-area thin film solar cells, etc. This paper reports the characteristics of rectangular core optical fibers for high power lasers developed for laser scribing systems.

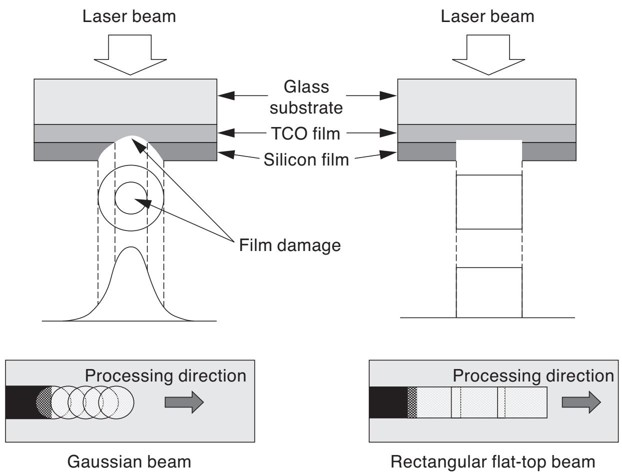
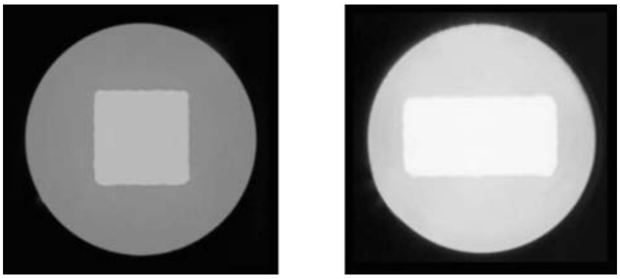


Fig. 2. Laser scribing in silicon thin film solar cells

2. Transmission Characteristics of Rectangular Core Optical Fibers

2-1 Transmission characteristics (Transmission loss)

The developed rectangular core optical fiber for high power laser is all quartz, which is reliable for high power laser beams, lining up various rectangular core profiles corresponding to the scribing widths. Example photos of their cross sections are shown in **Photo 1**.



50µm x 50µm core 50µm x 100µm core

Photo 1. Cross sections of rectangular core optical fibers

In order to correspond to various laser sources, different fiber NA (numerical aperture) types are also prepared. The transmission losses in various fibers in the YAG (Yttrium aluminum garnet) laser (wavelength: 1,064 nm) are shown in **Table 1**. The transmission losses in the fibers are less than 0.1 dB/10m, and in the fiber length of 10 m to 20 m used in actual processing systems, the laser power loss is mostly the loss at the incident coupling and the reflection loss on the fiber end face. If incident beams are coupled sufficiently, the transmission is at the level of 94%.

Table 1. Transmission loss of all quartz rectangular core optical fibers

Aspect ratio	Core profile (µm)	NA	Transmission loss (dB/10m)
1 : 1	35 × 35	0.10	0.1 or less
	50 × 50	0.10	
	50 × 50	0.18	
	480 × 480	0.15	
	600 × 600	0.10	
	600 × 600	0.15	
1 : 2	35 × 70	0.18	
	50 × 100	0.10	

2-2 Bending loss characteristics

As for multi-mode fibers, the bending loss generally becomes smaller as the fiber NA becomes larger. In case of fibers with the same NA, the bending loss is smaller in fibers with a smaller core profile[(4)]. An example of the bending loss characteristics of rectangular core optical fibers manufactured this time is shown in **Fig. 3**. When deciding the minimum bending curvature in actual processing systems, it is necessary to consider the bending loss characteristics together with the bending strength of the fiber to be used.

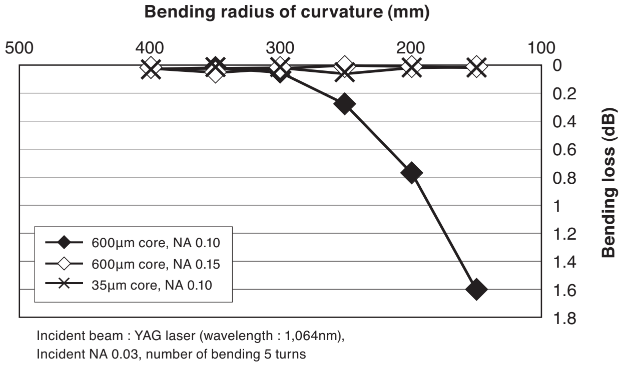


Fig. 3. Bending loss characteristics of rectangular core optical fibers

3. Output Property (FFP: Far Field Pattern)

The divergence of output beams (output NA) is a factor in deciding the size of an imaging lens, and the smallest possible one is preferable. It is very important especially in a system where the head is moved at high speed. **Figure 4** shows the output NA according to the change of the incident beam NA for the 50 µm optical fibers (fiber length: 10 m) of the fiber NA 0.10 and 0.18.

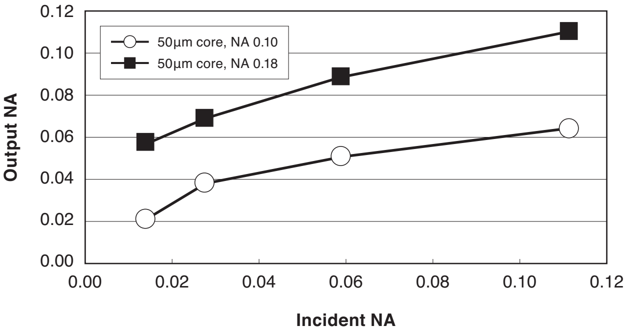


Fig. 4. Dependency of output NA on incident NA

For the incident beams, the YAG single mode laser (wavelength: 1,064 nm) was used, and the output NA was calculated by measuring the beam diameter at an optional distance from the fiber end at $NA = \sin\theta \fallingdotseq \tan\theta \fallingdotseq r/L$ (where, r is the radius of the beam at the position of L distant from the fiber end) when NA was small sufficiently.

The beam diameter was set within the range of 95% of the energy.

In the fiber for laser processing with a relatively short fiber length, the output NA does not become the fiber NA, and the incident NA is maintained to some extent. The output NA tends to become larger as the fiber NA becomes larger.

4. Imaging Pattern (NFP: Near Field Pattern)

4-1 Imaging pattern by multi-mode beams

Using the 50 μm core and 600 μm core fibers, the YAG multi-mode beams (wavelength: 1,064 nm) of the profile shown in **Fig. 5** were incident, and the imaging pattern of the fiber output end was measured.

As shown in **Fig. 6**, both rectangular core optical fibers obtained sufficient imaging patterns of the rectangular uniform intensity distribution, which means that both are effective in the formation of the rectangular uniform intensity distribution.

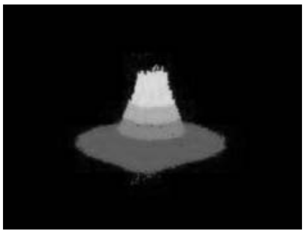
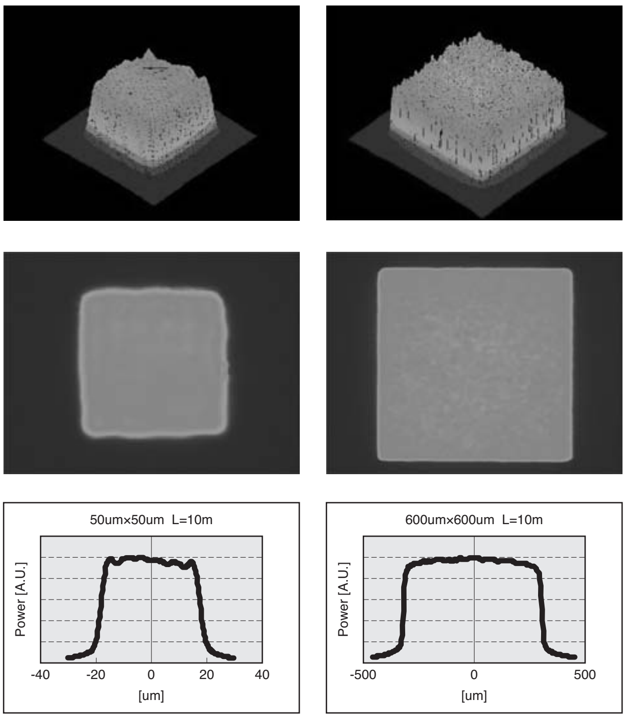


Fig. 5. Multi-mode incident beam profile



a) 50μm core, 10m fiber length, fiber NA0.10, incident NA0.06

b) 600μm core, 10m fiber length, fiber NA0.10, incident NA0.06

Fig. 6. Imaging patterns when multi-mode beams are incident

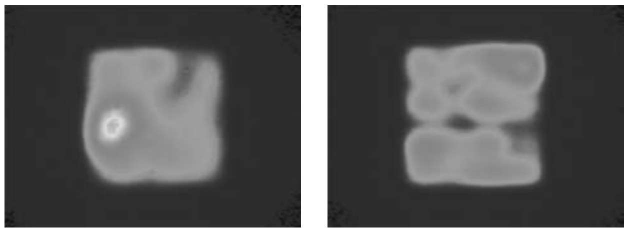
4-2 Imaging patterns of various fibers

The rectangular core optical fiber forms the uniform intensity distribution by the principle of overlapping beams. Therefore, flat-top beams are formed more easily in multi-mode beams with low coherence of incident laser beams. For this reason, it is important that as many modes as possible are generated and transmitted (excited) easily. For easy excitation, various imaging patterns measured to show the influence of various fiber specifications and the incident beam NA are shown in **Fig. 7**. In order to clarify the influence, YAG Gauss mode beams (wavelength: 1,064 nm) were used as a light source for evaluation.

First, as for the difference depending on the fiber NA, the imaging patterns for the different fiber NAs of the fibers with 50 μm core, 10 m fiber length, and incident beam NA 0.03 are shown in **Fig. 7, a)** and **b)**. In case of the fiber NA 0.10, the modes of incident beams are mainly excited. On the other hand, in case of the fiber NA 0.18, there is greater excitation of other modes.

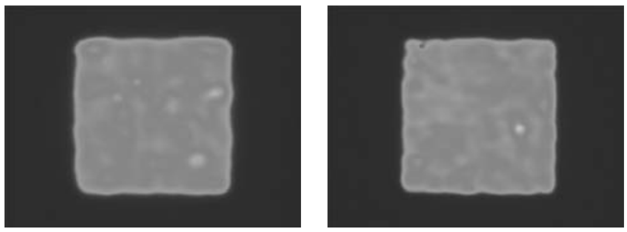
Then, when the fiber length is 50 m (**Fig. 7, c)**), there is greater excitation of modes, showing the improvement in uniformity. Even in the same fibers, as shown in the imaging patterns of **Fig. 7, b)** and **d)**, when the incident beam NA is enlarged from 0.03 to 0.12, there is greater excitation of modes, showing the improvement in uniformity.

When the core profile is enlarged, greater excitation of modes becomes possible in 600 μm core as shown in **Fig. 7, e)**, obtaining the uniform intensity of almost the same level as when multi-mode beams are incident.



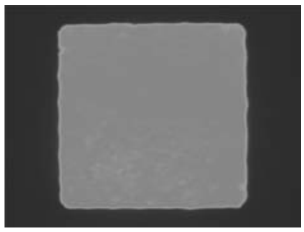
a) 50μm core, 10m fiber length, fiber NA0.10, incident NA0.03

b) 50μm core, 10m fiber length, fiber NA0.18, incident NA0.03



c) 50μm core, 50m fiber length, fiber NA0.10, incident NA0.03

d) 50μm core, 10m fiber length, fiber NA0.18, incident NA0.12



e) 600μm core, 10m fiber length, fiber NA0.10, incident NA0.03

Fig. 7. Imaging patterns when Gauss mode beams are incident

5. Durability

Various durability tests were conducted for the fibers using SUS flexible tubes for the fiber protection with the air gap type connectors to avoid damage at the incident alignment. The evaluation results are summarized in **Table 2**.

The fibers are judged particularly to have sufficient durability even in actual processing systems where the fiber bending is repeated.

Table 2. Rectangular core optical fiber durability test results

Item	Condition	Result
Repeated Bending (Cableveyor Test)	R=150mm(1 turn) 10,000,000 times	OK
Tensile Strength Test	50N	OK
Heat Cycle Test	5-60°C 6hrs/cyc × 10cyc	OK

6. Conclusion

This study indicates that rectangular flat-top beams can be formed by the rectangular core optical fiber developed for the thin film solar cells scribing system, and also indicates the influence of various fiber specifications and the incident conditions on the formation of the rectangular uniform intensity distribution.

To obtain flat-top beams, it is important to excite as many higher-order modes as possible, and multi-mode beams with low coherence are effective as a light source.

On the other hand, for minute profiling, a single mode laser source with high coherence is often chosen. In this case, it is recommended to use our product Diffractive Optical Element (DOE) homogenizer[5].

References

(1) Michio Kondo, "Photovoltaic Power Generation – Present and Future," Journal of Japan Laser Processing Society, Vol.15, No. 2, pp.1 - 5 (2008)

(2) Seiji Iwama, "Patterning of Thin Film Solar Cells by Solid Laser," Journal of Japan Laser Processing Society, Vol.15, No. 2, pp.16 - 20 (2008)

(3) Kazuhiko Sorada, "Laser Processing in Solar Cells Manufacturing Process," Journal of Japan Society of Laser Technology, Vol.33, No. 1, pp.26 - 31 (2008)

(4) Allan W. Snyder and John D. Love, Optical Waveguide Theory

(5) Takayuki Hirai, Keiji Fuse, Kenichi Kurisu, and Keiji Ebata, "Development of Diffractive Beam Homogenizer," SEI Technical Review No. 166, pp.13 - 18 (March 2005)

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

K. KONISHI*

- Assistant General Manager, Optical Components R&D Department, Optical Communications R&D Laboratories
  He is engaged in the development of optical fibers for high power laser.

T. KANIE

- Manager, Optical Components R&D Department, Optical Communications R&D Laboratories

K. TAKAHASHI

- Assistant General Manager, Optical Components R&D Department, Optical Communications R&D Laboratories

O. SHIMAKAWA

- Assistant Manager, Optical Components R&D Department, Optical Communications R&D Laboratories

Y. MITOSE

- Optical Components R&D Department, Optical Communications R&D Laboratories

T. SASAKI

- Manager, Optical Material Applications R&D Department, Optical Communications R&D Laboratories

T. TARU

- Assistant Manager, Optical Material Applications R&D Department, Optical Communications R&D Laboratories

T. NAGASHIMA

- Optical Material Applications R&D Department, Optical Communications R&D Laboratories

K. FUSE

- Assistant General Manager, Laser Optics Department, Sumitomo Electric Hardmetal Corp.

A. INOUE

- General Manager, Optical Components R&D Department, Optical Communications R&D Laboratories