DEVELOPMENT OF WIDE OPERATIONAL RANGE FIBER LASER FOR PROCESSING THIN FILM PHOTOVOLTAIC PANELS

(M1306)

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Abstract

Continued reduction of production costs for the manufacture of thin film photovoltaic solar panels is required to support the ongoing broad adoption of this important technology. Laser scribing is an integral manufacturing process for the production of monolithically-integrated thin film solar cells. An advanced generation 1.06 um pulsed fiber master oscillator power amplifier (MOPA) has recently been developed with performance attributes designed to meet current and next generation thin film laser scribing requirements for improving thin film solar cell device efficiencies, throughput, and yield. It features broad pulse width flexibility (200ps to 20 ns), excellent beam quality, and stable pulse output over a wide range of pulse repetition frequencies (50 kHz to 1 MHz). These performance attributes are expected to enable advanced laser process developments for amorphous (a)-Si, Cd-Te, CI(G)S (CuInGaSe), and next-generation thin film PV cell. As a result of this laser processing study, we have found that 10 to 20 -ns pulse width gives the best results for scribing TCO (Transparent Conductive Oxide)-layers while pulse widths shorter than 1ns are best for Mo-layers. Scanning speed of 2500mm/s and 5000mm/s have been achieved, respectively.

Introduction

Pulsed fiber lasers (PFLs) have become widely used for micro-machining applications because of their various merits, such as excellent beam quality, compactness, and high wall-plug efficiency. In particular, it has been reported that MOPA (Master Oscillator Power Amplifier) -type PFLs feature excellent control of temporal pulse shapes [1,2]. However, the tuning range of the pulse width is typically in the range from around 10ns to several hundreds ns in most cases. Throughout this range, thermal effects often negatively affect process quality [3]. To minimize thermally induced damage, the pulse width should ideally be in the range from 1ps to a few hundreds ps [3]. For this purpose, mode-locked lasers with typical pulse width of about 10ps have been reported [3-6]. Some of them have been effective at ablating the Mo films on glass without thermal effects [5,6]. However, mode-locked lasers are generally very expensive and tuning the pulse width is difficult. Pulse width tuning is helpful to optimise the processing conditions for specific solar cell device designs.

This paper presents a newly developed MOPA-type PFL whose pulse width can be tuned from 200ps to 20ns, by employing a directly modulated laser diode as the seed laser. With this simple configuration, the repetition rate can be widely varied from 50kHz to higher than 1MHz, and multi-pulse operation is also available. As a result of the process optimisation tests using this laser, pulse widths of 10 to 20ns seems preferable for TCO while sub-ns pulses are suitable to ablate the Mo-films.

Pulsed Fiber Laser Configuration

Figure 1 shows a photograph of the PFL. It contains the specially designed pulse generator used to directly modulate the seed laser diode operating at 1060nm. The output pulses are amplified by optical amplifiers employing Yb-doped fiber) and the average output power available is 15W.

Figure 1: Photograph of SEI (Sumitomo Electric Industries, Ltd.,)'s pulsed fiber laser

The pulse width, repetition rate and output power can be selected with the accessorial software using a USB interface. Moreover, the output can be turned on and off within the gating delay of 1ms by an external trigger signal.

The dimensions (in mm) of the PFL are 500 (Depth) x 482 (Width) x 200 (Height). The optical head box containing the collimator and the isolator is usually attached at the end of the delivery fiber. The output beam diameter is set to about 1.0mm. The beam quality is excellent, as shown in Figure 2, and M^2 is typically measured to be less than 1.1.

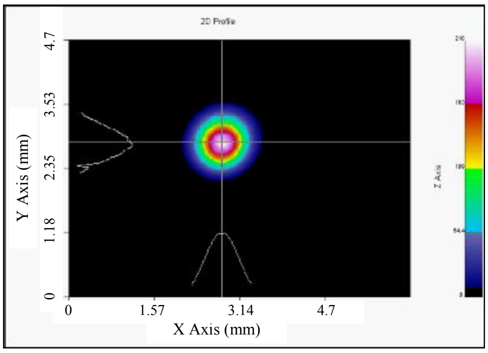

Figure 2: Typical output beam profile

Performances of PFL

The optical output pulse shape can be adaptively controlled by tuning the electric modulation pulse shape, namely the pulse width, the amplitude, the offset voltage, and the pulse patterns. Fig. 3 shows examples of the pulse shapes for the repetition rate from 50kHz to 2MHz. In Fig.3-(a), the electric pulse width has been set to 20 ns, which approximately corresponds to the full width of the bottom (FWB) of the optical output pulses. The full width of the half maximum (FWHM) of the optical pulses decreases as the repetition rate becomes lower, mainly because of the transient response of the fiber amplifiers. For the repetition rates grater than 500kHz, the FWHM of the optical pulse is almost coincident with that of the electric modulation pulse as shown in Fig. 3-(a).

In Fig.3-(b) and (c), the electric pulse width was set to 5ns, and the electric modulation amplitude was larger than that for Fig.3-(a) in order to realize gain-switching behaviour of the seed laser. In the operational mode shown in Fig. 3-(b), the pulse peak often exceeds 50kW while the FWHM becomes shorter than 1ns for the repetition rate of 100kHz, and the FWB is always about 5ns. The operational modes shown in Fig. 3-(a) and (b), and intermediate modes between them, can be easily controlled via the accessorial software.

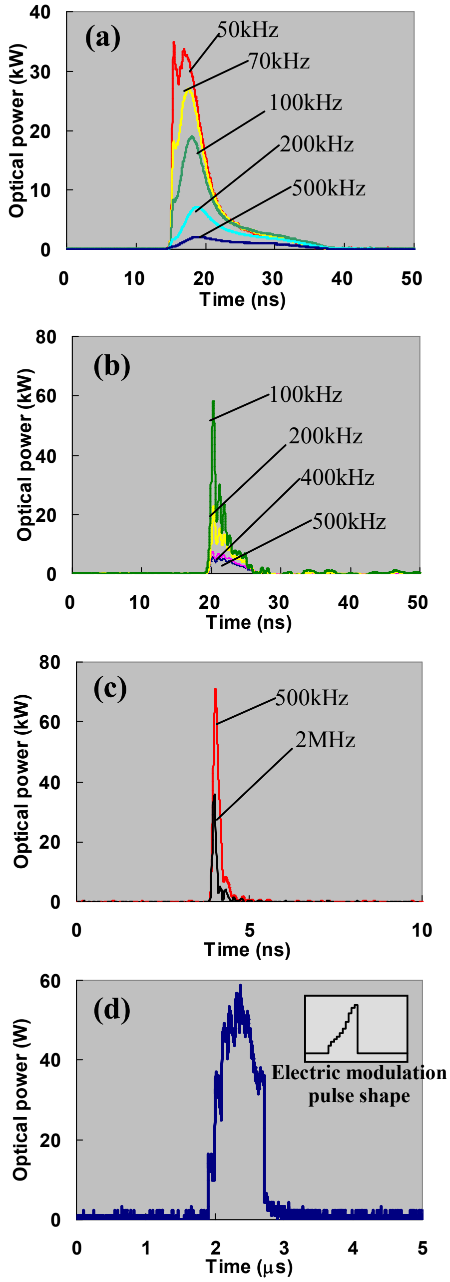

Figure3: Examples of the optical output pulses

The PFL may also be fine-tuned as shown in Fig. 3-(c). In this mode, FWHM has been compressed into about 200ps, which is expected to minimize thermal effect and to improve the laser processing quality [3]. It should be noted that the same PFL can also achieve pulse widths of as long as 1μs by optimising the electric modulation pulse shape as shown in the inset of the Fig. 3-(d). This operational mode is useful for micro welding or soldering applications.

Experimental

To demonstrate the advantage of the PFL, we have done P1 scribe tests on three types of the PV materials, namely

(1) NFL310SA2 made by Nippon Sheet Glass Co., Ltd

(2) TEC15™ made by Pilkington LTD

(3) MOLY made by AGC solar Belgium

Samples (1) and (2) consist of TCO films, and are intended for use in a-Si and Cd-Te solar cells, respectively. Sample (3) is coated with Mo, and is used for CI(G)S cells. All samples have been processed from the back-side.

For P1 structuring, the output beam diameter has been set to 1.0 mm. A beam expander was inserted after the optical head box to magnify the beam diameter 5 times. In order to scan the beam spot at speeds higher than 2000mm/s, the galvano scanner: Scanlab Hurryscan II-14 and the f-theta lens : Scanlab ID 114286 with the focusing length of 100mm have been employed instead of a high-speed linear stage. The beam spot diameter on the work pieces has been calculated to be 34μm.

Structuring TCO-layer on glass

Figs. 4 and 5 show the P1 scribe results on Sample (1) and (2), respectively. For both Samples, the operational conditions were as follows:

- Pulse operation mode shown in Fig. 3-(a)
- Repetition rate 160kHz.
- Scanning speed 2500mm/s,

The average power on the work piece has been set to 10W for Sample (1), and to 8W for Sample (2). In order to examine the processing quality, SEM, EDX, and 3-D analyses have been performed. No cracks or lift-off were detected. The 3-D analysis results show the thickness of TCO is 640nm and 550nm for Samples (1) and (2), respectively. To evaluate the galvanic isolation, the double cross was structured on the TCO films. The resistance between the isolated island and the surrounding area was measured, and for both samples, the resistance is higher than 100MΩ. In conclusion, high-quality P1 structuring has been demonstrated at scan speeds of as fast as 2500mm/s.

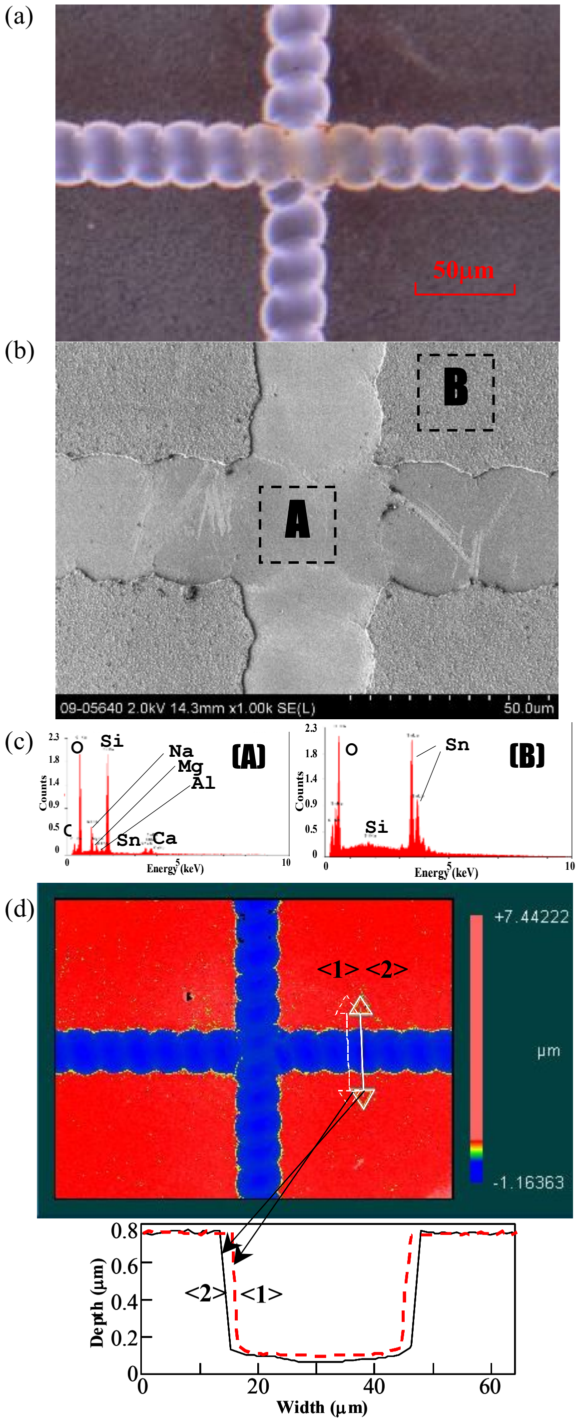

Figure 4. Sample (1) optical micro scope image (a), SEM image (b), EDX analysis results (c) for the areas denoted "A" and "B" in (b), and 3-D analysis results (d) of P1 scribing with 20ns-pulses, repetition rate of 160kHz and scanning speed of 2500mm/s. The average power on the work piece has been set to 10W

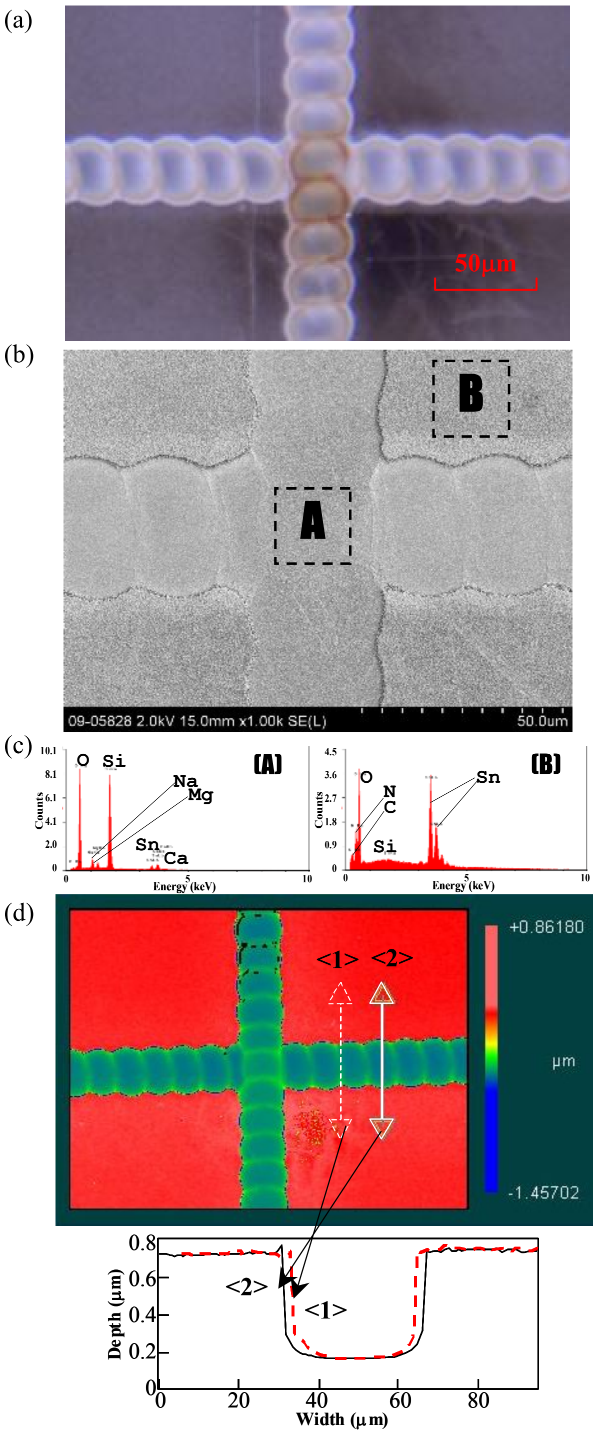

Figure 5. Sample (2) optical micro scope image (a), SEM image (b), EDX analysis results (c) for the areas denoted "A" and "B" in (b), and 3-D analysis results (d) of P1 scribing with 20ns-pulses, repetition rate of 160kHz and scanning speed of 2500mm/s. The average power on the work piece has been set to 8W

When the pulse operation mode shown in Fig. 3-(c), namely a 200 ps-pulse, is employed for the P1 structuring of TCO on glass, the spot size becomes much smaller, and the shape becomes elliptical. Moreover, the micro-cracks in the glass are evident in every spot as shown in Fig. 6, although the average power on the work piece has been set to only 6.8W. The excessively high peak power seems the cause of the damage to the glass.

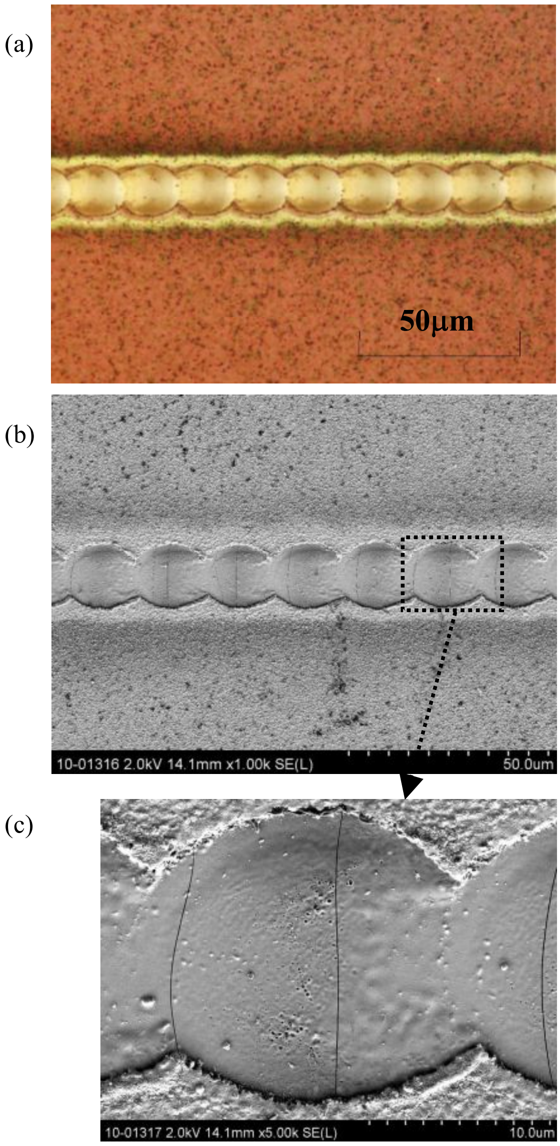

Figure 6. Sample (1), optical micro scope image (a), x1000 SEM image (b), and x5000 SEM image (c) of P1 scribing with 200ps-pulses, repetition rate of 150kHz and scanning speed of 2000mm/s.

Structuring Mo-layer on glass

Fig. 7 shows the P1 line structuring results on Sample (3) using the pulse operation mode shown in Fig. 3-(a). The repetition rate was 250kHz and the scanning speed was 5000mm/s. The average power on the work piece has been set to 8W. Thermal effect created micro-cracks with lengths of 20µm and widths narrower than 1µm. Moreover, significant lift-off occurs around the optical spots, and some roll-up can be observed between the spot.

In order to suppress the thermal effects, and also to avoid the glass substrate damages shown in Fig, 6, we tuned the pulse width to 500ps. Both the repetition rate and the scan speed remain at 250kHz and at 5000mm/s, respectively. The average power on the work piece was set to 5.7W. With these conditions, the micro-cracks have successfully been avoided as shown in Fig. 8. According to EDX analysis, there is no residual Mo on the glass surface. 3-D analysis result in Fig. 9 has shown that there has been no evidence of lift-off or roll up.

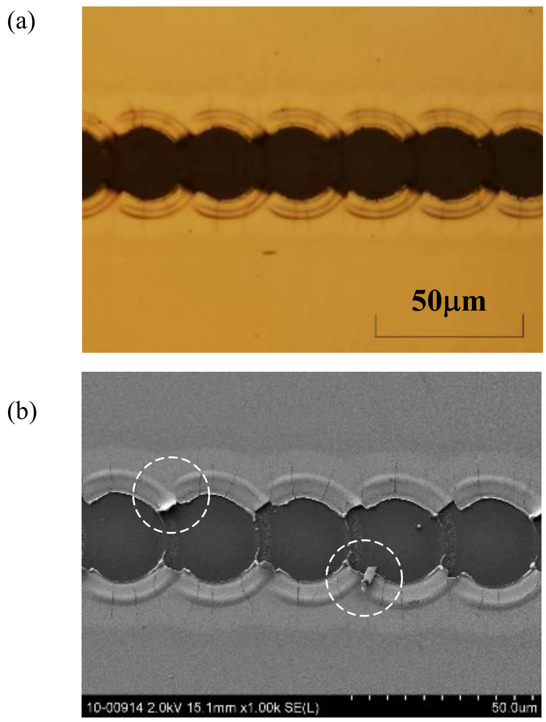

Figure 7. Sample (3), optical micro scope image (a), and SEM image (b) of P1 scribing with 20ns-pulses, repetition rate of 250kHz, scanning speed of 5000mm/s. Dashed circles in (b) denote the “rolling-up” of the Mo films. The average power on the work piece has been set to 8W

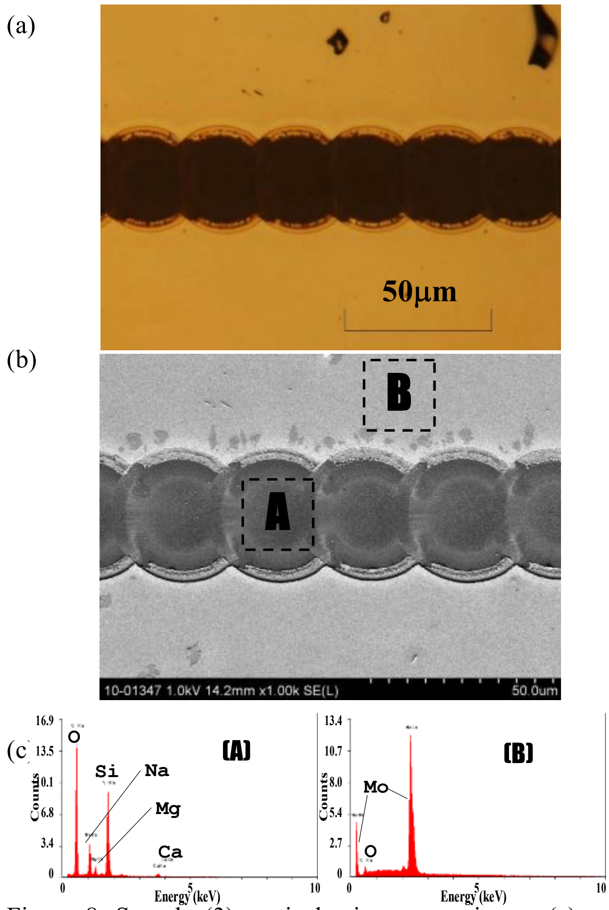

Figure 8. Sample (3), optical micro scope image (a), SEM image (b), and EDX analysis results (c) for the areas denoted “A” and “B” in (b) of P1 scribing with a pulse width of 500 ps, repetition rate of 250kHz and the scanning speed of 5000mm/s. The average power on the work piece has been set to 5.7W

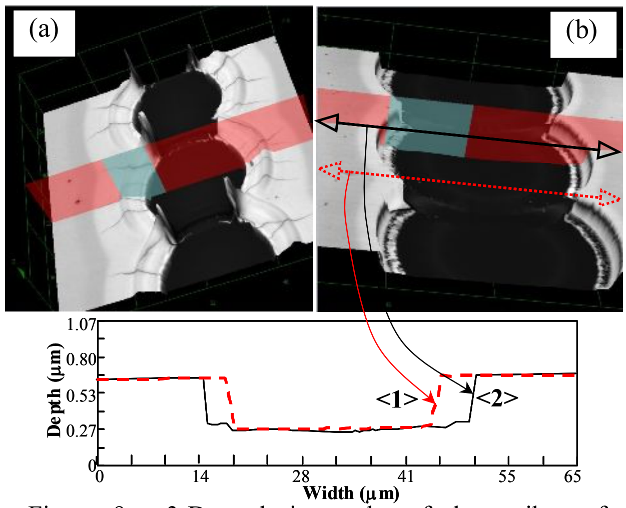

Figure 9. 3-D analysis results of the scribes of Samples (3) shown in Figs 7 and 8

Although optical microscope images look like double circles both in Figs. 7 and 8, the origin is quite different judging from SEM images or the 3-D analysis results shown in Fig. 9. The outer rim in Fig. 7 is the wrinkle of the expanded Mo-film around each spot, while the internal rim in Fig. 8 is a very thin residual layer. According to the cross-section shown in Fig. 9, the total thickness of Mo-film is about 400nm, and that of the residual layer is thinner than 60nm. This result might be attributed to the fact that the Mo layer of Sample (3) is graded. Fortunately, however, the last residual layer does not bring about any deterioration such as micro-cracking, lift-off, or roll-up without any beam homogenising technique. These results look as good as those reported in Refs. [5,6] which were done with 10ps-pulses.

Summary

SEI's newly developed pulsed fiber laser provides broad pulse width flexibility (200ps to 20 ns). Using this laser, P1 lines have been successfully structured on three kinds of coated glass for PV cells, namely a-Si, CdTe, and CIS samples. For the ablation of TCO films on a-Si and CdTe samples, a pulse width of about 10-ns is preferable, and the scan speed of 2500mm/s has been demonstrated. As for the ablation of Mo-layer, the processing quality is comparable to that reported with 10ps-pulses [5,6], The scan speed was 5000mm/s. Both kinds of the P1 structuring have been achieved at high speed using a single laser with temporal pulse control. We believe that this new PFL will be useful to reduce the capital expenditure and the production costs for manufacturing thin film solar panels. Moreover, temporal pulse control allows process optimisation for the next-generation PV cells with novel designs and/or novel materials in the near future.

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Meet the Authors

Shinobu Tamaoki received his B. S. and M. S. degrees from NAIST (Nara Institute of Science and Technology) in 2002 and Osaka University in 2000, respectively. In NAIST, he developed the fiber laser employing fluoride-based glass for telecommunication and medical applications. Since 2002, he has been with Optical Communications R&D Laboratories in Sumitomo Electric Industries, Ltd. He is currently engaged in the development of the fiber lasers and amplifiers both for the telecommunication and the industrial use.