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Real-Time Monitoring and Defect Detection of Laser Scribing Process of CIGS Solar Panels Utilizing Photodiodes

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ABSTRACT Laser scribing is developing rapidly in industrial applications as a method of material processing, especially in areas that require high levels of precision. This technology provides functionality and efficiency improvements in the manufacturing of solar panels. Due to the premium quality and speed requirements of the laser scribing technology, monitoring of this process in real-time is critical in order to promptly detect defects in the manufacturing process. However, common monitoring systems have been developed for other laser processes, like laser welding, which are noticeably slower than the laser scribing process. The goal of this research was to investigate the possibility of using photodiodes for real-time monitoring of the laser scribing process for Copper Indium Gallium Selenide (CIGS) solar panels. Various monitoring setup configurations were designed, developed, and examined to determine the viable option for implementation as a defect detection platform. Using different photodiode positions, the intensity of the light and the photodiode induced voltage for diffuse and specular reflections were tested, and the practical pros and cons of applying each configuration were analyzed. The capability of the monitoring system to distinct the different layers of the scribed CIGS cell was also examined to assess the penetration depth of the scribe. In addition, by performing several experiments with different scribe thicknesses and analyzing oscilloscope measurements, the optimal placement of the photodiode for accurate tracing of the scribing path was determined and verified. Key aspects of development of such monitoring system for solar panel applications were identified through this research.

INDEX TERMS CIGS cell, defect detection, fiber laser, laser scribing, photodiode, pulsed laser, real-time monitoring.

I. INTRODUCTION

Ultrafast pulsed lasers provide novel opportunities for various microscale processing applications due to their high peak powers and the ability for efficient thermal ablation. Laser scribing of thin film, which can be used in the manufacturing of solar panels, is one of the emerging applications of ultrafast lasers. The copper indium gallium selenide or Cu(In,Ga)Se2 solar cell (CIGS cell) is known as one of the efficient thin-film solar cells due to the conversion efficiency that it can provide, i.e., theoretical efficiency of 33% and efficiency record of 23% achieved for the laboratory cell [1], [2]. A schematic of a CIGS solar cell is shown in Fig. 1, which consists of Mo layer as the back contact placed on glass substrate, thin layer of $MoSe_2$, Cu (In,Ga)Se_2 as the photovoltaic absorber placed above the Mo back electrode, a buffer layer of CdS, and ZnO:Al as the front contact [3]. Manufacturing of CIGS thin film solar modules involves three steps (P1, P2, P3) to connect the front layer of ZnO from one cell to the back Mo contact of the next cell. First pattern is performed to separate the Mo back contact. Next, the absorber and buffer layers are deposited, and the second patterning is applied to scribe these layers down to the Mo layer. The third step is used to isolate neighboring cells after top contact deposition [4].

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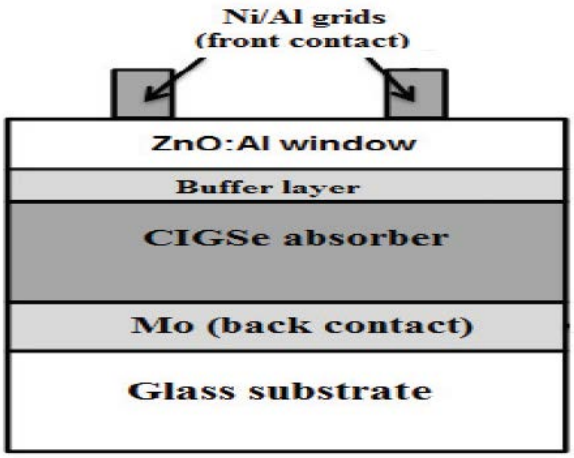

FIGURE 1. Schematic of a CIGS solar cell [3].

For manufacturing of CIGS cells, P2 and P3 scribes are typically done mechanically, while laser is used only for P1 scribe [5]. Mechanical scribing using an actively force-controlled stylus is the industry-leading method for CIGS scribing. However, the mechanical scribing method suffers from poor edge quality and creates wide irregular scribe lines. Hence, it leads to decreased efficiency resulting from the loss of the active solar cell area [5], [6]. Laser scribing technology has been actively developed in recent years and is replacing conventional mechanical methods for CIGS cell scribing [4], [7], [8]. In addition to advantages such as manufacturing accuracy, controllability, and high power of laser beam, laser scribing provides more other benefits than mechanical scribing to produce CIGS cells. The loss of power generation that occurs by the mechanical scribing method is reduced using laser scribing; so, an increase in solar cell efficiency is achieved [9], [10]. This occurs since layers between deposition processes are removed by the laser and monolithic cell-to-cell interconnections are created, resulting in minimal productive area loss [11]. Also, the performance of the patterning processes is improved by producing regular and deterministic edges [6], [12]. Fig. 2 demonstrates the comparison between pattern scribing by mechanical and laser methods [13].

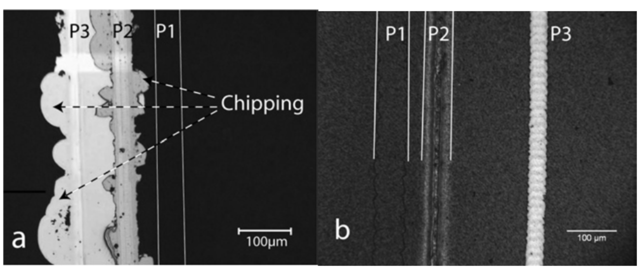

FIGURE 2. SEM image. (a) chipping problem by using mechanical scribing (b) laser scribing [13].

However, laser scribing process demands high quality requirements, as even a minor defect in the scribing line caused by disturbances in the process can deteriorate the quality of the final product [14], [15]. A defect in this field refers to a disconnection in the scribing line. Recognizing deflections and determining the precise location of defects during the laser scribing process of solar panels is critical since the quality control process for checking the product quality is implemented after manufacturing of products is completed, and if any defects are identified at this stage, the panel will be scrapped. This is while if online quality information about the laser scribing process can be supplied and the defects in solar panel scribing can be identified in real-time when the scribing process is going on, it will be possible to manually correct the defective point and salvage the panel. However, in contrast with other widely used laser applications, laser scribing is a fast process, the speed of which can reach several meters per second [14]. The high speed of the laser scribing process along with the high quality requirements of the process necessitates effective monitoring of this process. Monitoring systems for other common laser processes such as laser welding and laser cutting have been extensively studied and commercially established. However, these types of processes are remarkably slower than the laser scribing process. An effective real-time monitoring system for laser scribing process require sampling rate above 1 MHz for proper performance in order to provide information such as penetration depth, penetration loss, full depth, spatter, failures, etc., which enables process learning and error correction, and consequently enables process improvement and adaptation [16], [17], [18]. The scribing process parameters can be determined by the reference values obtained from a successful baseline scribe, which is compared to an active production signals, and analyzed in real time.

Optical methods are the most common among the various techniques utilized for laser process monitoring in real-time [19], [20]. Optical sensors such as photodiodes, different types of cameras, and spectrometers can be used for this purpose [21], [22]. Photodiodes have been considered in this study. Photodiodes are widely used in numerous domestic and industrial applications [23], [24]. In recent years, the use of photodiodes to monitor the laser processes have been growing due to the undeniable advantages that they provide. In addition to low cost and easy mounting, photodiodes can detect process emissions in a wide wavelength range. Their high defect detection rate with minimal errors makes photodiodes the desired option for monitoring low-speed laser processes [18], [25]. However, photodiodes have so far not been studied enough to be employed for monitoring the laser scribing process in real-time.

The objective of this study was to investigate the possibility of using photodiode to monitor the laser scribing process in real-time and explore the viable options for implementation in industrial applications. The goal of the monitoring system was to observe the scribing process of the CIGS solar panel to detect the defects and abnormalities that may occur in the scribing process or scribed line instantly. For this purpose, a test set-up for performing different experiments has been built to evaluate the feasibility and performance of the developed method considering the challenges that arise due to high-speed and high-quality requirements of the laser scribing process. The developed monitoring system was equipped with a pulsed ytterbium fiber laser, photodiode, camera adapter, and industrial computer PXI system with Data Acquisition card and Real-Time Controller module. Numerous experiments with different monitoring configuration setups were performed to assess the feasibility and identify the key aspects of applying photodiode for real-time monitoring of the laser scribing process. In one experiment, the diffuse versus specular reflections were tested using different photodiode positions and configuration set-ups. The intensity of the light, the photodiode induced voltage, and the challenges of applying each configuration were compared and analyzed. Material layer distinction test was also performed to evaluate the ability of the monitoring system to differentiate between diverse layers of scribed CIGS sample. This capability provided the opportunity to ensure the scribe has penetrated as intended. Furthermore, the optimal placement of photodiode in the monitoring system setup to precisely track the scribing path was determined. Finally, the whole setup was tested in real-time by conducting several experiments with different scribe thicknesses and analyzing the oscilloscope measurements. The system performed as intended to successfully detect as soon as the laser missed a pulse. The monitoring and defect detection method for laser scribing using photodiode, which has been investigated in this research, contributes to implementing such a system in the industrial applications of the CIGS thin-film solar cell laser scribing.

II. TEST SETUP

Fig. 3 illustrates the schematic diagram of test setup used in this study [26].

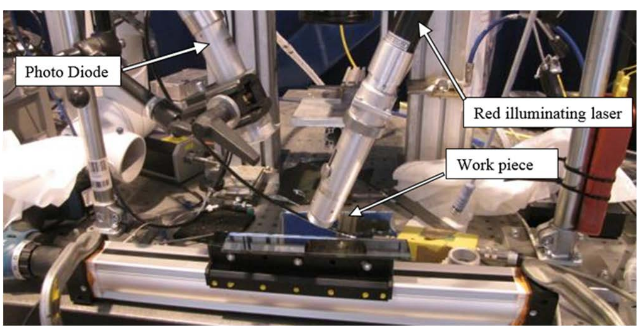

FIGURE 3. **Monitoring test setup [26].**

IPG pulsed ytterbium fiber laser with the nominal average power of 20 W, wavelength of 1064 nm, M^2 beam quality of 1.5, maximum pulse energy of 1 mJ, pulse repetition rate of 1.6-1000 kHz, and variable pulse length of 4-200 ns was used in this research [27], [28]. The laser system is equipped with Scanlab Hurryscan 14 II scan head with a 100 mm focal length tele-centric lens, which provides a working area of 54×54 mm^2 for the laser with a minimum laser spot size of 28 μm. However, the actual beam spot size is almost 40 μm. The marking speed of the scan head is over 1000 characters per second. The real-time control (RTC) board controls the digital interfaces of the scan head. SCAPS SAMLight software was employed for controlling the laser system. In order to monitor the laser working area, a Scanlab camera adapter with aperture of 14 mm was installed on the scan head to continuously follow the laser beam. The light emitted from the work piece is decoupled using the beam splitter and redirected through the camera port to the photodiode attached to the adapter. However, the scribing laser beam passes unattenuated through the dichroic beam splitter to the scanning system. NI PXIe-1071 system equipped with Data Acquisition card and Real-Time Controller module was chosen as the industrial computer. JDSU 1103P Helium Neon Laser was used to illuminate the scribing path externally for providing an input for the photodiode sensor [29].

III. EXPERIMENTAL TESTS

The key factors for real-time monitoring of the laser scribing process and detection of defects are the reflectance contrast of the workpiece layers and the capability to track the fast laser scribing process with high accuracy. In order to evaluate the possibilities and challenges of using commercial photodiodes to monitor the laser scribing process in real-time, different monitoring setups were designed and tested. The experimental tests included the following: pre-defect detection experiment, specular versus diffuse reflection test, distinction test between different layers of the material, and experiment to determine the optimal solution for tracing the laser scribing path. Different monitoring configurations were developed for each experiment. The average scribe width used in the experiments was approximately 50 μm.

A. DEFECT DETECTION TEST

In the first stage, the monitoring system was examined to identify defects that were intentionally placed on a CIGS scribe line. The monitoring system was initially tested to ensure that it could detect the defects as soon as the laser missed a pulse. The defects consisted of three non-lasered gaps in the scribed line. The result in Fig. 4 shows that when the photodiode identifies a scribing deflection, the photodiode output jumps to maximum value of 10, while the photodiode output is less than the maximum value in the flawless scribing regions. So, using this approach any deflection in the scribe line can be detected in real-time.

B. SPECULAR AND DIFFUSE REFLECTIONS

The diffuse and specular reflected lights were tested and compared using different photodiode positions, as it was crucial to examine which type of reflection provided the best contrast between the intact surface and laser scribed. In order to examine the specular light signal, the photodiode was placed in such a way that the beam was directly reflected from the workpiece into the diode, while the diode was positioned

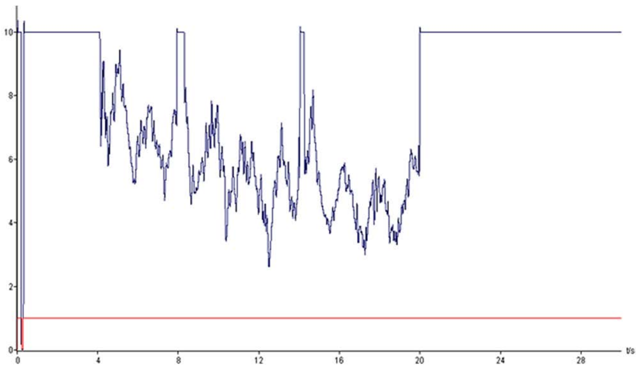

FIGURE 4. **Photodiode output signal.**

to the side of the beam to identify the diffuse reflection from the workpiece. For both examined reflections, the monitoring beam was positioned with an angle to the work peace and outside of the scan head, as shown in Fig. 5. The experiments were performed by moving the workpiece that had prescribed lines of varying width on its surface, along the path of the monitoring beam. Samples of CIGS were used as the tested materials. The scribe width on the CIGS samples was almost 50 μm [26].

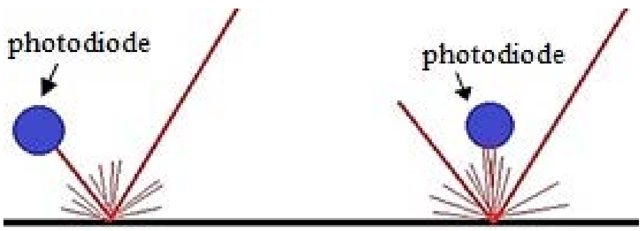

FIGURE 5. **Specular (left) and diffuse (right) reflections test.**

The results showed that the intensity of the light received through the specular reflection was greater; however, it caused considerable problems while monitoring a moving scribing process. Also, aligning the specular reflection beam was more difficult. On the other hand, it was easier to align the diffuse reflection as well as configure a set-up to monitor a moving scribe. In addition, the diffuse reflection provided more reliable results. Some samples of CIGS material employed in these experiments are presented in Fig. 6. The lines in the figure specified by the square were used for the tests.

FIGURE 6. **CIGS samples used to monitor specular and diffuse reflections [26].**

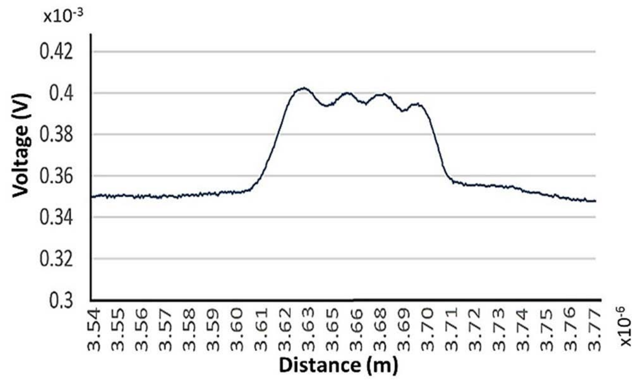

FIGURE 7. **The induced voltage of photodiode for diffuse reflection.**

Fig. 7 demonstrates the photodiode measurement passing over the CIGS sample consisting of four lines shown in Fig. 6. A considerable increase in reflectivity occurs when passing through the intact surface on the first line. Also, four recognizable peaks correspond with the scribes are shown in the picture.

Four peaks are also shown as drops in light intensity for specular reflection in Fig. 8. Compared to Fig. 7, the contrast between the lines is more obvious in this figure. However, as indicated by Fig. 8, the difference in intensity between the scribed and intact surface is less with the specular reflection.

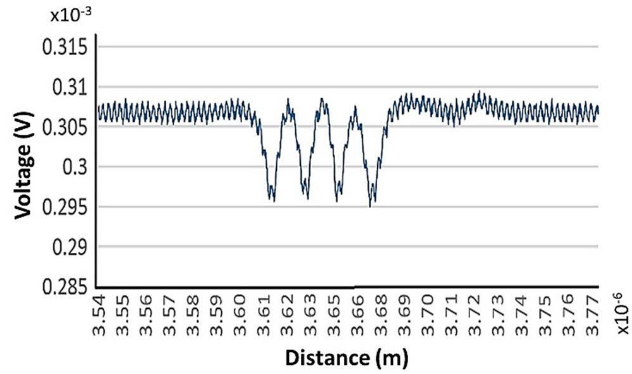

FIGURE 8. **The induced voltage of photodiode for specular reflection.**

C. CIGS LAYERS DISTINCTION

To evaluate the suitability of using photodiodes for monitoring the laser scribing process from another aspect, material layer distinction test was also carried out to examine whether the different layers of the material in question could be distinguished from each other based on their difference in reflectivity. Due to the nature and speed of the laser scribing process, reflection contrast is the only solution to distinguish between the material layers. The ability to distinguish between various layers of scribed CIGS sample based on layer reflection was examined using the same monitoring test setup. CIGS samples were scribed at different depths. The concept of the layer differentiation test based on layer reflection is displayed in Fig. 9 and Fig.10. Fig. 9 shows the layers of scribed sample material, while Fig. 10 illustrates the corresponding reflected light intensity curve. As shown in Fig. 10, the reflectivity level varies between different layers. For the scribed material shown in Fig, 9, the second layer demonstrates the greatest reflection. When passing through the intact surface, a significant drop occurs in reflection compared to the second layer. A drop in reflectance with a smaller magnitude compared to the intact surface layer is also evident when penetrating to the base material. Significant differences in reflection between various layers of a CIGS sample make it possible to distinguish the layers and identify to which layer the scribe has penetrated. The reflected light intensity provided by the installed photodiode monitoring setup removes ambiguities about whether the scribe has penetrated deep into the base layer or whether the top surface has remained intact. Modifying the laser beam parameters can improve the contrast between the layers since the contrast between the layers is proportional to the reflected intensity.

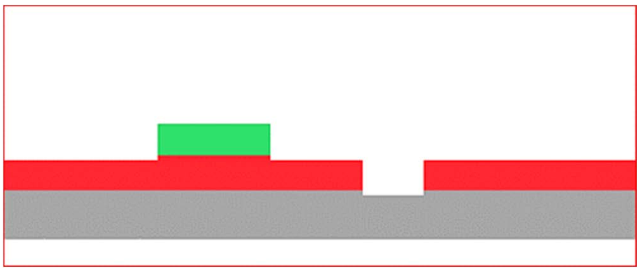

FIGURE 9. **Layers of the test surface. Grey: base layer, red: second layer, green: intact surface.**

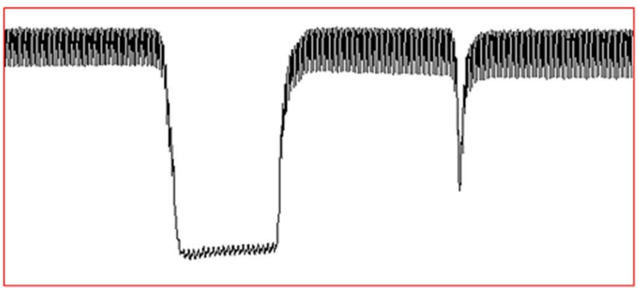

FIGURE 10. **Reflected light intensity curve corresponding to the scribed test surface.**

D. OPTIMAL PLACEMENT OF PHOTODIODE IN MONITORING SYSTEM SETUP

An effective monitoring system is crucial for precise laser beam tracking in order to achieve a consistent removal depth of material in the laser scribing process. To track the scribing path, the photodiode used for the monitoring purpose should be placed in a position with a visual predominant proper for viewing the workpiece. This could be achieved by placing the diode towards the workpiece from outside of the scribing scan head, or by observing the workpiece through the scan head itself, as shown in Fig. 11. However, following the scribing path in both setups is challenging due to inaccuracy that may occur with an externally mounted and independently moved diode, as well as the loss of intensity of the reflected signal when observing through the scan head. The monitoring setup illustrated in Fig. 11a was built by locating the photodiode in an external clamp and focusing on the target region, while the camera adapter of the scan head was used to focus the diode on the respective area in the setup shown in Fig. 11b. The latter setup allows observing the target area along the actual laser scribing path using the dichromatic reflector of the scan head camera adapter, the operation principle of which is demonstrated in detail in Fig. 12. The setup of Fig. 12 consists of a 1) scanner with two fully reflective articulated mirrors to direct the beam, 2) the camera adapter with a dichromatic mirror, which allows the scribing beam to pass, while reflecting the illumination, and 3) a 50:50 dichromatic mirror that partially reflects the beam and allows it to pass through to some extent. Part of the reflected beam is projected to the photodiode located on the right side [26].

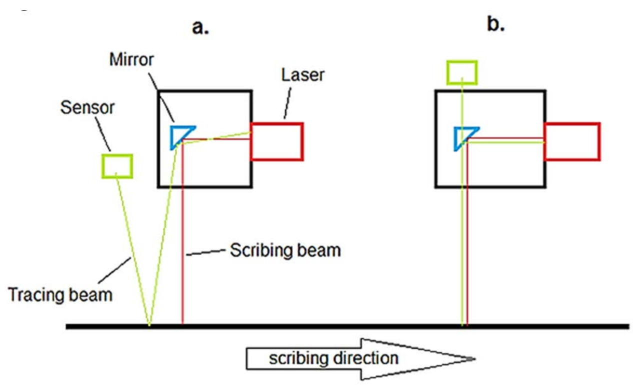

FIGURE 11. **Monitoring through (a) external mounted photodiode (b) integrated mounted photodiode in the scan head.**

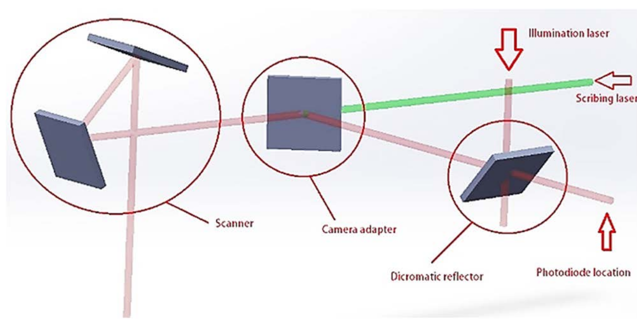

FIGURE 12. **Layout of the beam path through the scribing laser assembly.**

The ability of the developed system to monitor the laser scribing process using photodiode and detect the defects was demonstrated by carrying out numerous tests. The tests were performed in real-time while the laser was doing the scribe and the monitoring system was following the scribe. The largest thickness of the scribed lines was approximately

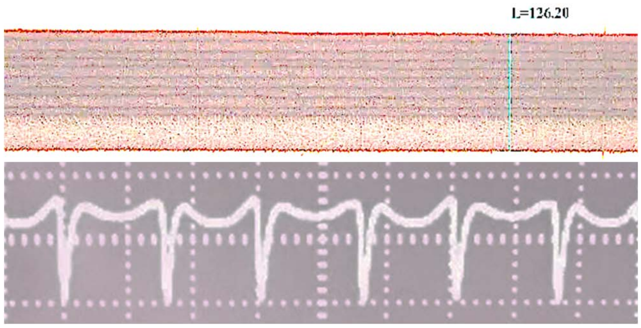

FIGURE 13. Scribe thickness of 126.20 μ and oscilloscope measurement.

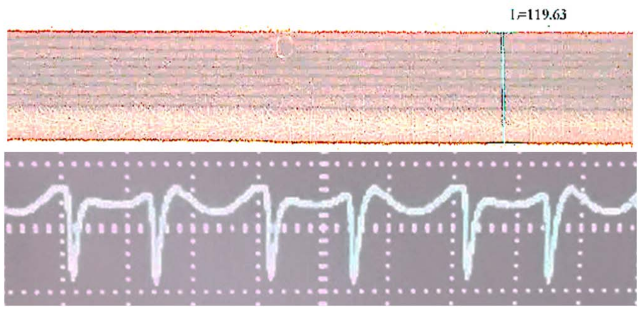

FIGURE 14. Scribe thickness of 119.63 μ and oscilloscope measurement.

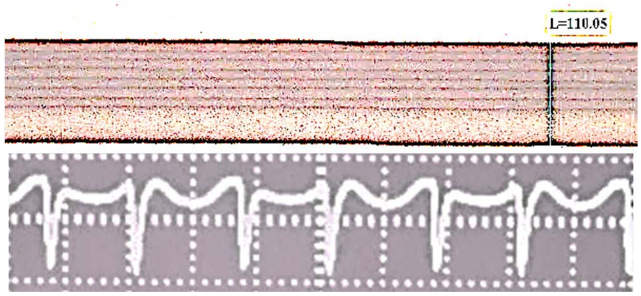

FIGURE 15. Scribe thickness of 110.05 μ and oscilloscope measurement.

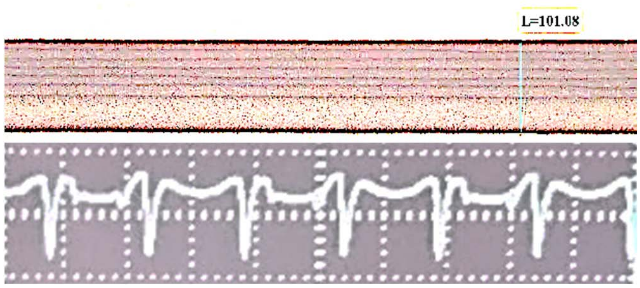

FIGURE 16. Scribe thickness of 101.08 μ and oscilloscope measurement.

130 μm, which decreased with a reduction of 10 μm in other samples. The microscope images of the lines used in the experiments together with the respective oscilloscope measurements are displayed in Fig. 13-22. It should be noted that the monitoring beam reciprocates over the line, hence, there is a periodically repetitive curve. One period of the curve is a single passage from the line. Each of the drops shows that the

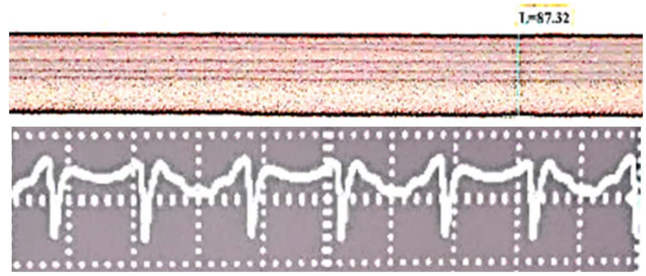

FIGURE 17. Scribe thickness of 87.32 μ and oscilloscope measurement.

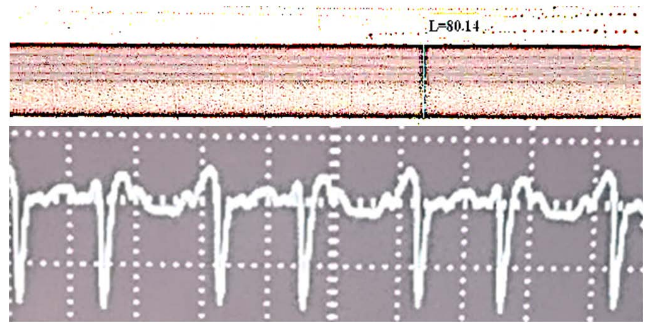

FIGURE 18. Scribe thickness of 80.14 μ and oscilloscope measurement.

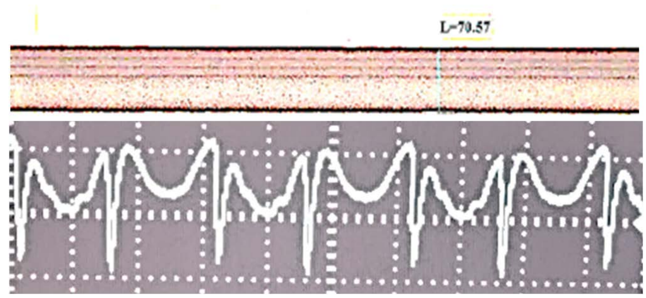

FIGURE 19. Scribe thickness of 70.57 μ and oscilloscope measurement.

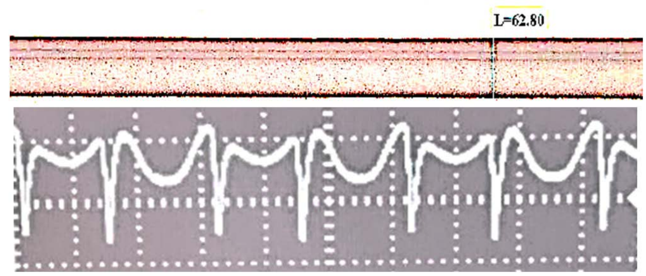

FIGURE 20. Scribe thickness of 62.80 μ and oscilloscope measurement.

light disappears from the photodiode and the lines are fully scribed.

Optical errors caused challenge in following the scribing event. As the line thickness decreased, the contrast between the scribed and the non-scribed surface decreased as well. Increasing illumination brightness assisted in providing enough contrast between material layers to be distinct, and eliminating outside interference as much as possible, and consequently, improving the results. Due to the movement of the laser beam in and out of the center location, a considerable

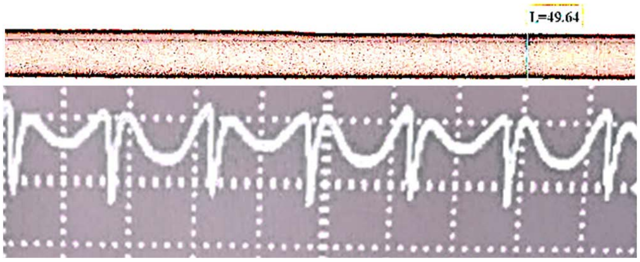

FIGURE 21. Scribe thickness of 49.64 μ and oscilloscope measurement.

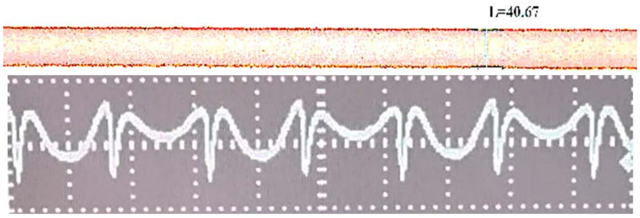

FIGURE 22. Scribe thickness of 40.67 μ and oscilloscope measurement.

change in intensity associated to the beam change was observed even on the non-scribed surface. Repeating the experiment with a completely un-scribed surface would yield a curve with a local maximum in the approximate position of the scribes. According to the results, the use of photodiode observation with the monitoring beam reflected through the scanner is a strong possibility for real-time monitoring of the laser scribing process. Compared to other photodiode monitoring setups, the developed system allows the greatest amount of laser movement. Based on the developed monitoring system, it is simply possible to design an algorithm using LabVIEW® or other monitoring software to immediately stop the process if the photodiode does not receive light reflection, which means it detects a defect in the scribe line.

IV. CONCLUSION

The available laser monitoring systems have been generally designed for moderately slow processes such as laser welding or laser cutting, for which the process speed does not raise a challenge for precisely monitoring the process. However, these existing monitoring systems are not proper for implementation for the laser scribing process since the speed of the process does not allow monitoring the process in real-time; hence, a novel system that can overcome the speed and accuracy challenges of the process is required to be established. The aim of this research was to investigate the possibility of using photodiode for monitoring CIGS laser scribing process in real-time. The monitoring system test set-up includes photodiode, fiber laser, camera adapter, and industrial computer PXI system equipped with Data Acquisition card and Real-Time Controller module. Numerous experiments were performed with different monitoring configuration setups to evaluate the feasibility and identify the key aspects of applying photodiode real-time monitoring system to a laser scribing process. Different choices were examined to determine the optimal placement of photodiode in the monitoring system setup aiming to accurately trace the scribing path. The results obtained proved the applicability of the suggested solution. Also, using different photodiode positions, set-ups for diffuse and specular reflections were configured and tested and the photodiode induced voltages were compared and analyzed. In addition, an experiment was performed to test the system's ability to distinguish between diverse layers of scribed CIGS sample. This feature provided a solution to determine the penetration depth of the scribe. The whole monitoring system developed based on the results of the configuration experiments was tested in real-time with different scribe thicknesses while the laser was doing the scribe. The oscilloscope measurements showed that the system performed as intended to successfully detect the scribed spots or as soon as the laser missed a pulse. The monitoring and defect detection system developed in this research is a step forward towards providing increased efficiency in manufacturing of solar cells by effectively monitoring the scribing process and detecting the defects in real-time. The proposed technology is promising and has the potential to be implemented in the industrial applications of the CIGS thin-film solar cell laser scribing.

The future research direction will be developing a method for divergence compensation in order to overcome the optical errors in tracking the scribing path. Other future plans include identifying the proper operating wavelength of the illumination laser and photodiode to intensify the contrast between the scribed and non-scribed surfaces and reduce the interference from other light sources.

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