Digital Micromirror Device Application for Inline Characterization of Solar Cells by Tomographic Light Beam Induced Current Imaging

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ABSTRACT

Light Beam-Induced Current (LBIC) imaging is a well-known characterization technique for solar cells, which allows to detect regions of low crystal quality. In this paper a fast, robust and reliable LBIC system is proposed by the use of digital micromirror device (DMD). The LBIC technique is usually performed by point-by-point mechanical sample scanning under a laser spot or by laser scanning, which leads to a measurement time of at least several minutes. In this proposed system with DMD, a new technique is introduced, in which a solar cell is scanned from different angles by a light-line instead of a light-spot. The obtained photocurrent data from these scans are used to reconstruct an LBIC image by using tomography principles. This leads to a lower number of measurements compared to any point scan method. This method helps in reducing measurement time and makes LBIC a fast characterization tool capable for inline investigations. Light-line scans over the cell from different angles are realized by a digital micromirror device (DMD) and its parallel interface controller. The DMD provides a fast solution for line-scanning the cell at speed up to 4 kHz, leading to a measure time of a few seconds for a 256x256 pixel image. Since there are no moving parts involved in this setup, it is a robust and compact system, which will be ideal for the field environment and inline characterization.

Keywords: DMD application, infrared laser, solar cells, LBIC, quality control, tomography

1. INTRODUCTION

Photovoltaics, which provides direct conversion of solar energy into electrical energy by using solar cells, is one of the options to cope with the challenge of global warming. Most of today's solar cells are made from multi-crystalline (MC) silicon material. The world-wide production capacity of MC silicon solar cells is steadily growing and has exceeded 1 GW in 2006, which corresponds to a totally produced solar module area of more than 6 square kilometers. MC silicon material is produced by a casting process employing slow crystallisation speed, which leads to grain sizes up to several cm. However, in all industrially produced MC silicon material, there are also some regions some cm² in size having small grain sizes below 1 mm and high dislocation density. These "low crystal quality" regions are a serious obstacle for obtaining high conversion efficiencies for large-area MC solar cells. Higher efficiencies can be obtained by monocrystalline silicon material, which is considerably more expensive than MC silicon material. The physical reason for the appearance of these low crystal quality regions is still under investigation. For monitoring the solar material quality, and for investigating the origin of insufficient solar cell conversion efficiencies, the appearance of low crystal quality regions has to be detected. In unprocessed wafers, different techniques of minority carrier lifetime imaging are applied for this purpose, such as local microwave techniques [1], infrared (IR) camera-based techniques [2], or photoluminescence [3]. The classical technique for studying the crystal quality in readily processed solar cells is the Light Beam-Induced Current (LBIC) technique [4]. Here a focused light spot is scanned across the surface of the cell, and the photo-induced current is measured and used to produce an image of the local photo-response of the cell. In regions of low crystal quality this response is lower than in good crystal quality regions, therefore low crystal quality regions appear dark in LBIC images.

Modern solar cell production lines have a cycle speed of about 2 seconds, hence every 2 seconds one cell is produced. In order to monitor possible reasons of a low product quality also after production, inline measurement tools are increasingly included in modern solar cell production lines with all measured data being stored. The implementation of LBIC would be interesting as an in-line monitoring tool, if it could be realized in less than 2 seconds. However, as it will be outlined in the following section, usual LBIC measurement times are at least in the order of several minutes, depending on the spatial resolution. Lower LBIC measurement times will improve the efficiency of the monitoring task, even if not all the cells in a production line are required to be imaged. Therefore, for implementing LBIC as an inline
tool in solar cell production lines, and generally for having a fast and efficient characterization tool for solar cells, a fast LBIC measurement procedure is highly desirable.

In this contribution, a novel robust, reliable and fast LBIC measurement instrument is proposed based on Digital Micromirror Device (DMD) system produced by Texas Instruments [5] which is also widely used for commercial video-projectors. A special measurement procedure called "Tomo-LBIC", which relies not on point-by-point scanning but on scanning a light-line under different angles is used in this system. This special scanning procedure is realized by a DMD. By using tomographic reconstruction principles, from the result of this line-scanning measurement, the 2-dimensional photo-response of the cell is reconstructed. Compared to traditional point-scanning, this measurement can be performed with a lower number of single measurement events, which may lead to a time-saving. It will be shown that the inevitable errors made by this measurement and image reconstruction principle are low enough to keep the results significant for monitoring low crystal quality regions. In the following, the Tomo-LBIC technique is described in detail, and some image reconstruction methods are presented. In the experimental section, various traditional ways to realize the LBIC measurement procedure are reviewed and their maximum measurement speeds are reported. Then technical details are given for our first DMD-based LBIC / Tomo-LBIC prototype realization. Finally, our first Tomo-LBIC measurement examples are introduced and compared with an LBIC image measured by point-by-point scanning.

2. TOMO-LBIC PRINCIPLE

2.1 Tomography principles

Fig. 1: Projections of a 2-dimensional object by parallel rays from 3 different angles

Tomography or Computer Tomography (CT) was invented to look inside of 3-dimensional (3-D) bodies and to reconstruct their internal 3-dimensional geometry. Any imaging system, which is able to look into a 3-D body, like an X-ray imaging system, produces 2-dimensional (2-D) images, which reflect e.g. the internal absorption of the body. From one such 2-D image, the 3-D structure of the body cannot be reconstructed. However, if the imaging is repeated from several directions, all these images together should contain all information about the internal 3-D structure of the body. The only remaining problem is to reconstruct the internal structure from this multiplicity of 2-D images. One possible way to perform such tomographic measurements is to transilluminate the body by a parallel beam of rays and to monitor the shadow of the internal absorption by a flat screen behind the body. This procedure is repeated under different illumination angles, which are equally distributed in a half-circle surrounding the body. Since here all rays are running in parallel, the 3-D problem can easily be split into a number of 2-D problems by considering all horizontal lines of the
detector separately. In fact, for each imaging angle, each such horizontal detector line (which produces a 1-D vector of data) contains incomplete information about the horizontal 2-D plane in this special height. All 1-D data lines in a special height for all imaging angles together should contain the complete 2-D absorption data of the plane in this height. Once all these horizontal 2-D planes are reconstructed, the 3-D body is simply the vertical stack of all these horizontal planes. So the decisive step in 3-D tomographic reconstruction is to perform the 2-D reconstruction from a number of 1-D vectors for different angles. Fig. 1 illustrates this process. The tomographic measurement procedure, producing a number of 1-D vectors from a 2-D plane, is mathematically called Radon-transformation. The Radon-transform of a 2-D plane is a number of vectors. In the following, we will only consider this 2-D problem having 1-D Radon vectors.

2.2 Tomographic reconstruction

If we assume that the image formation relies on weak absorption, according to Fig. 1 each element of one Radon-vector \( R_j^\phi \) represents the summed-up absorption of one line in ray-direction in the 2-D plane \( A_{ij} \). For example, for \( \phi = 0^\circ \) (all rays in x-direction), \( R_j^{0^\circ} \) can be defined as the sum over all absorption values in this line \( j \):

\[
R_j^{0^\circ} = \sum_i A_{ij}
\]

This Radon vector contains information about the distribution of the absorption in the 2-D plane in y-direction, but no information in x-direction. The simplest assumption one can made is that the 2-D distribution of the data in x-direction is homogeneous, hence that the image consists of parallel running lines of various intensities, which are given by the Radon vector \( R_j^\phi \). If \( D_R \) is the dimension of the Radon vector for \( \phi = 0^\circ \), this hypothetical 2-D reconstruction can be expressed as:

\[
A_{ij}^{0^\circ} = \frac{R_j^{0^\circ}}{D_R}
\]

Such a 2-D image containing only the information of a 1-D vector is called a single "backprojection" of a single Radon vector. Fig. 2b shows an example of image backprojection with three angles. This procedure can be repeated for all Radon vectors belonging to all angles. The superposition of all single backprojection in one plane, regarding the different angles \( \phi \), is the complete backprojection, which also may be called "primitive reconstruction". Fig. 2 illustrates two primitive backprojections of a simple circular shape by using a small and a high number of projection angles. We see that for a low number of angles, the primitive reconstruction of Radon data leads to inevitable image artifacts, which are basically stripe-shaped. For a large number of angles the stripe artifacts disappear, but the primitive reconstruction is still not the same as the original image. Instead, it appears considerably blurred. This blurring is inherent in the Radon transform / primitive reconstruction procedure and does not reduce with increasing number of angles.

![Original image and primitive reconstruction using data of 3 angles and of many angles](image)

Mathematically, the image reconstruction procedure is the task to reconstruct all elements of the original image \( A_{ij} \) from the data of the Radon vectors \( R_j^\phi \). If \( D_x \) and \( D_y \) are the x- and y-dimension of the original image, \( D_R \) is the dimension of
the Radon vectors, and $D_\theta$ is the number of projection angles, the product $D_\theta D_\phi$ has to be at least as large or better larger than $D_x D_y$, otherwise the reconstruction cannot be precise for simple lack of information. This means that for a correct tomographic reconstruction at least as many measured data are necessary than for a direct measurement. Nevertheless, it will turn out that, even for a lower number of projection angles, a sufficiently good approximate reconstruction is possible, depending on the image content.

There are a number of techniques available to reconstruct the original image from the Radon data [6]. The two most popular ones, which also have been used here, are the "filtered backprojection" method and the "iterative reconstruction" method, which both start from the primitive reconstruction image of the Radon data. The filtered backprojection method is directly removing the blurred appearance of the primitive image by mathematical image deconvolution. If we assume that the original image would contain only zeros except of one single value 1 at the centre position (0,0), it can be shown that the primitive backprojection of this single point for $D_\phi$ angles can be approximatively described as:

$$\text{PSF}_{i,j} = \frac{D_\phi}{D_R} \text{ for } x = 0 \text{ and } y = 0$$

$$\text{PSF}_{i,j} = \frac{D_\phi}{2\pi D_R \sqrt{x^2 + y^2}} \text{ anywhere else}$$

This is a so-called point spread function decreasing proportional to $1/r$ from the source (with $r = \sqrt{x^2 + y^2}$ being the distance from the source) with the central point remaining finite. Since the Radon transform is a linear procedure, the primitive reconstruction of an arbitrary original image can be summed up as:

$$A_{i,j}^{pr} = \sum \sum_{x, y} \text{PSF}_{i-x, j-y} A_{i,j}$$

This mathematical procedure is called a convolution of the image $A_{x,y}$ with the point spread function $\text{PSF}_{i,j}$ in sum-representation. After a tomographic measurement yielding the Radon data, only the primitive reconstruction of the image is available, but the original image is not. It can be retrieved by performing the inverse procedure of the convolution, which is called deconvolution. This procedure can be performed most easily in Fourier space, hence in the spatial frequency domain [6]. If $A_{u,v}$ is the (complex!) 2-dimensional Fourier transform of $A_{x,y}$, and $\text{PSF}_{u,v}$ is the Fourier transform of $\text{PSF}_{i,j}$, the convolution of both is a simple vector multiplication in Fourier space:

$$A_{u,v}^{pr} = \text{PSF}_{u,v} A_{u,v}$$

The inverse procedure would be a simple division: $A_{u,v} = A_{u,v}^{pr}/\text{PSF}_{u,v}$. However, in the presence of noise and measurement errors, this would cause divisions by zero, which usually corrupt the result. This corruption can be prevented by using the so-called Wiener filter deconvolution procedure [6], which reads as:

$$A_{u,v} = \frac{A_{u,v}^{pr} \text{PSF}_{u,v}^{*}}{|\text{PSF}_{u,v}|^2 + K}$$

Here $\text{PSF}_{u,v}^{*}$ is the conjugate complex of $\text{PSF}_{u,v}$ and $K$ is an adjustment parameter, which effectively determines the radius of the filter in the frequency domain. In fact, $K$ determines the "degree of deconvolution" of the image and should be optimized depending on the signal-to-noise ratio. Hence, for performing the "filtered backprojection" tomography reconstruction method for a measured set of Radon data $R_{\theta}^\phi$, first the primitive reconstruction of the image has to be performed by summing up (2) over all angles, then this image as well as the point spread function (3) have to be converted into frequency space by 2-D Fourier transformation, then eq. (6) has to be applied, and finally the result has to be converted into real space by performing an inverse Fourier transform to it. The result is the tomographically reconstructed image.

The limitation of this procedure is that, at least for a low number of projection angles, eq. (3) is only an approximation of the real point spread function. Hence, especially for a low number of angles, this procedure may lead to artifacts of the
reconstruction. These artifacts can be minimized by using an iterative reconstruction procedure, which is working in real space. This procedure is based on the fact that, though the primitive reconstruction is not the original image, it is the blurred original one. So the measured primitive reconstruction is taken as the first approximation of the reconstructed image: 

$$A^{1}_{x,y} = A^{pr,meas}_{x,y}.$$  

Then with this image the Radon transform is performed, from which again a primitive reconstruction into real space is calculated. This image $$A^p(R(A^1))$$ will certainly deviate from the measured primitive reconstruction $$A_{x,y}^{pr,meas}$$, but the deviations should be lowest in those regions, where the primitive reconstruction is closest to the original image. Therefore a difference image between the latter image and the measured primitive reconstruction is calculated, which is used to locally correct the first approximation image $$A^1_{x,y}$$ to yield the second approximation image: 

$$A^2_{x,y} = A^1_{x,y} - m(A^p(R(A^1)) - A_{x,y}^{pr,meas}).$$  

With the image $$A^2_{x,y}$$, which represents the second approximation, the same procedure has to be repeated, and so on. If the result has sufficiently approximated to the original image, the corrections will become zero and the procedure has converged to the final result. The parameter $$m$$ is the so-called loop gain factor, which also has to be optimized. If $$m$$ is chosen too large, the solution may oscillate from iteration to iteration, and if it is chosen too small, the convergence speed is too low. Also here, depending on the signal-to-noise ratio of the measured values, the number of iterations may define an optimum “degree of deconvolution”.

### 2.3 Tomo-LBIC

![Diagram of Tomo-LBIC measurement principle](image)

Until now we have assumed that the Radon vector for a certain angle $$\varphi$$ is measured as an intensity profile caused by the action of parallel rays running in direction of $$\varphi$$ in the plane of a 2-D image, which contains weakly absorbing structures. This intensity vector can be measured either by the parallel action of a number of $$D_r$$ light detectors opposite to an extended parallel light source or, alternatively, by a single detector and a focused parallel beam, which are successively laterally shifted in the direction vertical to $$\varphi$$. In any case, each element of the Radon vector is representative for the absorption averaged over one line behind the corresponding detector in the image plane in $$\varphi$$-direction. This was for the case that we have no direct access to the inner of the image plane. However, if we are illuminating a 2-dimensional solar cell from the top, we have direct access with our light beam to the inner part of the cell. Now imagine that we are illuminating this cell not with a focused spot but with a focused light-line stretching across the whole cell, as Fig. 3 shows. If the electric photocurrent of the cell is measured, then this current represents the average generated current over the illuminated line in the image plane in $$\varphi$$-direction. For this current, a region of low crystal quality in the cell will behave like a highly absorbing region in a corresponding absorption tomography experiment. If the position of this
illuminated line is scanned, as shown by the arrows in Fig. 3, the correspondingly measured current values represent the elements of a Radon vector of this angle $\phi$. If this procedure is repeated for different angles, a complete Radon data set is obtained. From these Radon data, by using one of the procedures described in the previous sub-section, the 2-D LBIC image can be reconstructed. This is the principle of the Tomo-LBIC measurement procedure. If the number of angles is chosen low enough, for a given data acquisition rate, this measurement can be performed in a lower time than a point-by-point measurement.

3. EXPERIMENTAL

3.1 Previous LBIC realizations

The classical way to perform LBIC is to move the sample mechanically below a fixed focused light spot or to move the light source over the sample by using an x-y table [4]. Meanwhile also focused Laser scanning systems are introduced [7, 8]. Note that there are basically 3 factors affecting the measurement speed, which are (1) the point-by-point scan rate, (2) the data acquisition time per point, and, very decisively, (3) the number of image pixels. In the past, stepper motor x-y stages have been used [4], which limited the scan rate to about 100 ms per point. Today continuously moving x-y stages with position sensors or laser scan units are used, which do not seriously limit the scan rate anymore. Instead, the scanning speed is limited by the data acquisition time. In a fast laser-scanning system, a 512x512 pixel LBIC image can be obtained within 4.4 minutes (1 ms per pixel) [7]. In the most advanced LBIC systems, images for 5 wavelength are taken simultaneously. The light of each wavelength is modulated at an individual frequency, and the signals are retrieved by lock-in detectors working at these 5 frequencies. Moreover, a homogeneous "bias light" is irradiated, which leads to a large d.c. current. That makes relatively long integration time necessary for a reliable separation of the different signals. With such a system, capturing a 512x512 pixel image takes about 3 hrs [9]. Even if only one wavelength with no bias light is used, since there are also physical and electronic limitations, the data acquisition time per pixel is usually limited to the range of 1 to several kHz at maximum. So the number of points per image is the final limitation of the image acquisition speed. For detecting low crystal quality regions, an image of 128x128 points would be sufficient, which would take a measure time of only 4 seconds, assuming a pixel rate of 4 kHz. However, in such an image with 1.2 mm spatial resolution (a solar cell measures 156x156 mm$^2$), even the grid lines, having a width of about 200 µm, would not be detected reliably. This requires a resolution of 512x512 pixel, which, for point-scanning at 4 kHz pixel rate, would lead to a minimum possible measure time of about 1 minute.

Recently a so-called "Fast LBIC" approach was introduced [10], which also works with illuminated line-scanning over the sample, but under only 2 angles (in x- and in y-direction). The illuminated line was produced by a row of SMD-LEDs, and no image reconstruction was used (which also would not be meaningful for only 2 angles). The images could resolve the bus bars, since they are several mm wide and run in the direction of one of the two lines, but not the grid lines. They could reproduce ring-shaped swirl-defects, which show a circular symmetry, but arbitrary local defects were imaged with strong artifacts, as could be expected for tomography with only 2 angles. No measurement times were given, but it should be only in the order of seconds. Nevertheless, this system can be taken as an early variant of the Tomo-LBIC system introduced here.

3.2 Optics

A simplified scheme of the optical system of Tomo-LBIC is shown in Fig. 4. The LBIC measurement is performed by infrared (IR) light of 940 nm wavelength, which is produced by a 30 W solid state laser (DILAS). This IR light has a sufficiently large penetration depth into the Si material to test the material quality. In addition, for aligning the sample, focusing the objective, and for demonstrating the operation of the system, a visible light source (150 W halogen lamp) is added. The visible light is coupled into the light path by a dichroic mirror in the laser, which passes the laser light through. The light enters the light engine of a commercial video-projector (Zeiss) via a homogenizer, which is part of the light engine. Attached to the light engine is the actual DMD device, which belongs to a DMD Discovery$^\text{TM}$ 1100 Kit (Texas Instruments). The light is focused to the solar cell, and also the scattered light is detected by a large-area reflected light detector, which is a high-quality solar cell. Before entering the light engine, some part of the laser light is detected for stabilizing the laser output. The DMD device has XGA resolution (1024x768 pixel), from which only a 512x512 pixel region is used. The reason is that our solar cells are all square-shaped, and, for performing the Fourier-based deconvolution procedure described above, the images must have dimensions of $2^n$ to employ Fast Fourier Transform (FFT) routines.
3.3 Electronics

Fig. 4 shows the block diagram of the electronics part of the Tomo-LBIC system. This system can also measure the light response of the cell under full-area illumination, which may lead to a short circuit current (Isc) of several amps. For measuring this high current, in addition to the LBIC current amplifier, a special Isc amplifier is provided. Additionally, there is an amplifier for the reflected light. All signals are digitized by a 16 Bit ADC interface (MEILHAUS), which also reads the amplifier gain settings and controls the LBIC/Isc switch. The DMD device is controlled by a fast ALP connection board (VIALUX) [11], which is equipped with 6 GB RAM for storing up to 64 k illumination patterns as 1 bit deep images. This controller, as well as the DAC interface, is connected to a PC by USB.

3.4 Operation

The system may work in two possible operation modes, which are conventional point-by-point LBIC measurement, or Tomo-LBIC measurement, based on line-illumination. All needed illumination patterns are stored at the RAM of the DMD controller and are subsequently read-out for illuminating the sample at a frame rate up to 4 kHz. For suppressing zero line drift and 1/f noise, generally a.c. measurement with the insertion of a non-illuminated phase after each
illumination pattern is used. Hence, for each illumination pattern the cell current is measured both under this illumination and with all pixels switched off, and both results are subtracted from each other. Note that the DMD device always generates a certain amount of stray light, even if all pixels are switched off. Therefore the a.c. measuring mode is indispensable for this kind of illumination. For increasing the signal-to-noise ratio, the measurement speed (DMD frame rate) can be chosen well below the maximum of 4 kHz, and the bandwidth of the LBIC signal can be lowered. The maximum number of patterns is limited by the RAM capacity to a number of 64 k (65536). This is sufficient to perform a point-by-point measurement of a 256x256 pixel image at max. A 512x512 pixel image can only be measured in Tomo-LBIC mode with a maximum number of angles of 128. Before the measurement, the PC generates and uploads the illumination pattern, depending on the measurement mode (standard or Tomo-LBIC), on the pixel resolution (128x128, 256x256, or 512x512; only Tomo-LBIC), and, for Tomo-LBIC, on the desired number of angles. This data uploading procedure may take several minutes. The actual measurement may then be performed within a few seconds, depending on the frame rate. Another measurement with the same parameters can be performed afterwards without uploading the pattern data again.

4. RESULTS

Though our system is not yet in its final state (so the laser power still has to be increased), first experimentally obtained results are already available. Fig. 5 shows three 256x256 pixel LBIC images of the same multicrystalline 12.5x12.5 cm² sized solar cell with different scanning specifications. Image (a) was conventionally measured in the point-by-point scanning mode. Note that in this mode the LBIC signal is a factor of up to 256 smaller than in the tomographic light-line scanning mode. Because of this low signal height, this image could not be measured with the maximum possible acquisition speed of 4 kHz but only at a lower speed of 800 Hz, implying some additional signal filtering. This image was measured in 116 seconds. The image is not completely free from noise, but it clearly shows the metallization grid and regions of high crystal quality as bright regions and regions of low crystal quality as darker regions. Figs. 5 (b) and (c) are Tomo-LBIC images, which have been measured with 32 angles (b) and 64 angles (c), respectively. These two images have been measured at the maximum acquisition speed of 4 kHz, so their measurement times were 13 and 26 seconds, respectively. The image reconstruction was performed by using the iterative technique with 100 iterations. We see that already the 32 angle Tomo-LBIC image clearly reveals the local differences in the crystal quality. Interestingly, the signal-to-noise ratio of this image is better than that of the conventionally measured image (a), which needed a significantly higher measurement time. So, obviously the Tomo-LBIC approach is indeed leading to a considerable timesaving, which does not go on cost of the signal-to-noise ratio. However, there are still some artifacts in the Tomo-LBIC images. They show a number of inclined lines in the region of the two bus bars, which are clearly tomographic reconstruction artifacts. The 64 angles image shows the best signal-to-noise ratio.

Fig. 5: LBIC images of a 12.5x12.5 cm² sized multicrystalline solar cell measured under different conditions: (a) Point-by-point scanning at 800 Hz, (b) Tomo-LBIC with 32 angles at 4 kHz, (c) Tomo-LBIC with 64 angles at 4 kHz
5. CONCLUSIONS AND OUTLOOK

A novel Digital Micromirror Device (DMD) based Light Beam-Induced Current (LBIC) system for imaging the local crystal quality of multicrystalline silicon solar cells has been developed. In contrast to earlier LBIC realizations, this system has no moving parts anymore and is therefore very robust, reliable, and fast, which is required for application in an industrial environment. Another advantage of this system is that it illuminates exactly the square-shaped regions of the cell belonging to each pixel with homogeneous intensity, whereas conventional spot illumination techniques always shows a round and usually gaussian intensity profile. The DMD illumination system allows to perform a special "Tomo-LBIC" measurement mode, which relies on scanning a light-line at different angles across the cell instead of a light-spot and evaluating the measured data by using tomographic reconstruction principles. This measurement mode leads to higher measured signal and thus allows to use a higher acquisition speed than point-by-point imaging. In addition, by using a relatively low number of imaging angles, the acquisition time can be further reduced. It has been shown that, for iterative image reconstruction, the artifacts are acceptable already for using 32 angles, which corresponds for a 256x256 pixel image to a reduction of the measure time compared to point-by-point measurement by a factor of 4.4. Moreover, the signal-to-noise ratio of the tomographically measured image is considerably better than that of the conventionally measured one, because of the higher induced current signal given by the illuminated light-line compared to a spot. Thus, Tomo-LBIC is an interesting new, robust, and fast characterization technique, which can be used under industrial conditions.

There is still lot of scope in the improvement of the present system, mainly by incorporating more powerful laser, software correction of artifacts due to bus bars, and by improvement in noise handling capacity of system. Moreover, the correction of the LBIC signal based on the reflected signal value is not yet implemented, but is planned in future.

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