Automatic Process for Time-Frequency Scan of VLSI

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Abstract

Electro Optical Techniques (EOP : Electro Optical Probing and EOFM : Electro Optical Frequency Mapping) are effective backside contactless methods for defect localization and design debug for VLSI. The image mode (EOFM) gives only one frequency at each scan. In this case, the frequency mapping is a long and hard task. Furthermore, temporal information is not included in EOFM mode. Building a map by point by point EOP is usually too long so it cannot be used as it is to extract all the frequencies of interest in a region of interest. To overcome this limitation, we have developped an automatic process using EOP mode with a wavelets approach and autocorrelation. Temporal and frequency information are simultaneously computed with only one acquisition. We will underline the challenge and define application boundaries of this technique.

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1. Introduction

In addition to light emission techniques, methods based on laser exploit optical stimulation or optical properties of reflected beam [1]. Electro Optical Probing is a popular timing-analysis laser-based technique, using Franz-Keldysh effects and free carrier absorption. Heinrich was the precursor of EOP approach [2] by proposing a non-invasive method which uses an infrared laser measuring the modulation of the free carrier density induced by the variation of electric potentials inside bipolar transistors. Since its introduction, Electro Optical Probing has become an essential tool to the failure analysis (FA) and design debug communities [3]. In backside EOP analysis, pulsed or continuous laser beam is focused on a node of the chip which has been thinned. Thereafter, the reflected beam properties are analyzed [4]. Intensity varies with temperature change [5], charge density [6] or electric field [7]. The analysis of the properties of the reflected laser beam can be traced back to its origin, in order to obtain information on the physical parameter studied. Two wavelengths have been used for EOP [8, 9] : 1064 and 1340 nm. The first one gives a better spatial resolution (shorter wavelength) and the laser beam absorption is sensitive to carrier density and to small bandgap variations. Two operation modes can be identified : Point mode, EOP or LVP (Laser Voltage Probing) (Probing on one node), or image mode EOFM (Electro Optical Frequency Mapping) also known as LVI (Laser Voltage Imaging) [10]. Each of them gives different kinds of information : temporal with EOP and frequency with EOFM. EOFM mode needs a preliminary choice of a specific frequency. A map, built point to point with standart EOP could take an incredible amount of time. In addition, it is difficult to compute a database with temporal and frequency information simultaneously. Previous research has already studied this problem. In [11], a fast probing in frequency is applied and gives good results in terms of speed but post processing are required to recover the temporal waveform : user needs to determine Fourier coefficients on each pixel and compute the inverse fourier transform to re-build the temporal waveform. Recently, a method based on signal processing has been proposed in [12]. In this case, the electrical signal is sent to an FPGA whose output act as a spectrum analyser with Fast Fourier Transform (FFT). Before this step, the temporal waveform is integrated by averaging. Once the FFT is computed, the frequency of interest can be found. But the FFT computing as a $O(n^2)$ complexity (n being the number of samples), and it could be long for complex signals. In addition, the integration by averaging recquires an important number of waveforms.

In order to address these concerns, this paper introduces a new processing scheme based on EOP mode, Wavelet filtering and Autocorrelation function which has a low computing complexity ($O(nlog(n))$) [13]. Our method is able to retrieve the temporal and frequency information simultaneously in a region of interest of the VLSI with just only one scanning. In a first time, the acquisition setup is described, detailing the two different laser modulation modes. The third section is dedicated to the signal improvement with Wavelets filtering and Autocorrelation function to determine its associated frequency. The fourth section, exhibits results of simultaneous acquisitions on different kind of technologies with asynchronous and synchronous mode. These modulation modes are discussed in the fifth section. Finally, concluding remarks are given in the last section.

2. Simultaneous acquisition description : setup

2.1. Acquisition setup

A complete and detailed description of the EOFM setup has already been given in [10]. Compared to the traditional approach, only two additionnal connections are needed between ATE (Automatic Test Equipment) and LSM. On ATE side X and Y positions are measured through two DPS (Digital Power Supply) channels in measure mode. X and Y connectors are used to follow the ramps coming from the LSM and giving the laser beam position. From the software side, two ATE functions measure and save the data. In addition, one post-processing tool is used to re-build the mapping. The acquisition setup is illustrated in FIGURE 1.

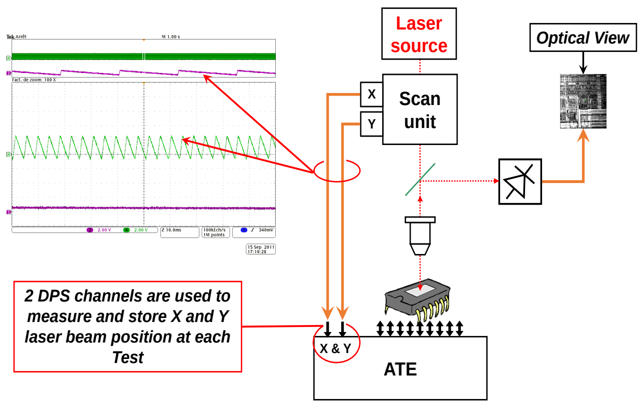


FIGURE 1: Acquisition setup.

2.2. Laser modulation : synchronous vs asynchronous

An expert begins by choosing a Region of Interest (ROI) of size $n \times n$ pixels. He has the possibility to choose the ROI's size from 32×32 to 512×512 pixels. After this step two ways are open to modulate the laser :

In synchronous mode, an external generator synchronizes the laser beam with a trigger. This generator gives the modulation frequency : for example if the choosen frequency is 1.4Hz, the laser beam stays 0.7s on each pixel. The acquisition is sequential.

One other mode of acquisition can be also implemented : the asynchronous mode. In this mode the data are

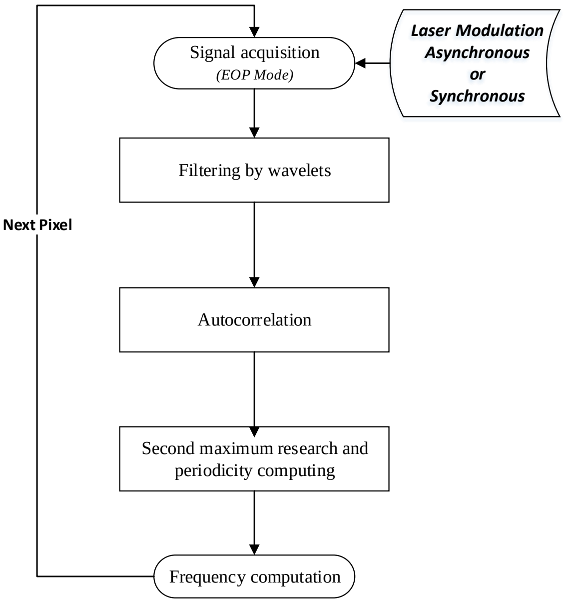


FIGURE 2: Flowchart of the frequency mapping process.

measured when the system of acquisition is ready and not sequentially pixel by pixel. This kind of acquisition is very interesting when the measure of interest is long to acquire. During this kind of acquisition, the laser scans the device faster than the time of acquisitions, the time of laser illumination for each pixel is shorter than the time required to get the measure of interest. Laser modulation is generally coupled with this kind of acquisition to avoid the illumination of the device under test during the measure and the transfer of the data. In that way, the image is randomly filled and a global view of device sensitivity can be observed with a partial filling of the pixel.

3. Signal improvement and frequency mapping

The process' flowchart is summarized in FIGURE 2. It is recalled that another variant of this procces has already been suggested in [14] with the light emission. In order to understand the process, next part will describe in detail each step of the flowchart.

3.1. Wavelets filtering

EOP acquisitions are not directly workable because several factors impact on the noise. Integration by averaging is necessary to improve the signal's quality. In order to improve the signal to noise ratio (SNR), a filtering based on Wavelets has been proposed in [15]. This process is based on Discret Wavelet Transform and coefficients thresholding. It enables using a weak number of averages and low laser power to recover the EOP signal. Thus, it reduces the invasive effect on the IC. Example of signal improvement is illustrated in FIGURE 3. EOP signals are now more workable and transitions are more visible. Consequently with

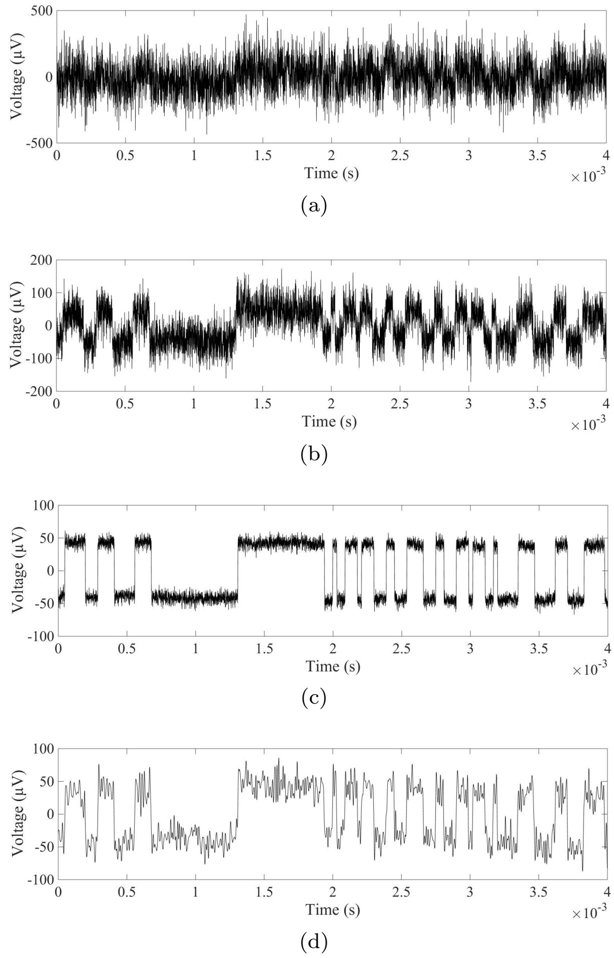


FIGURE 3: Probing (laser 1064 nm) on Digital/Analog converter STM32 : (a) One acquisition of EOP signal / Computing Time : $\approx 0.7\ s$ / SNR = -19.96 dB. (b) Signal rebuilt with 10 averages / Computing Time : $\approx 7\ s$ / SNR = 3.09 dB. (c) Signal rebuilt with 418 averages / Computing Time : $\approx 292\ s$ / SNR = 37.39 dB. (d) Signal rebuilt with wavelets transform and 10 averages / Computing Time : $\approx 8\ s$ / SNR = 22.9 dB.

this improvement, it is possible to determine the frequency of the EOP acquisition by using Autocorrelation function. This point is detailed in the next part.

3.2. Autocorrelation function

In signal processing, the Autoccorelation Function (AF) is a well known tool used to find periodicities in signal [16] and is defined by the following equation :

$$\Gamma_{xx}(\tau) = \int_{-\infty}^{\infty} x(t)x^*(t-\tau)dt, \tag{1}$$

where $x(t)$ is the filtered signal, τ is the lag and $x^*(t-\tau)$ represents the conjugate complex of $x(t-\tau)$.

It seems to be important to recall the impact of the filtering for the autocorrelation computing. In fact with a noisy signal, the AF could be corrupted. By consequences

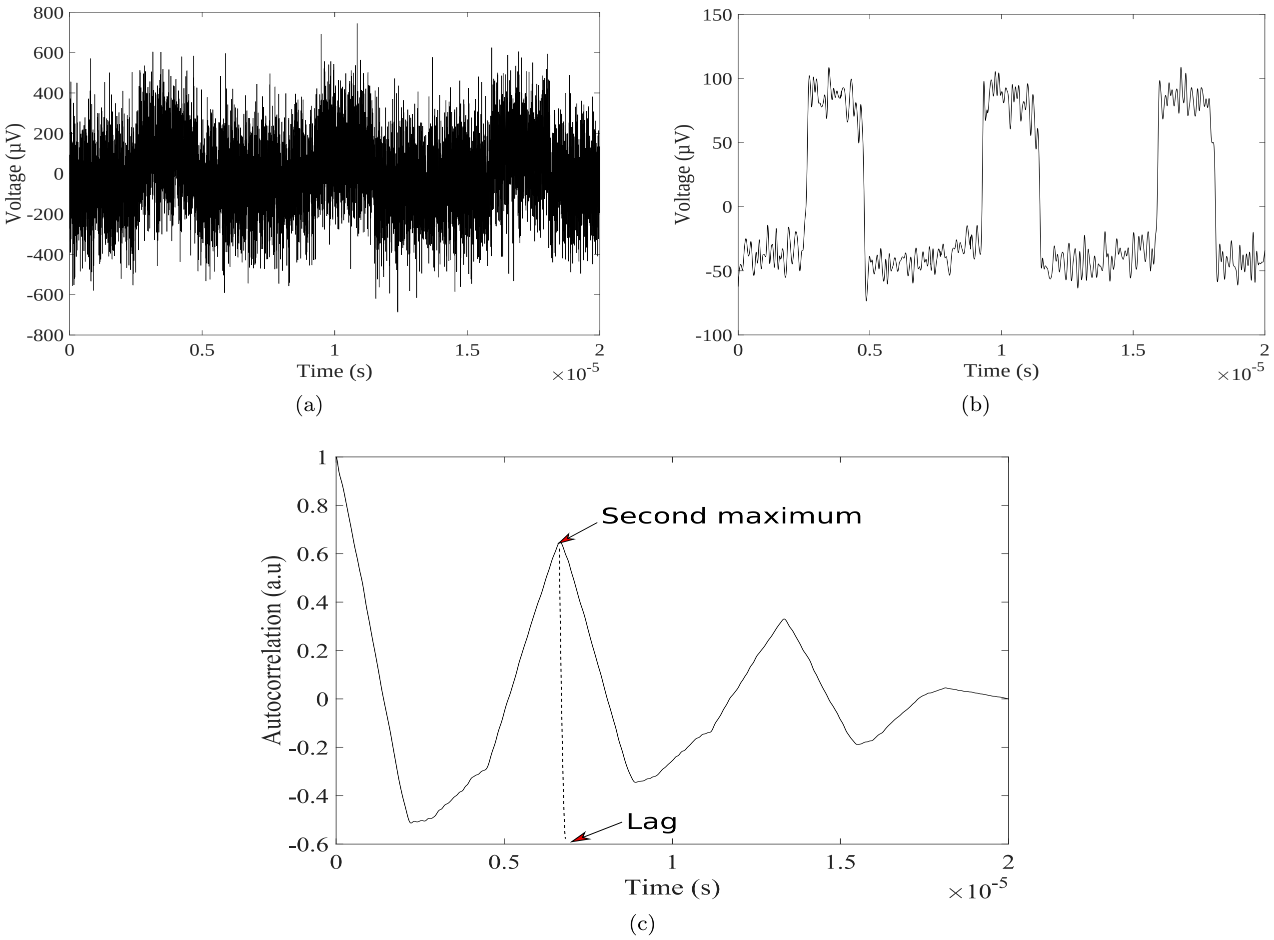


FIGURE 4: (a) Noisy signal acquired on PWM. (b) Signal (a) denoised with Wavelets filtering and its associated autocorrelation (c).

with a wavelets filtering, the signal is clearly denoised and the AF can be performed without errors. FIGURE 4 illustrates this aspect. Once the AF is performed, the periodicity can be computed by researching the second local maximum of the AF (see FIGURE 4c). Finally with this parameter, the signal's frequency can be deduced with the lag corresponding to the second local maximum, see (2).

$$f = 1/lag \tag{2}$$

After this step, the operation is reiterate for all the image's pixels to obtain a frequency map with all the present frequencies in the ROI and their corresponding temporal waveforms. To re-build the map, (x,y) coordinates are retrieved for each laser position. By consequences each (x,y) position corresponds to a pixel of the frequency mapping. This new automatic scheme can be applied directly on the acquisition setup or in post-processing. In fact, experts can acquire temporal waveforms in a fist time, stock them in a file and apply the frequency map later.

4. Application and results

4.1. Synchronous mode

This part illustrates the process in synchonous mode applied on a 90 nm microcontroller STM32, more precisly on the digital to analog converter. The topographic image is reported in FIGURE 5 with a 32×32 pixels ROI. This is the case where several frequencies could be met. A zoom is realized to see each pixel of the ROI, see FIGURE 5b. After this step a frequency mapping using the new process is computed on this area whose outcome is represented by FIGURE 5c. On each pixel, the expert can see the associated frequency. Once the map is realized, he can choose a pixel in oder to see the associated denoised waveform, see FIGURE 5d. With this example, it can be noticed that all the pixels are filled, the map is complete in fifteen minutes.

4.2. Asynchronous mode

Here, the asynchronous mode was used on ALI LM124. As the previous example, the topographic image is reported in FIGURE 6a with a 32×32 pixels ROI. The result of the mapping is illustrated in FIGURE 6c. Giving the fact

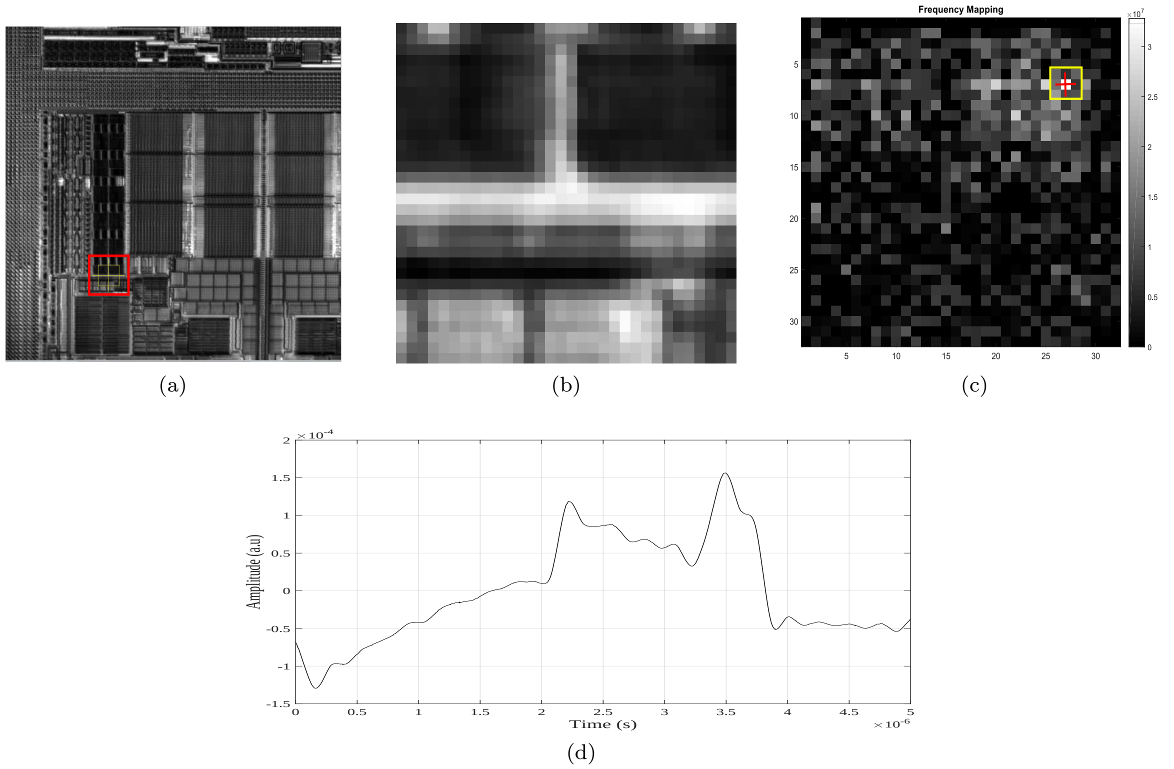


FIGURE 5: (a) Pattern of Digital/Analog converter (50X) STM 32 and 32×32 pixels ROI symbolized by the yellow area. Frequency : $100kHz$ / (b) Zoom on the ROI 32×32 pixels / (c) Frequency map on the ROI / (d) Waveform of the chosen pixel inside the ROI(Fig (c) red cross) / Laser 1064 nm.

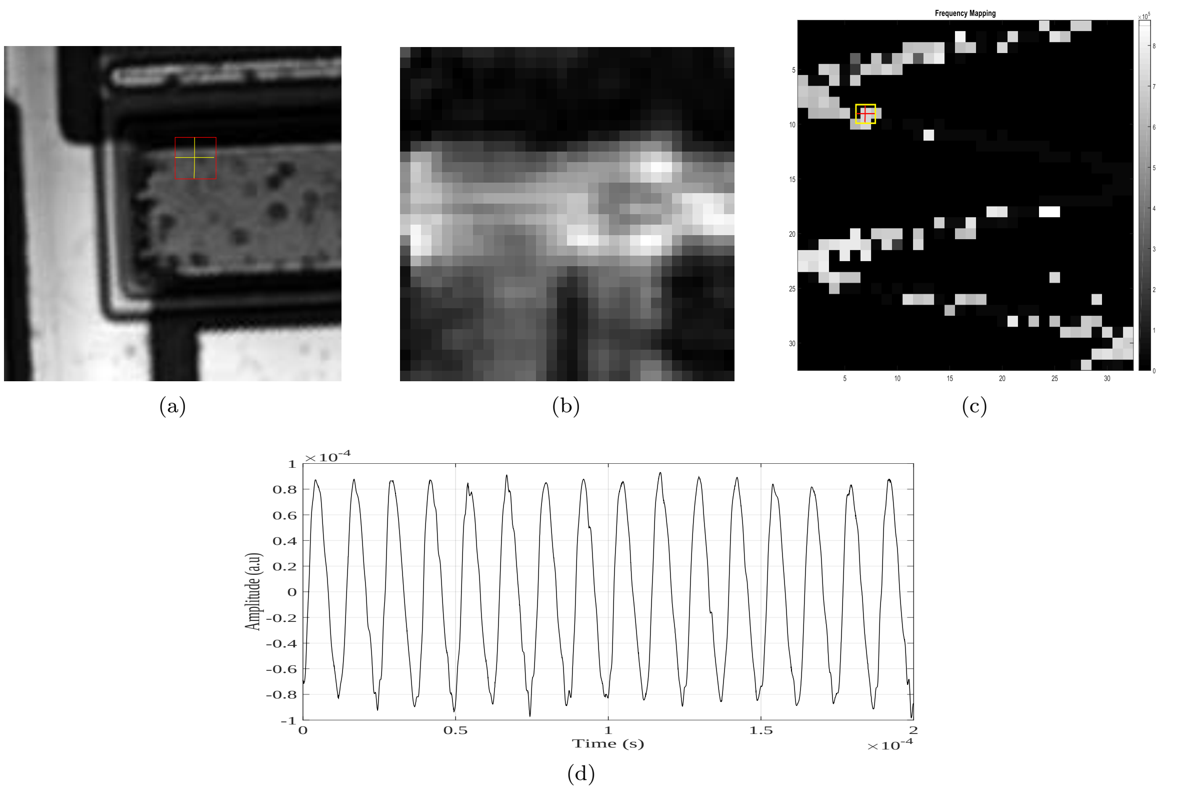
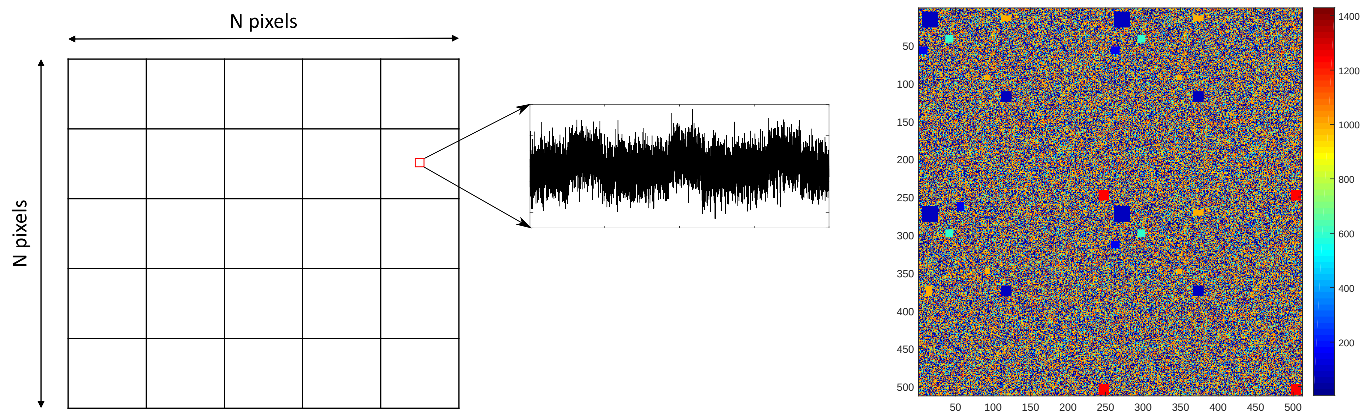


FIGURE 6: (a) Pattern of LM124 (50X) and 32×32 pixels ROI symbolized by the yellow area. Frequency : $80kHz$ / (b) Zoom on the ROI 32×32 pixels / (c) Frequency map on the ROI / (d) Waveform of the chosen pixel inside the ROI(Fig (c) red cross) / Laser 1064 nm.



(a)

(b)

FIGURE 7: (a) Synthesis image modeling data with one temporal waveform per pixel. (b) Process result on 512 pixels synthesis image where four different working frequencies can be met : 200, 500, 1000 and 1200 Hz.

the total acquisition time is undetermined in this mode, the acquisition was stopped after 8 min. Immediately, we can see that all the pixels were not filled. By consequences, the map is incomplete. An example of waveform is also given in FIGURE 6d.

5. Discussion

This section deals with the robusteness of this new frequency mapping process and the choice between asynchronous or synchronous laser modulation. In a first time, the aim is to show the capability to detect any frequency in a 512x512 image. With this purpose in mind, synthesis images have been created.

5.1. Synthesis images and theoritical results

In order to have the best evaluation as possible, synthesis images have the same characteristics as real data. They have a size of 512 x 512 pixels as an EOFM image. In this matrix each pixel contains a noisy 1-D signal of 10000 samples such as the inital setup. Furthermore some pixels have the same signal in order to modelize Region of Interest working with the same frequency. Example of 3-D synthesis data of NxN pixels is illustrated in FIGURE 7a. By simulating this kind of image, all the characteristics are known (working areas positions, number of frequencies and areas sizes). Once the syntesis data is performed, the new frequency mapping process is applied on each pixel of the matrix. Example of result on 512 pixels matrix is represented in FIGURE 7b. In this example, four different frequencies can be met. According to this result 100% of the frequencies are detected and all the temporal denoised waveforms are available. This result proves the efficiency of this new process. Now the question is what is the best way for modulating the laser ?

5.2. Laser modulation comparison

To compare characteristics of each mode, these are summarized in TABLE 1 and are discussed.

TABLE 1: Benefits and drawbacks of each modulation mode.

	Asynchronous	**Synchronous**
Benefits	- Acquisition time 10 ms/pixel	- All the pixels are filled
Drawbacks	- Some pixels are not filled	- Acquisition time 0.7 s/pixel - Need of external generator

As shown in TABLE 1, each mode has its benefits and drawbacks. The aim is to determine which mode is the most optimum for an expertise. The asynchronous mode allows to have a low acquisition time but as mentionned, some pixels are not filled and considering that the expert cannot control the modulation, he is not able to know the end of the acquisition. Consequently, even if the time per pixel is low, the entiere acquisition time could be long. Compared to this mode, the synchronous requires an external generator to modulate the laser. With this one, all the pixel are wandered. Thus, knowing the exact time per pixel, the expert could estimates the total acquisition time.

5.3. Execution Time : synchronous vs asynchronous

The acquisition time is a major factor to take into account to compare the two modulation modes. For different ROI sizes, acquition times are reported in TABLE 2.

In using this criterion, asynchronous mode is clearly the most interesting : for a full image in 512 by 512 pixels only 48 min are required compared to the synchronous mode where two days of acquisition are needful. To conclude this discussion part, these modulation modes present both benefits but also drawbacks. Indeed, the asynchronous mode

Table 2: Comparision of acquition times between synchronous and asynchronous mode for different Region of Interest sizes.

ROI size (pixels)	**Asynchronous 10ms/pixel**	**Synchronous 0.7s/pixel**
32x32	*10 s*	*12 min*
64x64	*40 s*	*48 min*
128x128	*3 min*	*32 min*
256x256	*12 min*	*12 h*
512x512	*48 min*	*48 h*

is clearly adapted for fast acquition but reveals problems in terms of robusteness. On the contrary, the synchronous mode is powerful for image reconstitution but not efficient in acquisition time. Experts have to find a compromise depending on its applicaton.

Conclusion and perspectives

In this paper, a new process to create a complete database (temporal and frequency) has been introduced. The aim is to draw a map where several working frequencies can be met with the corresponding temporal waveform. It is an automated process which requires only one acquisition to obtain both temporal and frequency information. It is based on a Filtering by Wavelets and Autocorrelation function. In terms of perspectives, this process opens the door to new multipoint probing applications : it is possible to improve the synchronous modulation mode by using the layout of the IC. With this diagram, the expert knows the exact positions of the transistors and can only probe on them. This extension would allow to have a major gain of time.

Another extension for this mode is the incorporation of a top pixel signal to improve the SNR of the temporal waveform. This new extension can be automated by choosing a correct SNR and the laser remains on the pixel until the SNR is obtained. Once this step is finished, a top pixel signal is sent to pass to the next pixel. The operation is reiterated until the last pixel of the choosen ROI. This SNR improvement could gives good results concerning the temporal waveform and the frequency mapping but it may take a long time. This challenge could be resolved with high speed acquisition scope. Any frequency information could be extracted from EOP signal, not only the main one but also all the harmonics. It can be used for failure analysis (comparison with a golden device) or for reliability purpose (any difference before / after stress or comparison with simulated stressed device.

A technique currently being patented, improves the process using compressive sensing.

Acknowledgement

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