Pulsed LASER and Its Applications

Ashish Bora, *M.Tech (RF and Microwave Engineering), IIT Kharagpur*

***Abstract*— This paper is based on the discussion of pulsed laser generation techniques and its application in recent years. The discussion starts with a brief introduction of continuous-wave laser and generation of a pulsed laser. The paper further includes different generation techniques for generation of pulsed lasers. The discussion progresses with their modern applications in the recent decade. The applications such as single event effects testing, transient fault injection in Integrated Circuits, pulsed laser deposition (PLD), in advanced metal processing such as bow-tie scanning and synchronized image scanning, and for signal generation through pulsed semiconductors have been discussed at the end.**

***Index Terms*—Pulsed laser, Q-Switching, Cavity dumping, SEE testing, PLD, bow-tie scanning, synchronized image scanning.**

I. Introduction

THE recent advancement in industry in the recent decades demands the signal sources consisting of high energies along with narrow frequency spectrums in which traditional electrical signals fail. These demands have been fulfilled by the use of laser in short pulses. A continuous-wave laser (CW laser) provides a constant signal power with respect to time. The balance is achieved between the loss and the gain of the laser cavity, which is proportional to the pumping rate and led by the population inversion. The loss in a medium includes the loss due to the stimulated emission rate and the cavity losses. However, the distribution of the energy for the continuous wave laser is still less than the laser distributed in the pulses. The basic technique to achieve the pulses is using a continuous-wave laser along with the modulator, which would act as a switch resulting in the transfer of the light in short time periods. However, this method proves to be inefficient and has shown many disadvantages since most part of the light is blocked by the modulator itself. Also, the CW laser's peak energy is always greater than the pulses being formed by using this method, as shown in Fig. 1. The modulator speed also becomes an aspect of limitation for the generation of a high-frequency pulsed laser.

II. Pulsed Laser Modulation Techniques

An efficient method proposed for the generation uses an intracavity modulation process. This method includes the modulation of the gain of gain and loss of the cavity by effectively switching on and off the modulator. There can be two ways for the energy can be: (1) stored in the medium of the laser in the form of large population inversion, which is used for lasing by releasing rapidly. By using this method, the pulsed laser emitted consists of energy that exceeds the energy of the

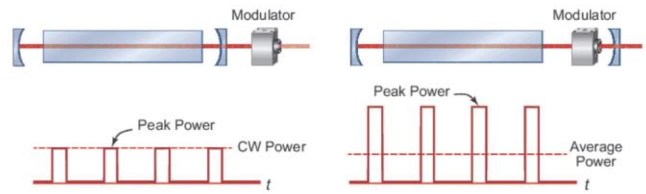

Fig. 1. Left represents external modulator and the right represents internal modulator generating the pulsed laser.

CW laser. Methods of pulsed laser generation using the internal modulation are (1) Gain Switching, (2) Q-switching, and (3) Cavity Dumping.

A. *Gain Switching*

Gain switching is achieved if the gain medium is pumped faster as compared to that of the steady-state value. Since the gain remains at the threshold value for the steady-state lasing as the rate of depletion of the population inversion is more as compared to the pumping rate. In the case of gain switching, the gain coefficient builds up much faster as the population inversion is increased rapidly than the stimulated emission rate in the laser cavity. A large amount of gain is experienced, which results in to increase in the intensity of the laser. As a result, there is a significant amount of stimulated emission, which depleting the population inversion rapidly, giving pulses of light. It is a technique in which the pump source is switched on and off by modulating internally. The output, gain and losses are shown in Fig. 2. Flashlamp pumping can be one approach to obtain pulses of range µs and ms. It is commonly used in semiconductor lasers since the electric current is more convenient to modulate for pumping purposes. Using semiconductor obtains us the pulses ranging ns to a few ps with the high pulse repetition rate (GHz). Optical telecommunications exploit the gain switching method, where a high repetition rate is desirable to increase the bandwidth of the information.

B. *Q-Switching*

The approach used in Q-switching does not involve the modulation of the light source, but it does include storing the energy in the gain medium. Ensuring the cavity losses are large, the pumping process builds up an excessive population inversion with lasing being prevented. By adding the loss in the cavity, the optical feedback is provided in the medium. The cavity feedback is switched on after a large amount of population inversion is available. The medium gain dramatically exceeds the losses, and the energy that was stored in the medium is released as an intense light pulse. This can be observed in Fig. 2. The Q-factor is defined as the ratio of the energy stored in the medium to the average energy dissipated in the medium. Since the Q-factor is being switched from high value to low value, hence the name Q-switching. It is divided into two categories, (1) Active devices and (2) Passive devices. Active devices include the use of acousto-optical switches, rotating mirrors, and electro-optical shutters. Passive devices are based on the optical response of the element switch automatically. Q-switching provides laser pulses of large energy of mJ and the pulse width of ns. The repetition rate provided ranges from Hz to a few kHz.

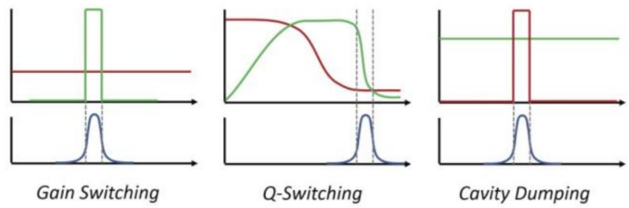

Fig. 2. The laser output (blue) along with the gains (green) and losses (red) are shown for various modulation method.

C. Cavity Dumping

Unlike the previous two optical pulse generation techniques, the cavity dumping process stores energy in the form of photons within the resonator. By keeping the mirror transmittances negligible for the cavity, the resonator losses are kept low. This leads to the photon get trapped within the cavity and thereby building up an intense pulse of the laser. By using the intracavity element, the extraction of the pulse is achieved by switching it on after one round trip time and dumping out the pulse from the cavity. The switch can be either an electro-optic shutter or an acousto-optic modulator. The advantage of cavity dumping over Q-switching can be that the pulse width increases along with the increase in pulse repetition rate in Q-switching. This can be observed in the shown Fig. 2. A high repetition rate of several MHz is allowed by the cavity dumping technique while maintaining the pulse width short. It can also be used along with other pulse generating techniques to obtain high pulsed energy as compared to the other techniques.

III. Mode-Locking Technique

The techniques used above for the generation of the pulse gives the pulse of the width of ns. However, some applications require ultrafast pulses with an even lower pulse duration ranging to fs (femtosecond). The technique proposed for this is Mode-locking, where at the round trip time of the pulses, the cavity losses are modulated periodically. Mode locking is a dynamic process that is steady-state, unlike the previous approaches, which are based on transient effects of the laser cavity. Several longitudinal modes are in the lasing; however, the modes are not necessary to be in phase with one other at the cavity mirror, resulting in fluctuations in the output power randomly. An ultrashort pulse can be thus generated if all the longitudinal modes of the laser are coupled together by interfering them constructively and destructively into phase, as shown in Fig. 3. An intracavity shutter can be used to coupling these modes, which is made to operate at the round trip intervals of the laser pulse. The intracavity shutter coordinates with the arrival time of the modes by locking the phases of the modes. Mode cavity can also be categorized for (1) Active devices which require amplitude and phase modulator for external modulation. (2) Passive devices are based on non-linear effects as well as variation dependent on intensities in the refractive index of the material. All the longitudinal modes which fall under the gain bandwidth lase simultaneously resulting in a bandwidth of NΔv. All these modes will interfere with each other if they are locked in phase behaving as Fourier series components of different frequencies, which are separated in time. Fig. 4. shows the separation of the pulses in the time domain, which is inversely proportional to the separation of the frequency components (1/Δv), which is approximately ten ns bases on the length of the cavity. The pulses having the large gain produces the narrowest pulse since the medium's gain-bandwidth dictates the laser bandwidth. The mode-locking technique used by the solid-state lasers produces pulses that range from 30fs to 30 ps and also operate at high pulses

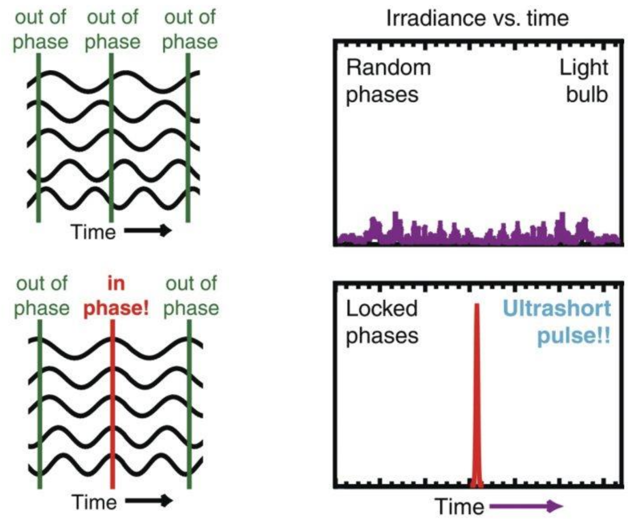

Fig. 3. The ultrashort pulses are extracted by locking phases of the respective frequencies.

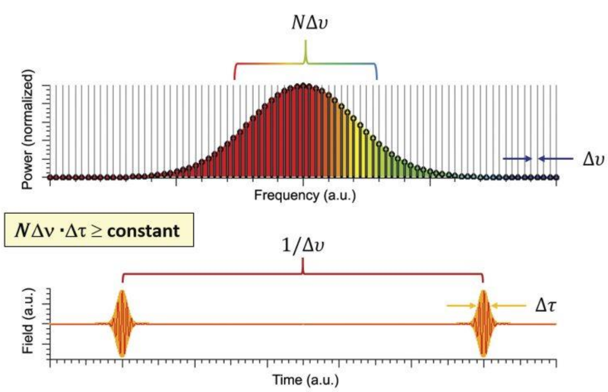

Fig. 4. The top shows the frequency domain and the bottom shows the time domain representations of the mode-locking technique.

repetition rate ranging from MHz to GHz. The energy produced by these pulses is in the range of pJ to a few nJ. The high repetition rate, along with the high energy, was not impossible from the methods as mentioned earlier. Hence, the modal locking method is preferred over regenerative amplifiers and cavity dumping.

IV. Applications Of Pulsed Laser

A. *Scanning of Integrated Circuits*

The use of a pulsed laser can also be seen for imaging purposes in Integrated Circuits. For a fully automated system, the pulsed laser provides various applications such as fault injection, default localization, and radiation sensitivity. The following paper [1] discussed the application of pulsed laser in visualizing the signal propagation and the default localization in the 8-bit ADC.

In recent decades various methods of laser scanning are developed in the microelectronics domain (in our case, the Integrated Circuits). The pump method is used to map the parameter variation of electrical parameters based on the localized interaction of semiconductors and the optical beams. Since the VLSI clock frequency has been increasing rapidly, the ultra-short laser has come to a grave significance for resolving electrical parameters of the semiconductor material temporally. The scanning techniques which results in subwavelength spatial resolution by the use of a pulsed beam is comparatively easier. The front side of the metal layer can be easily passed by focusing beam through the device substrate, i.e., backtesting. IC testing has to be time-resolved by the pulsed laser system is based on the NIR(near-infrared) picosecond laser for photogeneration.

The source here used for the beam is a Ti: Sapphire oscillator to pump a CW laser of 10 W. The source delivers the pulses of 1 picosecond at a frequency of 80MHz. The wavelength ranges from 730 – 1000 nm for the red-NIR region. The tunability mentioned here allows us to tune the depth of penetration in the semiconductor material for the laser pulse. The penetration of 12 um is achieved for the photogeneration of the active volume of the modern devices efficiently. Since the absorption coefficient of the Si drops at the wavelength higher than 950 nm drastically, we still desire sufficient photogeneration in the active volume. It was found that the compromise can be made for the wavelength range of 950-1000 nm depending on the doping level and the thickness of the substrate.

A pulse picker, which is based on an acousto-optic gate, is used to reduce the provided frequency of 80MHz since, in most cases, the frequency of the optic pules will be high enough for most of the devices under test to return to a steady-state in between two repeated pulses. A motorized rotation of the half-wave plate placed before a polarizer is used to control the energy of the pulses. The pulse is focused over the surface of the device under test using a microscope with a spot size of 1um. A CCD camera is used for visualizing the location of the impact of the laser pulses. The microscope mentioned here is customized to include a pulse leak detector for synchronization. For backside testing, a confocal reflectance measurement system uses a laser diode of 1.3 um for imaging the backside through the Si substrate. The scanning is carried out by moving the device under test under beam rather than using a reflecting mirror to exploit the condition of normal incidence. The pulsed laser energy has a maximum value of 1 nJ at a wavelength of 800 nm. To maintain the flow of the optic laser pulses, we are skipping the discussion of automation being used in the experiment. For convenience, we can assume a well robust assembly of the computer software has been operating for the imaging experiment.

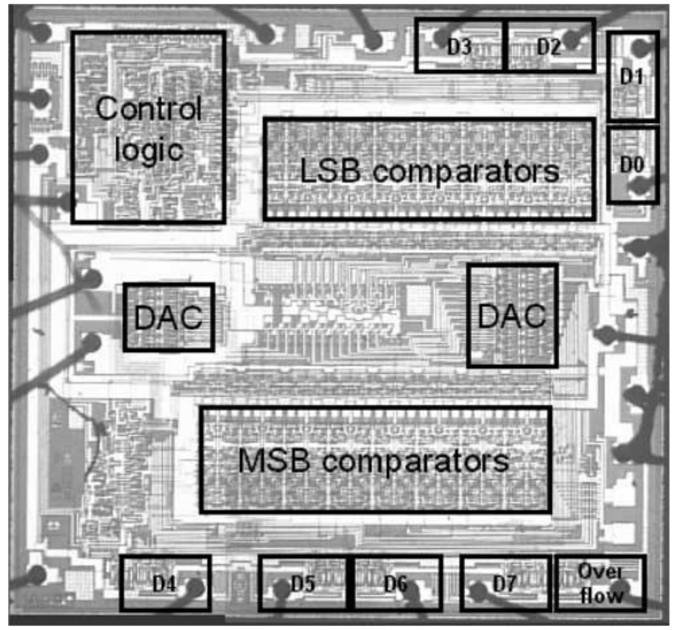

Fig. 5. Device under test (DUT) and the main blocks locations.

The device under test is optically reachable and is flexible with any operating frequency and supply voltage. Theoretically, the laser spot size has the limit of the spatial resolution of 1um. However, the size as small as 0.25 um features are also tested with successfully distinguishing closed electrical nodes. For even smaller transistors and features on the semiconductor material (for a gate length of less than or equal to 0.12 um), the spot may excite several transistors simultaneously placed adjacent to each other.

1. Testing of Single Event Effects

The pulsed laser is developed for reproducing the transient electric effects led by the interaction of the energy particle with the material (semiconductor). This is known as the single event effects testing. The major concern of the technique is single-event upsets (SEUs), which is the changing or switching off the logical state of the transistor in the device induced by the interaction of the electric parameter change with the exposed radiation. However, these techniques are not compatible with the industry demand in terms of accessibility and cost. It enables us to gain sensitive information regarding the spatial and temporal dependence of the radiation sensitivity of the IC.

2. Transient Fault Injection

The SEE testing of the system enables the generation of transient localized perturbation of the system, which is under test. The hardware-level fault injection is important to measure the reliability of the software which are built-in and to check their reliability since the fault injection techniques at the software level cannot predict all the possible faults like the faults related to the layout of the device. The transient fault injection technique is very useful for detecting the system's vulnerability to the invasion. This can be achieved by the use of temporal resolution, which helps us to find the critical phases of the timing diagram for the system.

After applying a constant level of voltage to the ADC input, output bits are acquired after each conversion of the ADC and the laser pulse. The digital error is computed by comparing the outputs to the expected conversion result. A map of conversion error is created by with each calculated error mapped to the corresponding location in the scan window by the laser beam.

The Fig. 5. shows a front view of the device under test to recognize the main functional blocks. The laser pulse was used to identify the errors in the areas. The transient fault injection is proven to be a reliable technique, at least for the functional block level. The merit of this method is that the image is only filled with critical data, unlike the cases of the images obtained by the electron beams in which metals lines are visible. It also provides information regarding the functionality of the device under test.

B. Pulsed Laser Deposition

Pulsed laser deposition (PLD) now have emerged in the recent decade as a unique tool for growing high-quality films. The complex compounds have been deposited using this technique and have also evaluated the properties of the respective materials. Apart from widely accepted techniques of ion-beam, magnetron, CVD (chemical vapour deposition), this technique also has started gaining recognition to grow electronic as well as optical films. The ablation plume is known to have a non-uniform and scattered distribution during the laser deposition process. This misleads widely a belief that using it does not provide any usable applications. However, the PLD is now used to develop a layer of film over the substrates of 100mm diameter. The two approaches for PLD can be (1) offset PLD

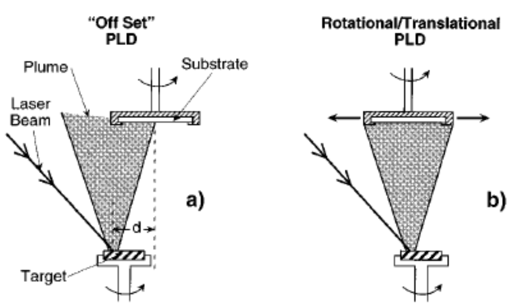

Fig. 6. Schematic representation of (a) OS-PLD and (b) rotation/translational approach in large area.

(2) rotational/translational PLD. In OS PLD, the positioning is done in such a way that the ablation plume impinges near the edge of the substrate that is rotating. In this method, the plume leaves normal to the target surface. Using these substrates, the first proposal was to deposit the films simultaneously over small substrates. The technique was further applied to develop the high-quality YBCO films in situ on a substrate of 50 mm diameter LiAlO3. In the second technique, which is rotational/translational PLD, the substrate is translated and rotated in a linear fashion using computer software.

An alternative to both approaches above mentioned is laser beam rastering, which is controlled by a computer. In this case, the target is half the diameter of the substrate, and the rotation axis has an offset to the centre of the substrate. Using a programmable mount, the focused laser is rastered over the target. The centre of the plume impinges the target substrate by

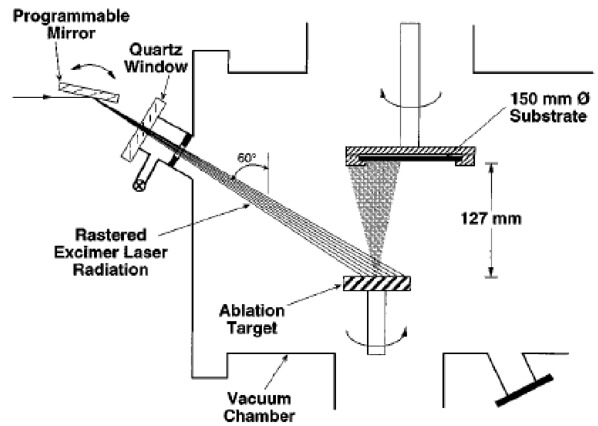

Fig. 7. Schematic representation of PLD with laser beam rastering with half the diameter of the substrate as the target.

keeping the programmable mount at a longer distance. The important factor is the thickness uniformity also. Another relevant issue is the film composition for most of the applications. The composition profile is shown in Fig. 8. of a YBCO film deposited by laser on a Si substrate by using beam rastering since it could provide three elements whose composition is mapped in the shown Fig. 8.

The rotational/translational approach provides good uniformity than the offset PLD over large areas. The dynamic changes in

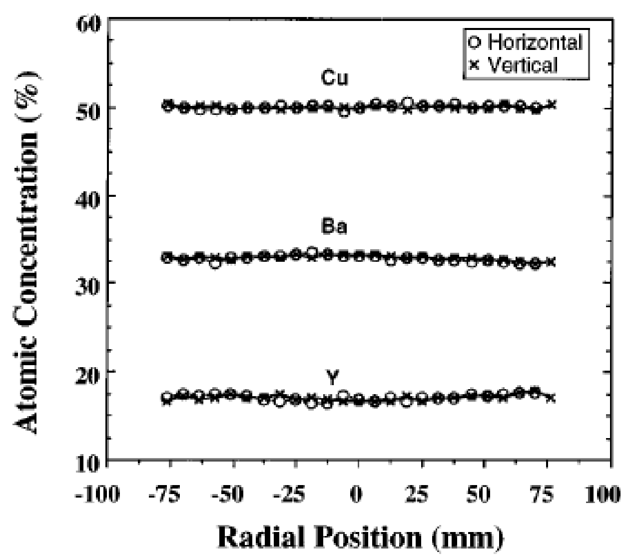

Fig. 8. Composition profile of YBCO film grown using PLD on Si substrate with diameter of 150 mm.

the topography of the substrate will hamper the performance of the two static beam approaches. The laser beam rastering, as compared to the above-mentioned beam techniques, is most compatible with large films with reproducible growth rate and good film quality. It has been observed that PLD is also compatible with materials that are temperature sensitive. The techniques like sputtering seem to be not flexible with the temperature-sensitive materials has been observed with the PLD. Thus PLD can be used to deposit films by patterning using the photoresist followed by the lift-off processing. The PLD furthermore has shown the deposition of highly uniform films over substrates of diameter 150 mm. the variation that was observed for the 150 mm was ±2.3% and for thickness is ±0.5%. The data discussed implies that the PLD techniques can be scaled to sizes that are compatible with the mainstream processing equipment used for semiconductors. However, the limitations of the PLD have not been seen so far, and uniformity over larger sizes of the substrates has been trying to achieve and the future. It is still being explored by the research groups as a deposition tool to deposit arrays of complex materials for various applications.

C. Advanced Material Processing

The pulsed laser is widely used in the processing of various materials for applications such as patterning and structuring of the surfaces. Some popular techniques include synchronized image scanning (SIS) and bow-tie scanning (BTS), which are discussed in the following sections. The pulsed laser materials are providing high speed and accuracy along with high-resolution and flexible production. With the introduction of the above-mentioned methods such as SIS and BTS, qualities such as accuracy, speed, and efficiency are achieved for complex repeating array materials over a large area. Also, two-dimension and three-dimensional miniature structures can be developed with the help of laser ablation.

1. Bow-Tie Scanning

This technique is popular since the recent developments in the

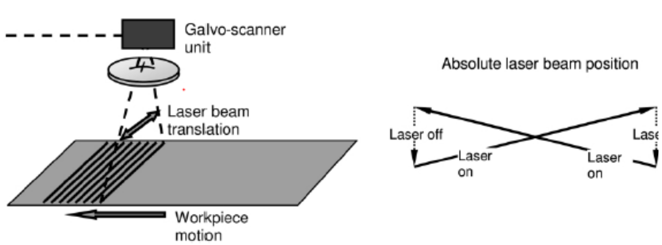

Fig. 9. Schematic of bow-tie scanning (BTS) technique to provide straight line processing.

speed and correctness of the galvanometer systems inaccurate and regular patterning of films on planar systems. This method is best suitable for requirements for regular lines or the patterns which are generally dense in a regular array of contact holes (e.g., solar panels). Fig. 9. shows the BTS schematic where a laser is focused on a straight line while the substrate is moving at a constant speed in the perpendicular direction. This type of simultaneous beam scanning and substrate motion is used widely for microvia and scribing drilling. The beam is deflected using the galvo-scanner with the laser on and returns to the next track for a new start. This technique has recently been employed for large substrate processing for solar panels and flat panels displays. Here we shall discuss solar panel processing in detail. For line scribing of ITO on substrates of glass for thin and fine production of the solar panel, the tools operating at 1.06 um are used widely, which provides the power of few Watts. The solar panels processing is enabled by the use of BTS, mask projection with high accuracy and precision. Solar panel with thin film and using a dual laser system is shown in Fig. 9. along with the manufacturing process. The dual laser system has a wavelength of (1.06 um and 532 um). To scribe the lines of nearly 30 um wide, the IR YAG laser beam is used in the ITO layer first. This is followed by the Si layer deposition, and a YAG laser is applied for machining interconnects of 50 um diameter through the Si layer from the rear side of the plate. The electrodes of aluminium are deposited and track nearly 25 um wide with the help of YAG laser for competing for the processing of panel. It takes nearly a minute to process a layer of 580 mm by using a 400 mm panel.

2. Synchronized Image Scanning

SIS technique is developed to achieve good speed, accurate production for long arrays, and excellent reproducibility of the micro-structures. The substrate is made to move continuously, and the technique is used as a mask projection method; instead, multiple lasers are used to form a machine feature of each laser. The Fig. 10. shows the schematic of the synchronized image scanning in which the mask consists of building blocks for the feature that is required, and the image blocks are projected in a

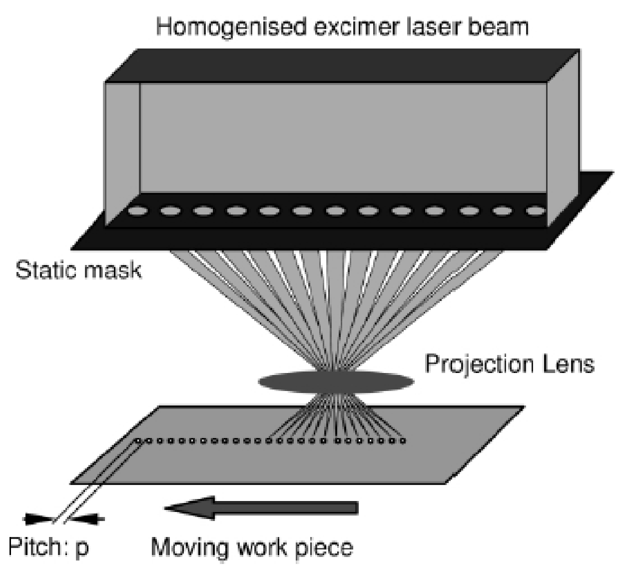

Fig. 10. Schematic representation of synchronized image scanning (SIS).

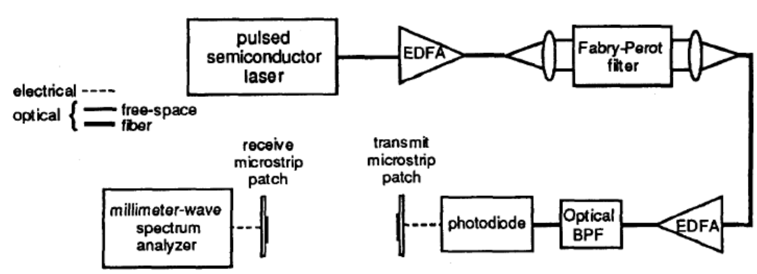

Fig. 11. Experimental setup of generation of the millimeter wave fed by a optical signal through a wireless link.

linear array. The triggering occurs each time the substrate has to move by one mask pitch of the image. By using the laser ablation, each and every feature is build of the same image succession. To obtain the desired amount of laser pulses on either side of the area to machine the featured depth required, the substrate can be scanned repeatedly.

D. Signal Generation Using Pulsed Semiconductor

For the applications such as a phased optical array, mobile communications, the generation of millimetre-wave and microwave is of great interest. Thus the advancement of optical fibres over coaxial cables and waveguides has to lead us to consider generating optical generation of millimetre waves. The techniques alternatively used are the optical heterodyne method by using two laser sources, external modulators, or pulsed semiconductors. The optical heterodyne method involves locking of a minimum one phase frequency. Along with the mode-locking, a feedback arrangement is needed to reduce the line-width of the electrical signal. The harmonic generation technique, which uses single optic sources, is also a method that is less complex to implement. The presence of unwanted frequency harmonics serves as a disadvantage. These harmonics limit the depth of modulation that can be achieved for the desired frequencies. The other solution that can be suggested is the use of an optical amplifier for amplifying the signal of the desired frequency by boosting its output power. However, the gain provided by the optical amplifier is limited since the optical frequencies, and the optical carriers add near the average output power and the photocurrent that has been detected. Thus for generating the signal, we may investigate the pulsed semiconductor lasers for which the output microwave spectrum of the pulse is frequency comb of much harmonic content as shown in Fig. 12. After investigating the signal generation through a pulsed semiconductor laser, we obtain a modulation depth of 100%.

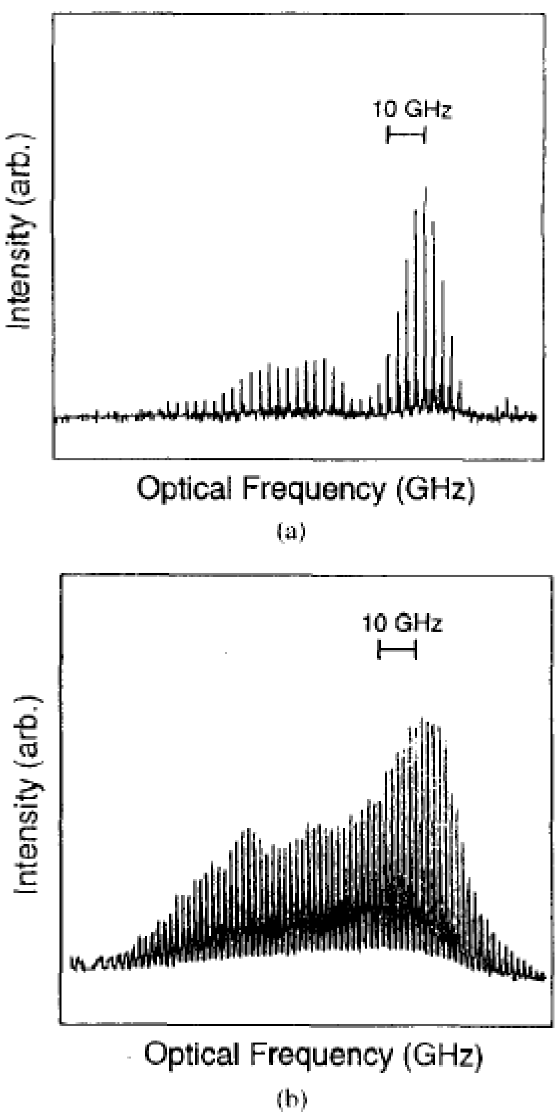

Fig. 12. Representation of optical spectra recorded before the optical filtering.

The paper discussed actively mode-locked and gain-switched laser to generate millimetre waves with their respective frequencies. The advantage we get by this method is the narrow electrical line width that is obtained without feedback arrangement. The important factor that has to be considered is the losses that are associated in the optically fed millimetre-wave links is RF power coupling at the output of the photodiode in a transmission medium. A0 microstrip patch is used for the radiation through the selected medium as shown in Fig. 11. Thus the optimization of the patch antenna is necessary for terms of feed probes positions and the dimensions of the patch. The analyses of the pulsed semiconductor also show that large RF power is also possible for even greater frequencies, and when the width of the pulse is increased. The optical filtering method was used for the feeding of the millimetre-wave wireless links, which incorporated a microstrip patch without any matching structures. Both the mode-locked and the gain-switched laser were used and demonstrated for the discussion. Future research proposes techniques that involve the use of high-speed photodiodes to be coupled efficiently to the microstrip patch radiators.

V. Conclusion

We had a discussion on the significance of pulsed laser and the reason it is preferred in a few applications in the industry. The techniques for modulation of continuous-wave laser to produce the pulsed laser of desired pulse widths along with their merits and demerits respectively was discussed in the paper. The applications which have been started in the few decades were discussed such as image processing of the integrated circuits, bow-tie scanning, SIS, PLD, and signal generation using a pulsed laser. The abundance use and research for the applications of pulsed lasers are currently going on in the film deposition of different materials over the substrate with different film layers as per desire. The fresh technique currently being used is annealing of the materials and cutting of materials. However, these techniques are currently inefficient and require further study and analysis.

References

[1] V. Pouget, D. Lewis, P. Fouillat. "Time-Resolved Scanning of Integrated Circuits With a Pulsed Laser: Application to Transient Fault Injection in an ADC", IEEE Transactions on Instrumentation and Measurement, 2004.

[2] H.J. Booth. "Recent applications of pulsed lasers in advanced materials processing", Thin Solid Films, 2004

[3] D. Novak, Z. Ahmed, R.B. Waterhouse, R.S. Tucker. "Signal generation using pulsed semiconductor lasers for application in millimeter-wave wireless links", IEEE Transactions on Microwave Theory and Techniques, 1995

[4] A. Douin, V. Pouget, D. Lewis, P. Fouillat, P. Perdu. "Electrical modeling for laser testing with different pulse durations", 11th IEEE International On-Line Testing Symposium, 2005

[5] Reinhard Noll. "Laser-Induced Breakdown Spectroscopy", Springer Nature, 2012

[6] Van Smaalen, S.. "Theoretical study of pulsedlaser-induced resonant desorption", Surface Science, 19870402