Fast and Accurate Laser Drilling with High-Speed Digital Scan Head and Smart Controlling Methods

Novanta
PHOTONICS

In laser via-drilling industry, improving the drill job throughput while maintaining high drill hole position accuracy has always been the continuous drive. One push that has direct impact on throughput improvement is to speed up the galvanometer based laser beam scan head used in the drilling machine. The LIGHTNING™ II Plus scan head from our Cambridge Technology brand with newly engineered galvo design has achieved step response time as fast as 225µs for 300µm via-hole pitch with a 100mm f-theta lens. This enables via-hole scanning frequency up to 4400 pps at this pitch size. Another route to improve throughput is through smart drilling control methods. In this paper, we will discuss two drilling control algorithms that Novanta has developed. The closed loop method uses real time in-position signal from the scan head before firing the laser. This method achieves fast drilling with guaranteed position accuracy. The other method is the 'dynamic' open loop method in which the controller uses the jump time look-up table to determine the time to wait before the next move instead of waiting for the in-position feedback signal, resulting in even higher throughput. In addition, the look-up table can be re- created on demand to compensate for the dynamic characteristics change in scan head over its lifetime. Finally, the paper will explain how flexible and accuracy laser timing control can be used to further optimize the laser drilling process.

Introduction

Laser drilling plays an increasingly important role in processing via-holes in high density interconnection (HDI) printed circuit board (PCB) used in electronics devices like smart phones and tablet PCs [1,2,3]. It is also used extensively in making via-holes in semiconductor packaging where the silicon IC chips are mounted [1]. Table 1 summarizes the size and accuracy requirements for micro via-drilling on both HDI PCB and package substrate [4]. The smaller via-hole and increased pitch density have been required to address the need of compact and more powerful electronics devices [4].

	HDI PCB	Package Substrate
Via-Hole Diameter	60-100µm	50-60µm
Via-Hole Pitch	Mostly 300 - 400µm	Mostly 200 - 300 µm
Via Position Accuracy	+/- 10~15µm	+/- 7~15 µm

Table 1 Summary of Micro Via-Drilling Requirements

Today there are various strategies to improve the laser drilling process to meet the requirements of higher throughput and better accuracy.

The first strategy is to use a CO2 laser with high peak power and fast rise time to increase the material ablation rate to achieve fewer drilling cycles and shorter processing time. Figure 1 shows an example of high- peak/short-pulse CO2 laser compared with other types of CO_2 lasers [5].

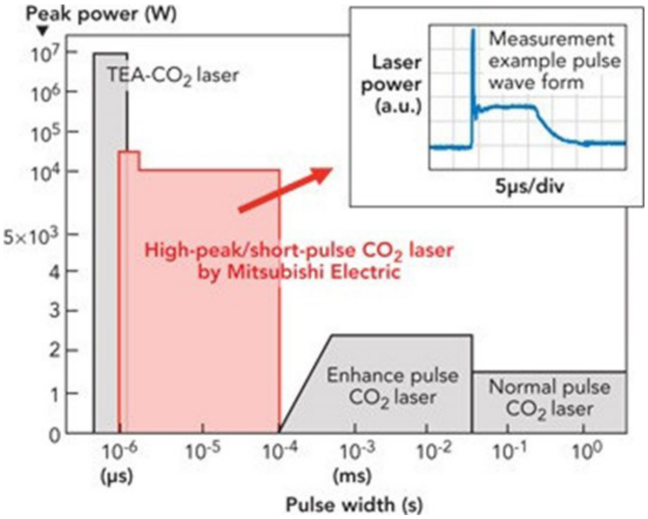
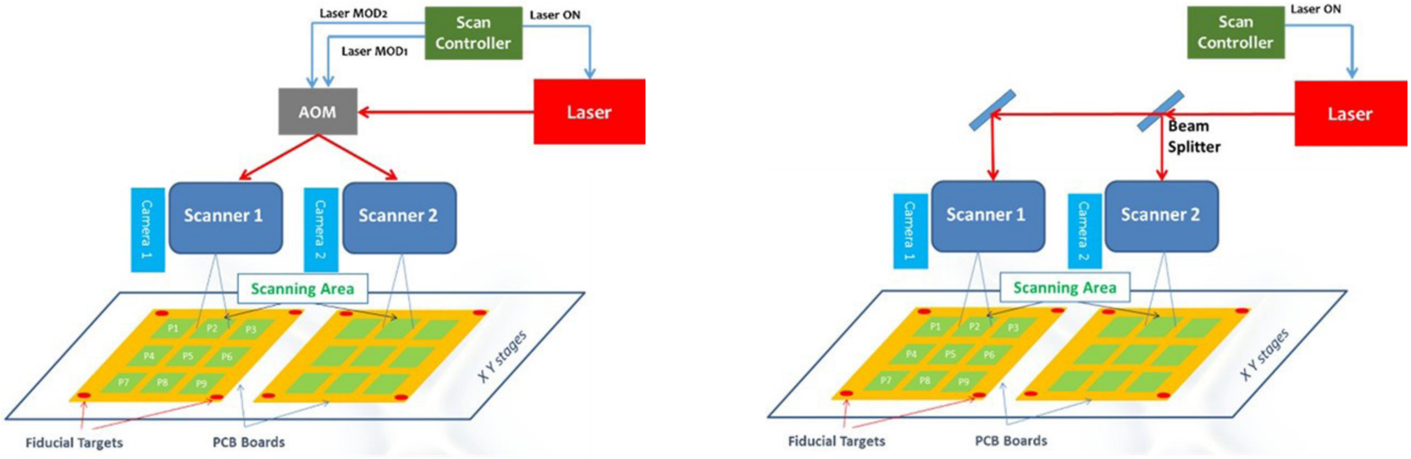


Figure 1. Comparison of the CO2 laser pulse. The red region refers to the high-peak/short pulse CO2 laser developed in 1996 by Mitsubishi Electric [5].

The second strategy to improve the laser drilling throughput is through the innovation in the scan head design. One of the key components used in a laser drilling machine is the galvanometer-based scan head that steers the laser beam to the intended via positions. The jump time it takes for the scan head to steer the laser beam from one via to the subsequent one constitutes a large percentage of the total processing time. High position resolution and efficient servo drive of the scan head is also key to enable high via-hole position accuracy. In this paper, we discuss the latest result on the jump time of 225 μs for a 300 μm via pitch achieved with a LIGHTNING II Plus scan head.

The third strategy is through careful management of the scan head motion and laser firing to minimize the total time required to coordinate the laser and scan head actions. We will discuss and compare two drilling control methods developed with Cambridge Technology ScanMaster Controller (SMC): the closed- loop method that requires in-position feedback signal and the ‘dynamic’ open-loop method that uses a look- up table to plan jump time for even higher throughput. The additional benefit from SMC such as flexible laser timing will also be presented.

The fourth strategy for cost-effective throughput improvement that has been adopted widely in the industry is parallelization. Two scan heads are employed to run drilling job at different sections of the work station. Figure 2 shows typical configurations of dual-head drilling. Depending on how the laser is shared between the two scan heads, the dual-head configuration can be beam splitting or beam switching. Beam splitting avoids the use of an acousto-optic modulator (AOM) that results in up to 20% laser power loss and adds additional time when switching the beam between the heads. However the challenge for beam- splitting is that it requires high peak power laser since the laser power onto each scan head is divided by half. Therefore the implementation of this configuration can be limited by the laser peak power available. Most commercial drilling machines adopt the beam switching configuration.



(a)

(b)

Figure 2. Typical configurations of dual-head drilling (a) beam switching and (b) beam splitting.

ScanMaster Controller can support two scan heads and can be used in either of these two configurations. Figure 3 shows the schematics of a single ScanMaster controller controlling two digital LIGHTNING II Plus scan heads via GSBus interface. Cambridge Technology's proprietary GSBus interface is a 24-bit high resolution, bidirectional data bus that can support up to 8 channels. It provides real time status data including the position feedback. This real time position feedback enables the two controlling methods discussed in details later in this paper.

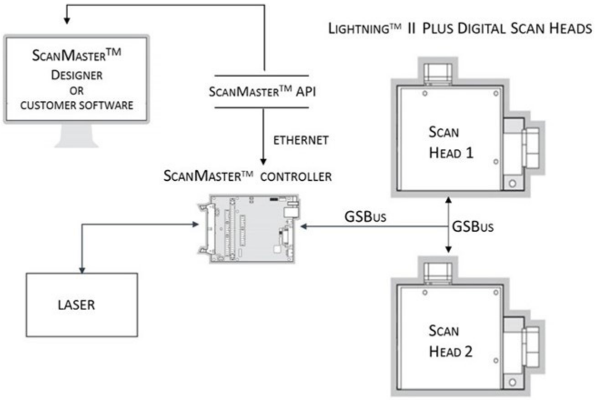


Figure 3. Schematics of dual-head configuration with one SMC controlling two LIGHTNING II Plus scan heads.

Digital Scan Head for Laser Drilling

Our LIGHTNING™ digital scan head family has been designed to achieve high speed, accuracy and stability required by advanced laser materials processing including laser via-hole drilling. Its fast and precise dynamic performance is the result of design optimization on the mirror, motor, and servo driver. Lower mirror weight and inertia is desired for the mirror to be driven at higher acceleration or speed. Beryllium with its low material density, high stiffness and machinability makes it ideal material for scan head mirror. While the mirror aperture is designed to deliver required laser beam spot size on the material, the back of the mirrors are machined to honeycomb or drilled structure to minimize the inertia while maintaining structural stiffness. The servo uses pulse width modulation drive so it's very power efficient and capable of driving highly dynamic range of the motor motions. The low-drift 24-bit position encoder embedded in the motor assembly, predictive state-space servo control and the 24-bit command resolution provide the highest position resolution and repeatability available. The LIGHTNING servo also has an adaptive thermal model that constantly adjusts the motor control. This, together with water-cooling in the motors, makes the LIGHTNING digital scan head extremely thermally stable for 24/7 operation. The latest motor design is improved to be more powerful and power efficient with LIGHTNING II Plus scan head. This allows it to be driven harder and thus accelerate faster than its previous generation.

Step Response Time

With laser via-hole drill application, the individual axes of scan heads are often accelerated and decelerated to their physical limits to obtain the minimal jump time when steering the laser beam from one via to the next. Step response time is a direct measure of the jump time. For a given step size and with a specified position accuracy tolerance (or a position error window), it is defined as the time from when the step command is issued to when the scanner enters the error window defined around the final position of that step. As jump time is the major component of a drilling cycle time, step response time of scan heads is a critical metric for the laser drilling process.

Based on Table 1, to characterize the step response time of the scan head, we chose the hole spacing of 300 µm and the via position accuracy of 4 µm. For both HDI PCB and package substrate drilling applications, the f- theta lens used with the scan head is usually around 100 mm. This hole spacing and the accuracy window on the focal plane translates to a jump step size of 1.5 mrad in rotational motion for the scan head and the position error window of 19 µrad. The x-axis mirror is smaller than the y-axis mirror and has the shorter step response time. The drilling sequence usually takes advantage of it and uses x-axis to make most movements.

In this experiment, we compare the step response time of a LIGHTNING II Plus scan head and a LIGHTNING II scan head. The mirror aperture sizes of both scan heads are 25 mm. After the x-axis of the scan head is commanded with a square wave of 1.5mrad step, its motor position was probed in real time from GSBus into an oscilloscope.

Figure 4 shows the motor response and settling curves of x-axes of these two scan heads. The step response time of the LIGHTNING II Plus scan head at 300 µm step size is measured to be as fast as 225 µs, compared to 246 µs for the LIGHTNING II scan head, an approximate 10% improvement. This means the LIGHTNING II plus digital scan heads can jump up to 4400 holes (points) per second, i.e. 4400 pps, which makes the LIGHTNING II Plus digital scan head one of the fastest scan heads for laser via-drilling application.

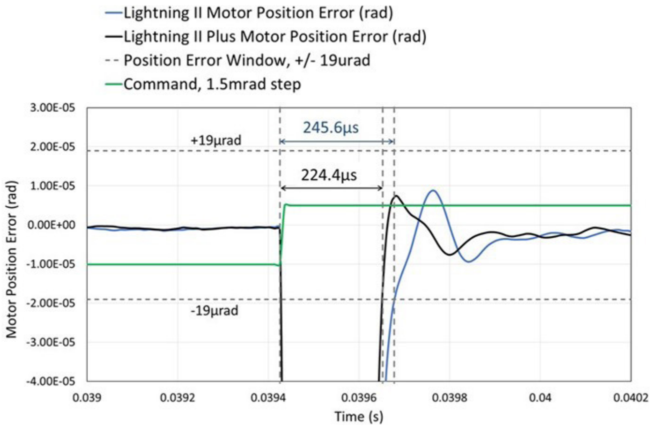
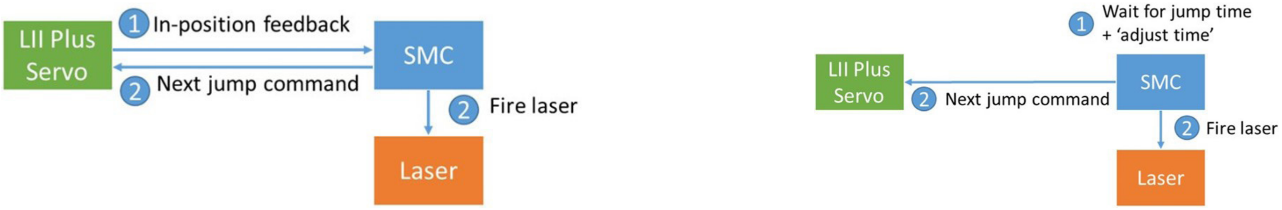


Figure 4. Zoomed-in waveforms of LIGHTNING II Plus (black) and LIGHTNING II (blue) motor position error. The command wave-form (green) is a 1.5mrad step (the scale for command is 100x larger). The position error window is set at +/-19µrad (dashed horizontal cursors). The step response time is measured from the start of the command to the moment the position error is within the position window. LIGHTNING II Plus step response time is Δtplus = 224.4µs, 10% faster than LIGHTNING II step re-sponse time of Δt = 245.6µs.

Control Methods for Laser Drilling: Closed- loop and Open-loop

While jump time of the scan head determines a large portion of the drilling cycle time, control methods can still be leveraged to reduce the cycle time and improve job throughput.

A controller's role in laser drilling is to coordinate laser firing with the scan head jump and to ensure that the laser only fires when the scan head is at the appropriate position. In general, there are two ways to do that: one is to wait for the acknowledgement signal that the scan head is 'in position' before firing laser. Since this method reacts upon position feedback, here it is referred to as closed-loop method. The other method is to wait for the empirically pre-determined jump time of the scan head as jump delay before firing laser, called open-loop method. ScanMaster Controller offers both closed- loop and open-loop control options for laser drilling. Figure 5 illustrates the event sequence for closed-loop (Figure 5(a)) and open-loop (Figure 5(b)) control used in SMC.



(a) (b)

Figure 5. (a) Closed-loop and (b) Open-loop methods in SMC

Closed-Loop Drilling Control

The closed-loop method is not commonly available in other scanning controllers. In closed-loop control, upon receiving the “in-position” acknowledge signal, the controller sends out the laser signal and issues the next jump command at once. Since the laser is only asked to fire when the scan head is within the allowed position error window, the drilling accuracy is guaranteed at all time. The closed-loop method is often chosen for micro- via drilling on package substrate where the micro via accuracy requirement is general higher.

The key enabler for closed-loop method without introducing large delay in SMC is Cambridge Technology proprietary GSBus interface that provides 24-bit real time status feedback. Thus the high precision and timely position feedback is readily available on the bus synced in the same data frame for SMC when it communicates with the two digital scan heads. The communication lag between the servo boards and the SMC is minimal (<10µs). Figure 6 shows the oscilloscope screenshot in which the in-position signal (SRVACK) from the servo board and the laser on signal from the SMC (LASON) during a closed-loop drilling job are displayed. One can see that the lag between the laser on signal and the in-position signal is as short as 7.4 µs.

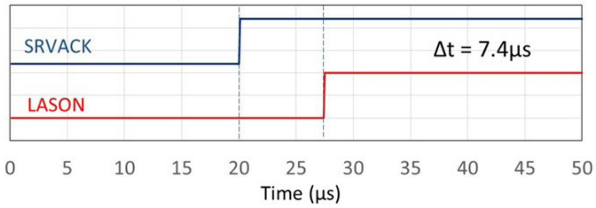


Figure 6. In-position signal (SRVACK, blue) and Laser On signal (LASON, red) in a closed-loop drilling job.

Open-Loop Drilling Control

The open-loop method using ‘empirical’ jump delays is a more commonly adopted methods in the laser drilling industry. In some implementations, the scan head is characterized and a jump time look-up table is generated at the time the scan head is built. After it is incorporated into the laser drill machine, the look up table may require periodic calibration to account for the small and gradual mechanical aging of the scan heads over their lifetime. This calibration of the jump times for various jump sizes has been largely an iterative, trial-and-error manual exercise and can be an inconvenient and painful process. If the user fails to recalibrate the look-up table frequently enough, the jump time values become incorrect (usually shorter than what needs to be). The laser firing will occur before the scan head actually reaches the position and the laser drilling is thus inaccurate. For this reason, the open-loop method has generally been considered less accurate than the closed- loop method.

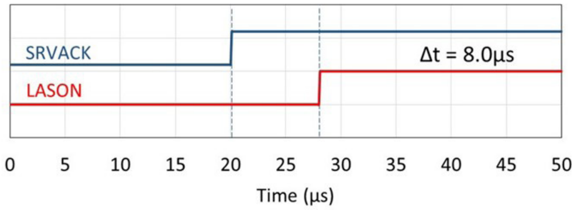
The open-loop control method employed in Cambridge Technology SMC and LIGHTNING scan heads has addressed this concern. SMC in open-loop mode also relies on jump times in a look-up table to plan the delays before it fires the laser and issues the next jump command (Figure 5 (b)).

What differentiate it from other open-loop implementation is that it can generate the jump time look-up table automatically and upon request. This makes the entire process easy and quick. The function to calibrate jump time and re-generate the look-up table is available through a single-click button on the GUI interface or a few lines of script command with the application programming interface (API). And it only takes a second or two to calibrate one scan head axis. For example, to calibrate all 4 axes of the two scan heads, with the smallest jump being 0.1mm, the field size being 80mm, the entire calibration process takes only ~4s to complete. Its ease of use and negligibly short calibration time not only brings convenience to the users, but also encourages them to perform jump time calibration on a frequent basis – it's even possible to recalibrate before every drilling job. This way SMC can always have the data reflecting the current state of the scan heads to achieve high drilling accuracy.

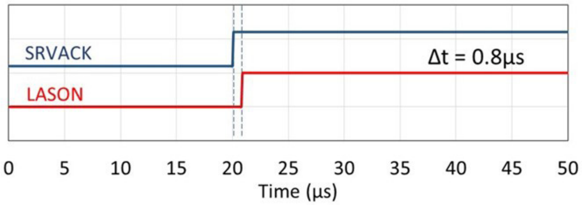
Note in the above discussion for both closed-loop and open-loop methods, in each hole drilling cycle, the SMC does not wait for the laser firing to complete; it issues the next jump at the same time as it fires the laser. This is to take advantage of the fact that the scan head takes some time to kick off its motion from stationary.

Laser Fire Adjust Time

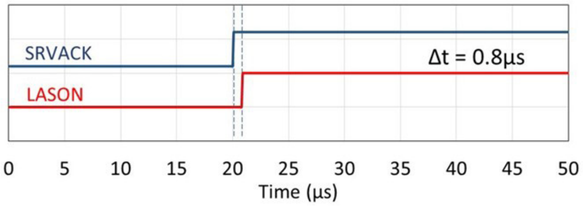
Now let's discuss another tool to increase the throughput benefits with open-loop mode. By default, the wait time for the laser to fire is set the same as the scan head jump time predicted in the look-up table, so the job throughput of open-loop method will be the same as closed-loop. But as the mechanism of open- loop does not rely on the in-position signal to act, it allows room for users to 'innovate' ways to reduce the cycle time of drilling each hole. One important feature of SMC open-loop mode is that it adds a parameter called 'laser fire adjust time' to adjust off the look-up table jump time. The 'laser fire adjust time' is a 'signed' value so when it's negative the wait time is reduced. This 'adjust time' can be used to compensate for the communication time, although the lag time between the LIGHTNING servo board and the SMC is found to be very short (<10µs) (Figure 7 (b)). It can also be used to compensate the time it takes for the laser to reach the peak value to drill (Figure 7 (c)). This time varies with the laser characteristics and the substrate material properties, and it needs to be characterized with an actual laser drilling test. In one drilling experiment done with SMC and LIGHTNING II plus scan head, the best 'laser fire adjust time' was found to be -20µs. For an HDI PCB with 400,000 to 500,000 holes to drill, the time saved per board is 8 to 10s.



(a) 'laser fire adjust time' = 0µs



(b) 'laser fire adjust time' = -10µs



(c) 'laser fire adjust time' = -20μs

Figure 7. In open-loop drilling, when (a) 'adjust time' = 0μs, the laser on signal (LASON, red) lags the in-position signal (SRVACK, blue) by 8μs; (b) set 'adjust time' to 10μs to compensate the lag time, for this particular hole, the time difference is reduced to 0.8μs; (c) set 'adjust time' to -20μs to compensate laser stabilization time, now the laser command signal is before the in-position signal.

Laser Timing Control Optimization

In a dual-head beam-switching configuration (Figure 2(b)), the scanning controller sends 'Laser On' signal to the laser and sends two 'Laser Modulation' signals to the AOM (usually there's a circuit before the AOM to process these two signals). Figure 8 shows the basic timing settings of 'Laser On', 'Laser Modulation 1' and 'Laser Modulation 2' signals. The setting of the five time durations (t1 ~ t5) in Figure 8 are all determined by the drilling process requirements and the requirement to maximize the job throughput. As the two scan heads typically perform the same drilling job, the duration of 'Laser Modulation 1' and 'Laser Modulation 2' are always set to be the same (t2 = t4). The t1 is usually set to be just sufficiently long enough for the laser to reach stable peak power for drilling. And t5 is set to be minimal while still long enough to accommodate the fall time of the laser. The time of t3 is required for AOM switching the laser beam from scan head 1 to scan head 2. It needs to be set longer than the AOM switching time, but as small as possible to minimize unnecessary time overhead that impacts the throughput. A typical AOM can switch beam faster than 1μs (for example 350ns). Therefore t3 can be set as small as 1μs.

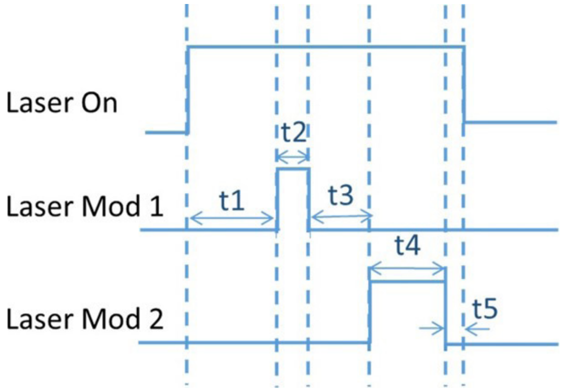


Figure 8 Laser On and Laser Modulation signals

Note that these laser signal timing requirements and constraints can vary with different laser models and different drilling processes. Therefore it is important for a controller to allow users to experiment with these laser signal timings for the best results. SMC allows flexible and accurate laser timing control. The user can set laser signals and laser delays in SMC to achieve any laser timing combination needed to optimize the laser drilling quality and throughput. In addition, the laser timing resolution can be set as small as 20ns, but for most practical purposes, a timing resolution of 1μs is found to be good enough.

Conclusion

This paper presented Novanta's scanning solution and performance for the laser drilling application. In addition to increasing the laser peak power, it is highly desired to increase the scanning speed and optimize the laser and scan head coordination to improve overall drilling throughput and accuracy.

The approaches we've taken are two-fold. First, the motor of the LIGHTNING II Plus scan head is engineered to be more powerful and efficient, enabling the fast jump time of 225 µs for 300µm via pitch using a 100mm f-theta lens. This translates to the drilling frequency up of to 4.4 kpps at this via pitch. Secondly, the control algorithms are developed to provide flexible and powerful tools on the laser and scan head control to achieve the optimum laser processing quality while maximizing the throughput. Both closed-loop and predictive open-loop methods can be easily employed. Additional features such as the automatic look-up table update and flexible 'laser fire adjust time' enable the laser process developers to reduce the overhead time as much as possible and easily maintain the process quality over time. Finally, SMC laser timing control gives the process developers ultimate flexibility to set any laser timing needed for optimized drilling process.

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