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Implementing Laser Marking of Printed Circuit Boards

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Introduction

Manufacturers of electronic devices, from home audio equipment to automotive keyless entry systems, are increasingly seeking a reliable, cost effective method for uniquely identifying and tracking products through the manufacturing cycle, sales distribution and after-sale warranty verification. An autonomous, automated tracking system requires that a permanent, machine-readable code be applied to an internal printed circuit board to uniquely identify each product. The code must be durable enough to survive manufacturing processes including wave solder and board cleaning, must not affect circuit performance, and must store information in the small space available on real-estate conscious printed circuit boards.

The 2D matrix code provides a means to store alphanumeric character strings in very small areas of the printed circuit board. Laser marking technology provides a method for permanently applying 2D matrix codes to most commonly used board substrates and conformal coatings. The high-resolution and high-accuracy of beam-steered laser marking systems provides the means to create well-defined codes for high-reliability reading regardless of code size. Laser marking also provides a fully computer-controlled marking process for easy implementation into an automated product tracking system.

The operating principles of beam-steered laser marking systems utilizing both CO_2 (carbon-dioxide) and Nd:YAG (neodymium:yttrium aluminum garnet) lasers will be discussed in terms of compatibility with substrate materials, marking performance, cost of acquisition and operation, maintenance, and integration with computerized product tracking systems. Subjects will include the data capacity of 2D matrix codes (Figure 1) and their corresponding sizes with the marking capability of laser systems. Installation in SMEMA-compliant manufacturing lines while maintaining a laser safe environment will be discussed. Samples of overall productivity will be presented for several board marking scenarios including single board and multi-up board configurations.

Figure 1 - 2 D Matrix Code

2D Matrix Codes

Two-dimensional 2-D symbologies like Data Matrix encodes information digitally in the form of a checkerboard pattern of on/off cells and thus allow marking and reliable reading of low-contrast codes directly on parts without a label (see Figure 1).

Data Matrix is the most popular 2-D symbology which has found extensive use in automotive, aerospace, electronics, semiconductor, medical devices and other manufacturing unit-level traceability applications. Data Matrix codes are typically not replacing conventional barcodes in these applications but instead extends barcode applicability to areas where they have not been applied in the past.

Data Matrix symbology was invented by RVSI but has been placed in the public domain so that anyone can print or read Data Matrix codes without paying a license.

In summary, specific advantages of Data Matrix codes over conventional 1D barcodes include:

- **Encode information digitally**, as opposed to the analog encoding of data in conventional barcodes.
- Can accommodate **low-contrast printing** directly on parts without requiring a label
- Offer **very high information density** – the highest among other common 2D codes, which means that you can place a lot of information in a very small area.

- They are **scaleable**, which means that you can print them and read them in various levels of magnification – only limited by the resolution of the available printing and imaging techniques.
- Due to the high information density inherent to Data Matrix codes, they also offer **built-in error-correction** techniques which allow fully recovering the message encoded in a Data Matrix symbol even if the mark is damaged and missing as much as 20% of the symbol.
- They are read by video cameras as opposed to a scanned laser beam used for reading conventional barcodes, which means that they **can be read in any orientation**.

Data Matrix Storage Capacity

Data Matrix codes can in general store up to 3,116 numeric or 2,335 alphanumeric characters or up to 1,555 bytes of binary information. (See Figure 2)

Symbol Size	**Data Capacity**		**5 mil Examples**	**7.5 mil Examples**	**10 mil Examples**
Row x Column	*Numeric*	*Alphanumeric*			
10 x 10	6	3	1.27 mm	1.90 mm	2.54 mm
12 x 12	10	6	1.52 mm	2.29 mm	3.05 mm
14 x 14	16	10	1.78 mm	2.67 mm	3.56 mm
16 x 16	24	16	2.03 mm	3.05 mm	4.06 mm
18 x 18	36	25	2.29 mm	3.43 mm	4.57 mm
20 x 20	44	31	2.54 mm	3.81 mm	5.08 mm
22 x 22	60	43	2.79 mm	4.19 mm	5.59 mm

Figure 2 – 2D Matrix Capacity

Code Generation

Direct laser marking of 2D matrix codes provides the user with a cost-effective means to permanently apply unique serial numbers to high volumes of circuits. The process does not require labels, stencils, punches or any other auxiliary hardware or consumables to mark the serial number. As a fully computer-generated process, the laser marking system can respond to real-time input from operators or information networks and can alter the marking content in milliseconds to keep pace with high production speeds.

Legible marks are created by thermally altering the marking surface using the heat generated by the laser light. The laser marking beam is directed across the surface of the substrate just like a pencil on paper to create the marking image.

For printed circuit board applications, several different techniques can be employed depending on the specific materials to be marked and background conditions (see Figure 3).

Solder mask or other Conformal Coatings on FR4 Boards

The laser marking beam can either alter the texture of the coating, giving it a lighter contrasting appearance, or can completely remove the coating to expose the underlying substrate or ground plane. Either technique can produce sufficient image contrast for 100% readability. Altering the surface of the solder mask is probably the most frequently used technique.

Uncoated FR4

The heat from the laser will bleach the color out of the surface of the FR4 resulting in a near white appearance.

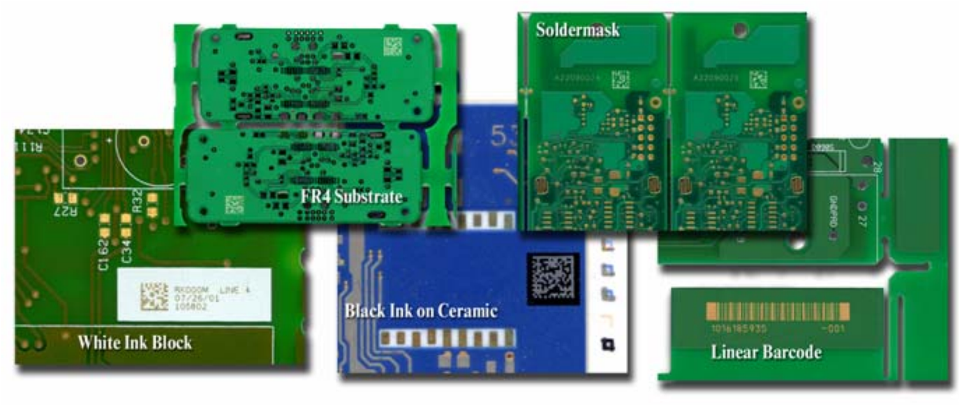

Figure 3 – Marking Techniques

Silk-screened Ink Block

Some users print a white block on the board during their normal silkscreen process to act as a background to the marking image to solve specific readability problems. Printing a white block gives the user complete control of the color and consistency of the background as it contrasts with the laser mark. This technique is particularly helpful when…

- The background color of the board is similar to the color of the laser mark.
- Underlying circuitry would obscure the marking image.
- The board material is not suitable for laser marking, such as ceramic substrates.

It is very important that the ink is applied uniformly from board to board. If the ink is too thin or inconsistent in thickness, a readable code cannot be guaranteed.

It is also important that the ink be uniform in color and that it be able to withstand the manual operations that the board will be subjected to after marking, like soldering, cleaning, and day-to-day handling. It is important to note that the permanence of the laser marking will be subject to the permanence of the ink.

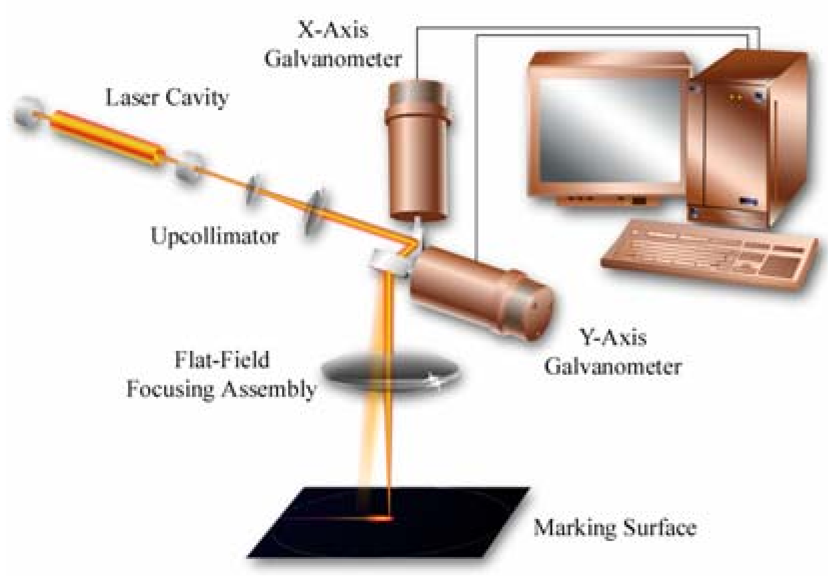

Figure 4 – Laser and Optics Train

Laser Marker Design

The heart of the system is the laser marker consisting of the laser source, the laser beam shaping and focusing optics and the beam-steering optics (See Figure 4).

Laser Source
The laser is a light amplifier generating a bright, collimated beam of light at a specific wavelength. The type of laser is chosen for the substrate material to be marked. For FR4 and solder mask applications, most users choose the air-cooled CO_2 laser operating at the 10,640nm far-infrared wavelength. This laser offers several performance and cost advantages, and produces excellent marking results.

Upcollimator
The objective of the beam-shaping optics is two-fold, to reduce the power density on the beam-steering mirrors, and increase the power density on the marking surface. The first element in the optical train is an optical telescope called an upcollimator. The upcollimator increases the diameter of the laser beam prior to focusing on the work surface. Although this may sound counter-productive, the diameter of the focused spot is determined by the diameter of the incoming laser beam and the focal length of the focusing optics. As the diameter of the incoming laser beam increases with upcollimation, the diameter of the focused spot on the work surface will be correspondingly smaller and the power density higher for maximum marking power. In addition, the larger beam diameter immediately after the upcollimator reduces the power density on the surfaces of the beam-steering mirrors to insure long term, reliable operation without thermal damage to the mirror surfaces.

The practical limitation to increasing the beam diameter is the size of the steering mirrors that are required to direct the beam without clipping or distortion. As the beam diameter increases, the increased mass of correspondingly larger mirrors reduces the maximum travel speed and detrimentally effects positioning accuracy. Each manufacturer optimizes the combination of upcollimation ratio and mirror size to achieve the best overall performance.

Beam-Steering Galvanometer System
The up collimated laser beam is projected through a system of two beam-deflecting mirrors mounted to high-speed, high-accuracy galvanometers. Each mirror deflects the laser beam 90 degrees from the direction of travel. As the mirrors are rotated under computer direction, the two angles of deflection move the laser beam on both the X and Y-axis in the laser field to "draw" the desired marking image.

Flat-Field Focusing Assembly
The last element in the optical train is the flat-field focusing assembly. After the laser beam is deflected from the final beam-steering mirror, it is focused to the smallest spot possible on the marking surface. As the laser light is focused to a smaller diameter, the power density and associated marking power increase.

The flat-field focusing assembly is a multi-element optical device designed to maintain the focal plane of the focused laser beam on a relatively flat plane throughout the marking field. If a simple focusing optic were placed before the beam-steering galvanometers, the focal spot would follow a pendulum arc from the final steering mirror, lifting the focal point of the marking beam off the board surface except at the center of the marking field.

Focal Length and Depth-of-Field
It is important to understand the relationship between the focal length of the flat-field focusing assembly, the size of the marking field, the resulting beam-waist and power density and the corresponding depth-of-field.

The laser beam will traverse the entire marking field with as little as 15 degrees of mirror rotation. As the focal length of the focusing optics increases, the distance traveled across the target surface will increase resulting in a larger marking field. However, the diameter of the focused spot (beam waist) will also increase resulting in a wider marking line width and reduced power density as the laser light is spread over a larger area.

The height of the beam waist also increases with longer focal lengths due to the shallower angle of the light cone, thus increasing the depth-of-field. Greater depth-of-field improves the tolerance for variations in board thickness and/or board positioning on the vertical axis. The laser manufacturer must consider all of the effects on marking performance associated with the choice of focal length.

Image Generation
The result of the laser optical train is to focus the laser beam to a small spot and to move the focused laser beam over the target surface with speed and accuracy. Marking images can consist of graphic logos, man-readable text, machine-readable codes (2D matrix and linear), and virtually any black-and-white two-dimensional image. With the typical CO_2 laser configuration used for printed circuit board marking, the focused spot diameter and associated marking line width is about 0.0035" to 0.004". Man-readable text characters can be as small as 0.040" and 2D matrix codes can be constructed from individual features as small as a single 0.004" dot.

Panel Transport/Laser Head Positioning

Printed circuit board handling is accomplished with an edge-belt, in-line conveyor equipped with adjustable guide rails to accommodate differing board widths (see Figure 5). Printed circuits may consist of individual boards or panels of multiple circuits. The conveyor and controls are designed to SMEMA Mechanical/Electrical Equipment Interface Standards to integrate with an automated assembly line or with a stand-alone downstacker/upstacker.

The conveyor transfers individual panels from an assembly line or from a bare board downstacker into the laser system when the laser system is not busy and the conveyor is available as outlined in SMEMA Mechanical/Electrical Equipment Interface Standards. When the conveyor transports a panel into the marking position, the panel is registered with pneumatic tooling to stop the board and locate it against the fixed rail of the conveyor and a hard stop. Typical conveyor designs can accommodate panel widths from 0.5” to over 24”. Manual adjustment of the conveyor width is standard with powered and programmable adjustment optionally available. Other options include internal and external board flippers, pin registration, hardened conveyor rails for ceramic substrates and dual independent conveyors for improved panel handling.

The laser marking head will typically have a marking field of 2” x 2” to 4” x 4” square. To mark over an entire panel, the laser marking assembly is mounted to a programmable X-Y Axis motion system that positions the marking head over each marking location.

This configuration of pneumatically registered panel and XY motion of the laser marking head will provide the user with an overall marking accuracy of +/- 0.005" as referenced to the panel stops. Higher precision XY motion can be used for marking on high-density circuits where greater accuracy is required. If the panels have not been cut accurately, and the circuitry location is not consistent board-to-board, a fiducial find camera can be employed to locate the laser marking in reference to a visual feature on the panel instead of the hard panel stops. Once a Panel is marked, the conveyor transports the panel back to the assembly line or to a panel up stacker.

Figure 5 - Laser Marking Head and Board Transport

Operating System

Computer control of the panel transport and generation of the marking image provides the user with a powerful real-time responsive marking tool.

The marking image is typically created by typing in marking text and designating text characteristics such as font, character height and location in the marking field, creating machine readable codes including 2D matrix and linear barcodes, and importing, sizing and placing graphic symbols in the marking field.

Once the marking image has been created, the XY coordinates for each marking location are entered into the array table. The marking image is subsequently marked at each designated location on execution of the marking program. Because the entire marking image is computer generated, any element of the image can be instantly changed circuit-to-circuit in the array including serialization of individual boards.

Most printed circuit board laser marking systems provide the user with system diagnostics to test and confirm the correct operation of individual system functions. These can include operation of the in-line conveyor, operation of the pneumatic panel stops, operation of the laser head motion system, operation of the laser marker and operation of any options such as 2D matrix code verification.

The laser marking system is easily incorporated into plant-wide information networks for immediate response to real-time input. Information relevant to specific marking tasks (panel ID, beginning serial number, quantity to mark, etc.) can be obtained circuit-to-circuit, job-to-job or in batch form at the beginning of a shift. System status and production progress can be communicated back to a central control. The laser marker can retrieve marking information from any of a number of database formats on the network. As the computer software is configured to the user's specific information management architecture, the computer screens can be modified as well to accurately and efficiently communicate with the operator.

2D Matrix Code Verification
Most printed circuit board laser marking systems are employed for serializing individual circuits with both 2D matrix codes and accompanying man-readable characters. Verification of the legibility and content of the 2D matrix codes is an important step in the overall quality program.

The 2D matrix reader is mounted to the laser marking head adjacent to the beam delivery optics with a field-of-view of the marking location. After marking of each circuit, the reader verifies the integrity of the mark before indexing the laser marking head to the next marking location. The reader will retrieve the alphanumeric text string from the 2D code and compare it with the text string that was to be marked.

The reader will also evaluate the legibility of the code based on a variety of parameters including foreground/background contrast, geometric accuracy (skew, squareness, etc.) and the dimensional accuracy of both the laser marked cells and the unmarked cells. The 2D matrix codes are then categorized as passed (green) warned (yellow) or failed (red). For overall production efficiency, the laser system can be programmed to verify only a select few 2D codes on a panel, then to automatically switch to verifying every code if the code legibility falls below a specified level.

Today's readers do an excellent job reading lower contrast 2D codes. If the laser marking system is installed on an assembly line with older 2D matrix readers downstream from the laser marker, the verification reader can be configured to evaluate the codes based on the performance of the older downstream readers to assure consistent performance throughout the assembly process. System response to a warned or failed code is normally specified by the user and can include visual and audible notification to a line operator, "X"-out of the failed code and repeat of the serial number on the next circuit, or communication of the XY coordinates of the failed code to the network.

Laser Safety
The design and manufacture of all laser marking systems in the U.S. is regulated by the Center for Devices and Radiological Health (CDRH). Most laser marking systems are built to be compliant with CDRH Class I requirements. This includes light shielding around the marking area with interlock doors that will activate a shutter in the laser head should an entry way be opened during the marking cycle. Certification to Class I requirements assures that the user cannot be exposed to high intensity laser light during operation of the system.

Laser Marking Performance
The overall productivity of the laser marking system is comprised of multiple functions that constitute the marking cycle. The steps required to mark one multi-array panel are…

1. Transport of the panel to the marking area and pneumatic registration in position.
2. Fiducial location *(optional)*
3. Marking of the first circuit in the array
4. Verification of the 2D matrix code *(optional)*
5. Motion of the laser marking head to the next circuit in the array.
6. Repeat steps 3 and 4 for the remaining circuits in the array.
7. Transport of the panel out of the laser marking system *(synonymous with bringing the next panel in)*

Table 1 shows the calculated estimates for two panel marking jobs. PCB #1 is a simple 4-up array with a marking time of 0.5 seconds per circuit. PCB #2 is a 10-up array with a 1.5 second marking time per circuit and two fiducials on the panel for marking alignment. **Table 1 – Calculated Estimates for Two panel Marking Jobs**

Example PCB #1

Circuits per panel:	**4**
Mark time per circuit:	**0.5**
Circuits to verify per side:	**4**
Fiducials per side:	

Example PCB #2

Circuits per panel:	**10**
Mark time per circuit:	**1.5**
Circuits to verify per side:	**10**
Fiducials per side:	**2**

Fixed Values *(seconds)*

Transport In:	3
Transport between circuits:	1
Board Flip:	7
Transport To/From Flipper:	6
Transport Out:	6

Function Timing *(seconds)*

Transport In:	3
Fiducial Find:	
Mark/Verify Circuits:	8
Transport Out:	6
Side Total:	*17*
Panel Total:	**17**

Function Timing *(seconds)*

Transport In:	3
Fiducial Find:	3
Mark/Verify Circuits:	30
Transport Out:	6
Side Total:	*42*
Panel Total:	**42**

Cost of Acquisition and Operation

The capital investment costs to incorporate laser marking of printed circuit boards can vary considerably depending on the degree of automation and the type of laser required. Continuing with our example of a fully-automated, SMEMA-compliant in-line conveyor laser marking system, typical pricing will range from $110,000.00 to $150,000.00 depending on options, networking, etc.

Cost of operation is minimal. Utilities requirements are 110VAC, 1-phase, 12A. A compressed air source is required for the pneumatics. Total utilities costs at maximum laser power *(the lasers actually operate at less then 80% rated power)* are $0.12 per hour. The primary consumable item is the CO_2 laser tube that must be replaced every 3 to 5 years at a cost of $1,100.00. Assuming a 40-hour workweek and tube life of 3 years, the tube replacement cost would equate to $0.18 per hour for a total operating cost of $0.30 per hour under worst case conditions. Actual operating costs should be lower due to less than maximum electrical usage and longer tube life.

For the two examples above, operating costs for laser marking of either PCB #1 or PCB #2 would be less than $0.00035 per circuit.

Options

Numerous options are available to expand or change the capabilities of the laser marking system. Some common additions/modifications include…

- Nd:YAG laser for engraving metallic and ceramic substrates or completely removing solder mask to expose the underlying ground plane.
- The Nd:YAG laser is a solid-state device that produces very intense, high peak power pulses of light at the near-infrared wavelength of 1,064 nm. A "YAG" laser rated at 50-watts CW can produce peak powers in excess of 75 kW with pulse widths of less than 200 nanoseconds. The high peak power provides the necessary energy to engrave even hardened steels.

  A useful variation of the Nd:YAG laser is the frequency doubled Nd:YAG laser operating at a wavelength of 532nm. The doubled "YAG" laser has found applications in clean room environments where reduction of marking debris can justify the added expense of the 532nm laser. The shorter wavelength also results in a smaller focused laser beam and associated marking line width for "micro" marking applications.

  The Nd:YAG laser is a more complex optical instrument than the sealed-tube CO_2 laser and comes with increased maintenance requirements and a higher price tag. Depending on the choice of laser, maintenance can require bi-monthly lamp replacement or diode replacement every 3 to 5 years. The laser may require watercooling and 220VAC electrical power. Cost of operation can run from $0.50 to $0.90 per hour inclusive of consumables, and acquisition costs can be from $20,000 to $30,000 higher than an equivalent CO_2 laser marking system. The frequency-doubled version of the Nd:YAG laser can add an additional $20,000.00 to the overall price of the laser marking system.

- Verification System to verify the correct operation of the laser marking head, optics and computer.
- For applications requiring a single marking location for each board, deletion of the XY motion of the laser marking head to reduce system cost. Manual adjustment of the laser marking head on the X-axis and manual adjustment of the board stop on the Y-axis for system setup.
- Manual or Programmable Z-Axis Motion of the laser marking head to accommodate different panel thickness or marking of board mounted devices.
- Barcode readers to retrieve information from job documentation pertinent to the laser marking job.
- Vision system to locate pre-existing identifiers of bad circuits. Note: It is possible for today's vision technology to incorporate 2D matrix verification, linear barcode reading, fiducial alignment, and pattern identification in a single camera system.

Summary

The electronics industry has been searching for a cost and technically effective means to apply machine-readable codes to printed circuit boards since the 1980's. Early attempts included laser marking linear barcodes on the edge of 0.064" thick FR4 boards, a subsequent challenge for barcode reader alignment, and marking linear barcodes next to circuit traces, also a challenge for scanning barcode readers. Barcode content was usually limited to just a few alphanumeric characters due to space limitations and the barcode character-per-inch specifications.

The development of the 2D matrix code combined with the resolution, permanence and speed of beam-steered laser marking technology offers manufacturers a reliable, cost-effective, flexible and verifiable means to uniquely identify every product through production, distribution and after-sale.