Vixar

Laser Printer Scanning Units Based on VCSEL Arrays

Wade V. Campbell
wcampbell@vixarinc.com

Contents

1 Executive Summary

Competitors in the printer market are on a constant mission to improve image quality and the printer speed. Laser printer technology traditionally relies on one (or sometimes two) laser(s) and a rotating polygonal mirror. Due to the limitations of increasing the rotational frequency of the polygonal mirror, an array of lasers is the obvious way to make significant quality and/or speed improvements. VCSELs are the preferred laser technology for this application (lower cost, lower power consumption, ease of manufacturing two-dimensional arrays, and high modulation rates). This approach has been used in a few high-end laser printer designs, but, as VCSEL technology has improved, use of VCSEL arrays is expected for laser printer manufacturers to increase to remain competitive.

2 Laser Printer Technology Background

2.1 Light Exposure Process

The heart of a laser printer is the light exposure process (see figure below) which is instantiated in the laser scanning unit. The core component of this system is the photoreceptor, typically a revolving drum or cylinder. This drum assembly is made out of highly photoconductive material that is discharged by light photons.

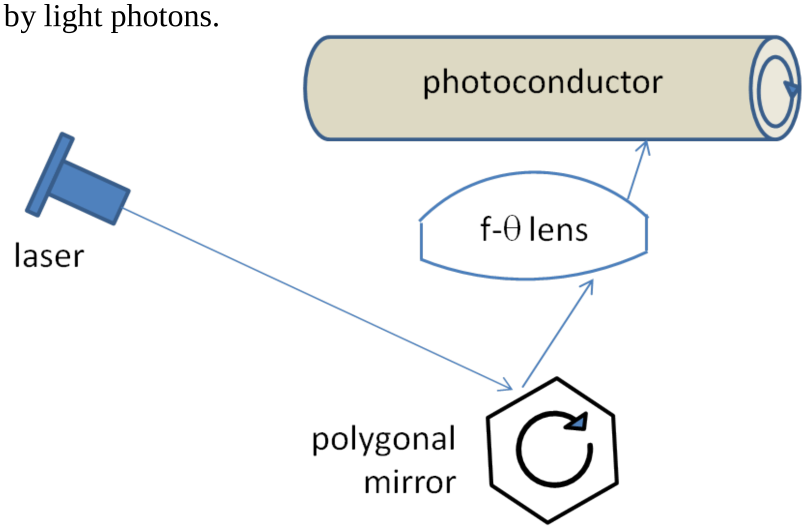

Figure 1

As the drum revolves, the printer shines a laser beam across the surface to discharge certain points. The laser light emission is modulated depending on whether the portion of the scan line should be dark or not, and then impinges on the polygon mirror. The polygon mirror is rotated by motors and scans the laser beam to the f-θ lens. The f-θ lens focuses the beam across the entire photoconductor region generating an electrostatic latent image line. The photoconductor rotates and the scanning sequence repeats continuously until the latent image of the entire page is created. In this way, the laser "draws" the letters and images to be printed as a pattern of electrical charges -- an **electrostatic image**. After the pattern is set, the printer coats the drum with positively charged **toner** -- a fine, black powder. Since the toner has a positive charge, the toner clings to the negative discharged areas of the drum, but not to the positively charged "background." With the powder pattern in place, the drum rolls over a sheet of paper. Before the paper rolls under the drum, it is given a negative charge. This charge is stronger than the negative charge of the electrostatic image, so the paper pulls the toner powder away.

3 Improving the Printer Quality and/or Speed

The major parameters that determine the image resolution and print speed are the polygon mirror rotational frequency, number of facets in the polygon mirror, and the number of multiple light beams. The relation between these parameters is given by the following equation [1].

$$R = (60\,VD) / (Nm)$$

Here, R (rpm) is the polygon mirror rotational frequency, V (mm/sec) is the print speed, D (dot/mm) is the print density, N is the number of facets in the polygon mirror, and m is the number of beams applied to the photoconductor.

One solution to improve image resolution or print speed is to increase the polygon mirror rotational frequency. However the polygon mirror rotation has its own limits due to the motor's mechanical stability. For example, if we are to develop a printer that possesses 2400 dpi resolution, 500 mm/sec print speed, and use a single beam laser, the required polygon mirror rotational frequency would exceed 230,000 rpm. This is far beyond the capability of polygon mirror motors available in the industry. Besides, it would also create additional mechanical vibrations to the lenses, undermine the printer's reliability, increase the noise output, and increase the printer's power consumption and temperature.

Increasing the number of laser beams is an alternate approach. Attempting to increase quality and/or speed using multiple, discrete lasers proves to be a tedious and costly approach due to the need to adjust individual beams. Because of this, a monolithic array of lasers is the preferred approach. Some laser printer designer/manufacturers may want arrays of at least 16-32 lasers to get sufficient benefit for increased driver cost that may be associated with driving large arrays. Edge emitting lasers (EELs) with 2 or 4 devices in a monolithic array are available, but VCSEL technology has an advantage in the ability to produce larger monolithic arrays due to higher yields and the fact that the surface emitting nature of the VCSEL allows for 2D arrays.

Beyond ease of producing large monolithic laser arrays, there are other critical requirements for the light source in a laser printer.

4 Light Source Requirements for Laser Printer Applications

4.1 Wavelength

The optimal light source wavelength is determined by the wavelength at which the photoconductor has its highest and most stable sensitivity. Organic photoconductor (OPC) drum coatings have virtually replaced inorganic coatings in laser printing equipment for several reasons, including light sensitivity characteristics and the fact that the inorganic photoconductor materials are highly toxic [4] [5] [6] [7]. Organic OPCs (e.g., phthalocyanine pigments, azo pigments, and perylene pigments) are most sensitive in the 500-850 nm region, as seen in the figure below [8]. One group of OPCs is sensitive to exposure with near-infrared light and the other to visible light. The near-infrared light-sensitive materials include phthalocyanines (polymorphs of TiOPc), squaraines, and trisazo pigments. The visible light-sensitive materials include perylenes and bisazo pigments.

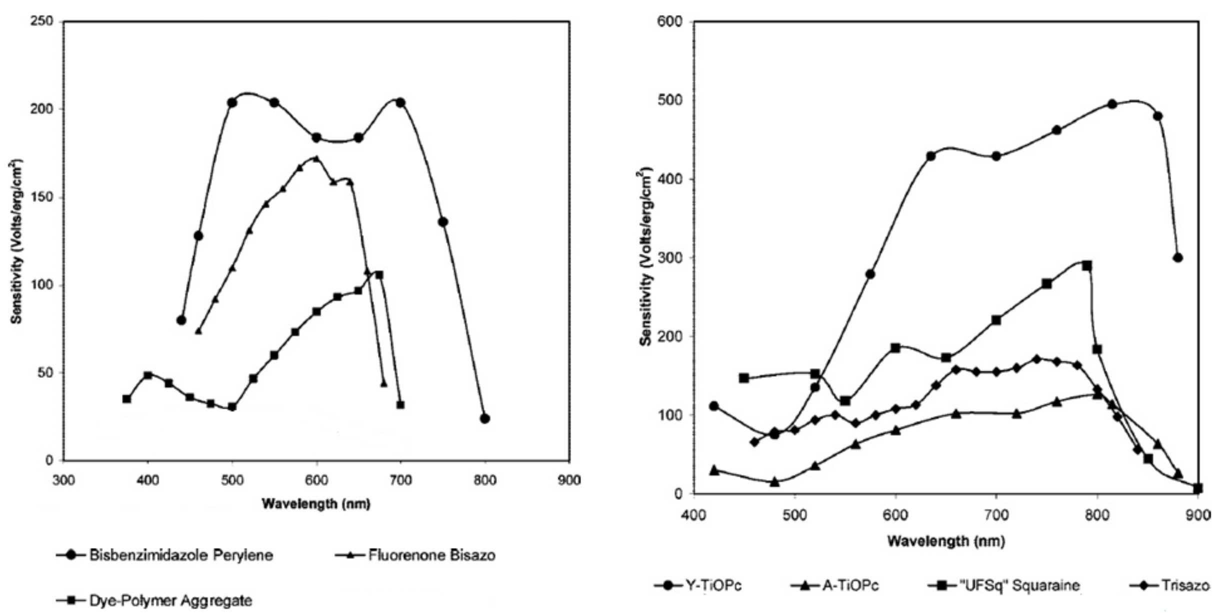

Figure 2: Photosensitivity action spectra of typical visible (left) and near-infrared (right) light-sensitive OPC materials.

Many commercial OPCs utilize phthalocyanines. Companies want to obtain patent rights to their photoconductor material, so they often create unique polymorphs, though in many cases the actual differences can be quite small.

There is a preference for using shorter wavelength lasers as the theoretical spot size is smaller, and hence print resolution can be improved. In practice, high quality, cost effective laser sources are only available in the red to infrared range. VCSEL technology is available in the range from 670nm to 1000nm achieving the desired performance characteristics in the shorter wavelengths of this range has been challenging. The technology has recently overcome these challenges, making it attractive for laser printing.

4.2 Beam Shape

The beam shape should have a Gaussian profile or have Gaussian "shoulders" with a flat center, and operate with a single transverse mode (i.e., be single mode instead of multi-mode). Multi-mode beams that have concave centers are more difficult to focus and can degrade the image quality.

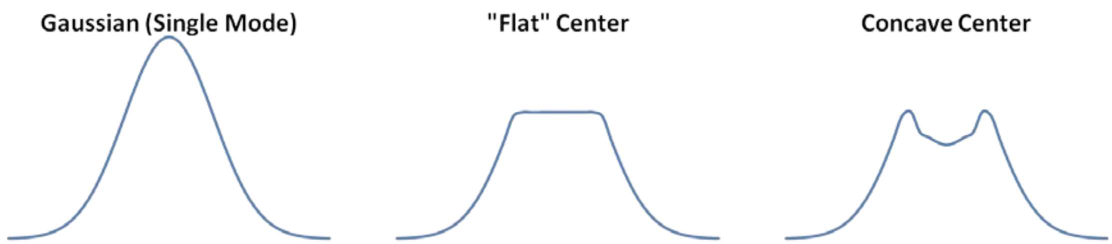

Figure 3

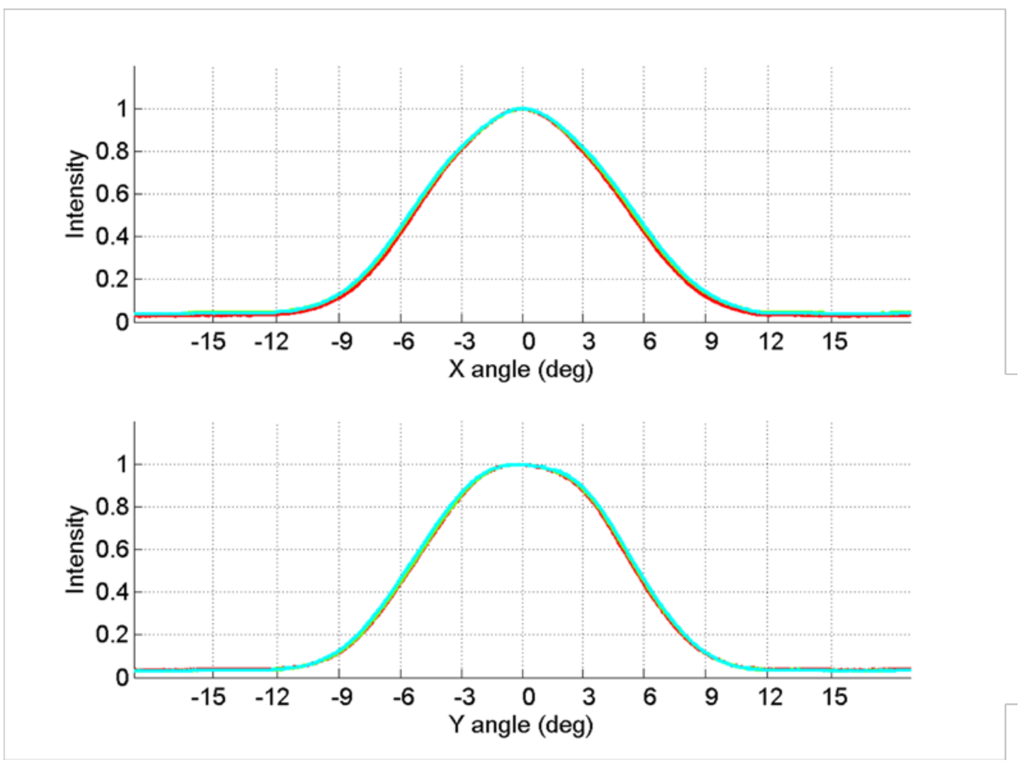

Figure 4: VIXAR's Red VCSEL Beam profile: Intensity versus angle from normal in x- and y- directions, for multiple currents

4.3 Output Power

The light output must be sufficient to irradiate enough energy to effectively remove the electrical charge from the photoconductor, thereby producing the latent image. The required launch power level typically ranges from about 2 mW to 8 mW, but is highly dependent on the particular photoconductor material used, the efficiency of the optical path, and the duration of the illumination. For example, one laser scanning unit design using a prevalent organic photoconductor (OPC) material (phthalocyanine pigment) requires 3 mW of launch power [2].

Whatever the required output power, it must be delivered over the range of operating temperature, which is typically 0-60°C. This is important since VCSEL output power decreases with temperature, often significantly at temperatures in the 60-85°C range (depending on the particular VCSEL design).

In the light exposure system of a laser printer, the power from a single beam is described by the following equation [1].

$$P = (kVS) / (Nm)$$

Here, P(mW) is the power required per a single beam, S (mJ/mm) is the sensitivity of the photoconductor, and k is a constant determined by other printer design factors. This equation means that the emitted power from a single beam can be relaxed by increasing the number of laser beams, which means that individual VCSELs in an array can individually emit lower output power and still meet the required output power level.

The figure below displays the output power as a function of temperature for VIXAR's single mode red VCSELs.

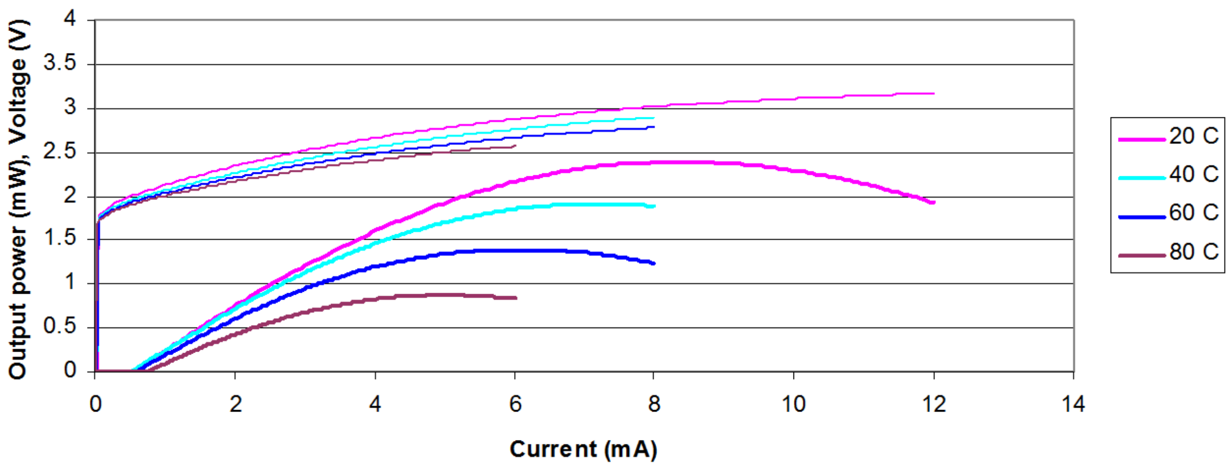

Figure 5: VIXAR's Single Mode Red VCSEL

4.4 Polarization Direction

The polarization direction of the VCSEL array must also be uniform and stable to match with the polarization dependent mirrors or lenses used in the ROS system. Polarization instability will lead to power fluctuations at the photoconductor surface, which will degrade the image quality. VIXAR has developed red VCSELs with a stable linearly polarized beam (see figure below).

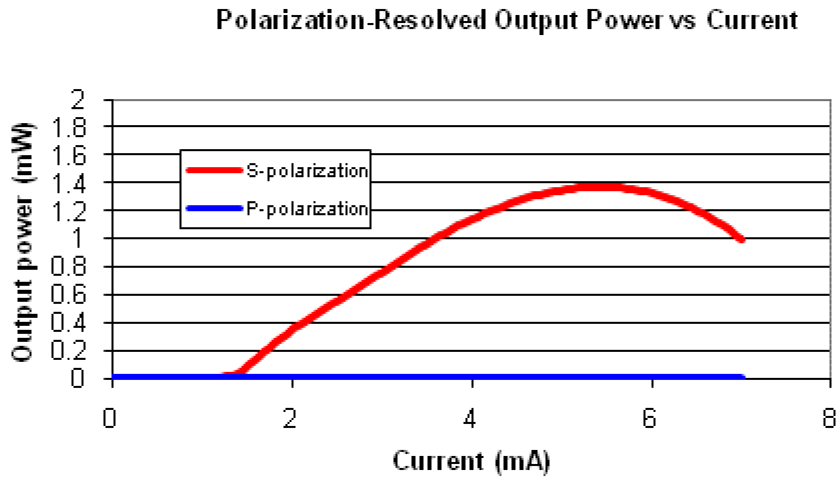

Figure 6: VIXAR's Red VCSEL Polarization Stability

4.5 Power Profile of a VCSEL Pulse

As described in the "Light Exposure Process" above, the VCSELs are pulsed (modulated) to create the image. The output power over the duration of a pulse must be relatively constant, since variations cause a toner density fluctuation which degrades image quality particularly in halftone images.

Turn-on speed and droop, illustrated below, are the two factors that can conspire to cause the output power during a pulse to vary. Droop is defined as the power drop induced by internal heating within the VCSEL [3]. In monolithic VCSEL arrays, heating from adjacent VCSELs may also contribute to droop.

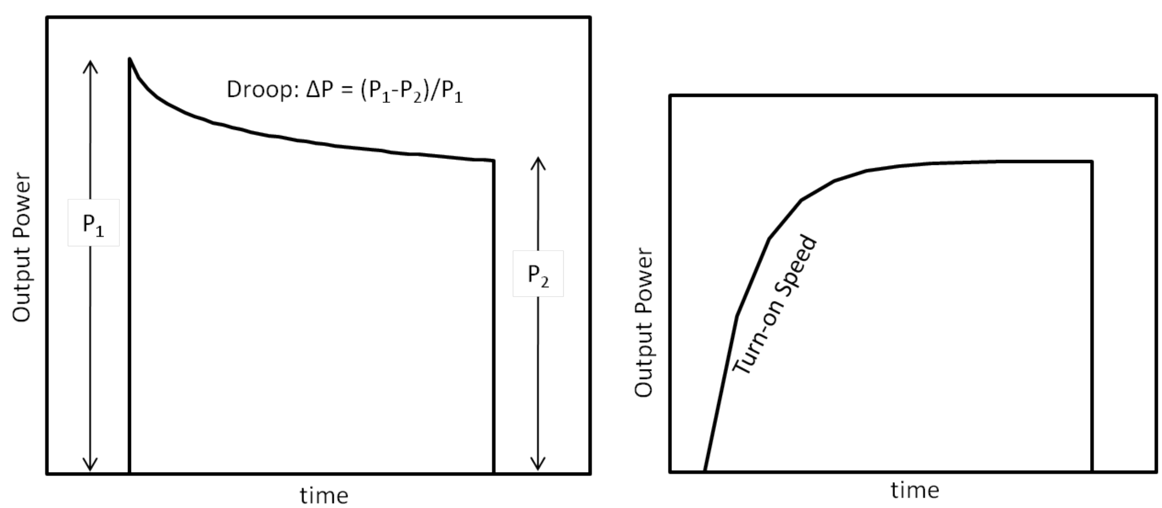

Figure 7: Possible Impacts on Pulse Power Profile

If turn-on speed and/or droop result in a significant variation in output power over the duration of a pulse (i.e., > 5% [2]), toner density fluctuations result which degrade image quality, particularly in halftone images.
Both droop and turn-on speed can be impacted by the pulse duration (width) [3]. The frequency (GHz) that the VCSEL must be capable of is described by the equation below [1].

$$\text{frequency (GHz)} = kVD^2 / m$$

For a 2400 dpi printer at 2 pages/second with 32 lasers, the frequency would be on the order of 100 MHz, which is a pulse width of 10 ns. Increasing the speed by a factor of 4 or resolution by a factor of 2 would result in a pulse width of 2.5 ns, as so on. Therefore, the pulse widths of most interest are this order of magnitude (3-10 ns).

Since the bandwidth of a printer ranges from DC to 100 MHz or more, it is important for the peak pulse power to be independent of duty cycle. The figure below shows the lack of duty cycle dependence in a red VCSEL for duty cycles ranging from 0.1% to 50%.

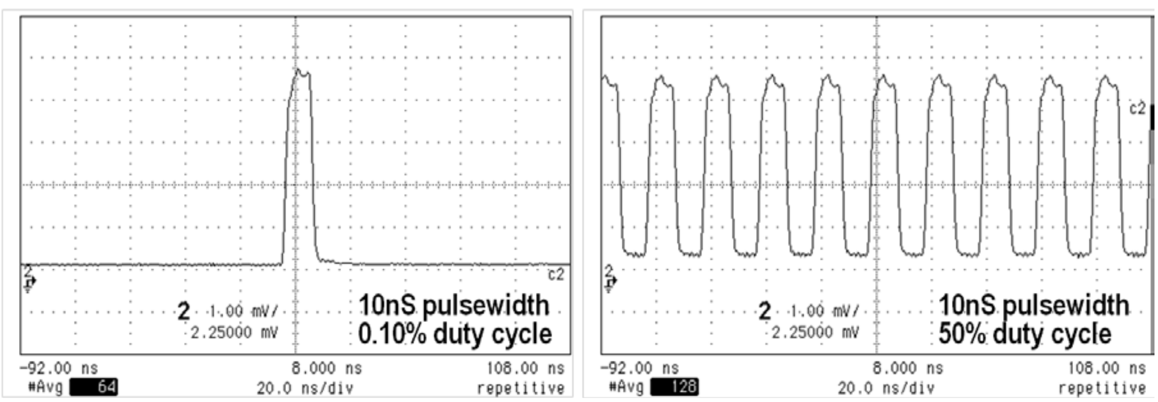

Figure 8: VIXAR's Red VCSEL Lack of Duty Cycle Distortion

4.6 Pitch Between Lasers in the Array

To increase the image density, it is desirable to reduce the spacing between the individual beams, while thermal crosstalk may become an issue if they are excessively packed. Typical pitch required is ~50 µm, but depends highly on the specific implementation. Below is an example of an 8x8 array with 60 µm pitch.

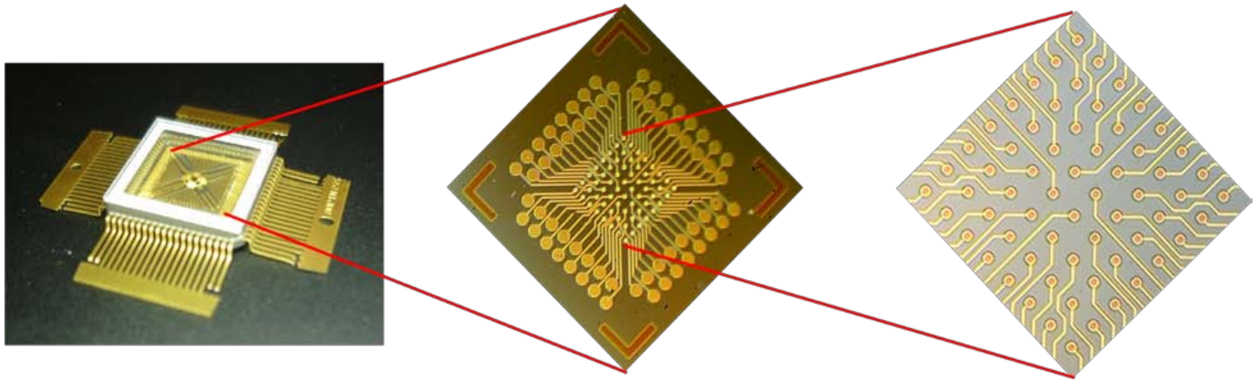

Figure 9: 8x8 Red VCSEL Array, 50 µm pitch

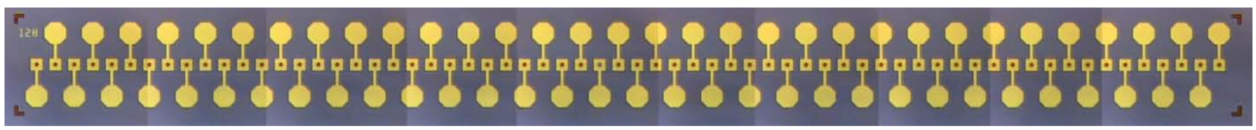

Figure 10: 1x64 VCSEL Array, 75 µm pitch

4.7 Uniformity Across VCSELs in the Array

In order to achieve uniform image quality, the output power and beam divergence angles of the VCSELs in an array must be reasonably uniform. The output power must be uniform across the VCSELs in the array (e.g., no more than a standard deviation of 5% [2]) at the current used to achieve the required output power. Threshold current is also important to have uniform across the VCSELs, since uniformity of threshold current helps ensure uniformity of output power as the current varies.

The beam shape must also be consistent across the VCSELs in the array. While SMSR may be used to ensure a Gaussian shape, the Gaussian shape must be consistent from VCSEL to VCSEL. Up to a 5% variation in FWHM is an acceptable level of uniformity for angle divergence [2].

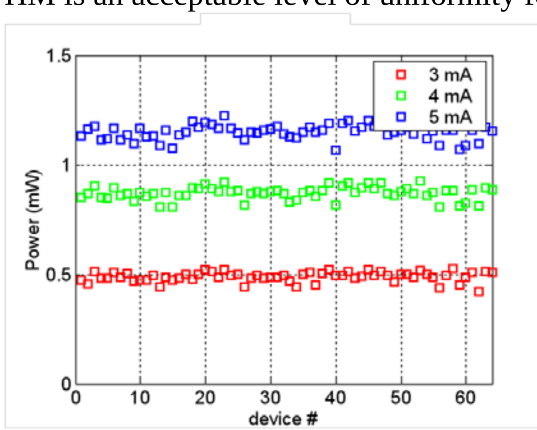

Figure 11: Example of Uniformity of Output Power across VCSELs in 8x8 Array

4.8 Reliability

Vendors typically want lasers that have a TT1%F of several thousands of hours (e.g., 2000-4000) at humidity levels of 50-60%. The diagram below shows results from reliability testing in humid conditions that is ongoing at VIXAR. This and other reliability results indicate that VIXAR's red VCSELs have a TT1%F well beyond that required for laser printing applications. (See the VIXAR Application Note titled "Reliability of VIXAR's Red VCSELs" for more details.)

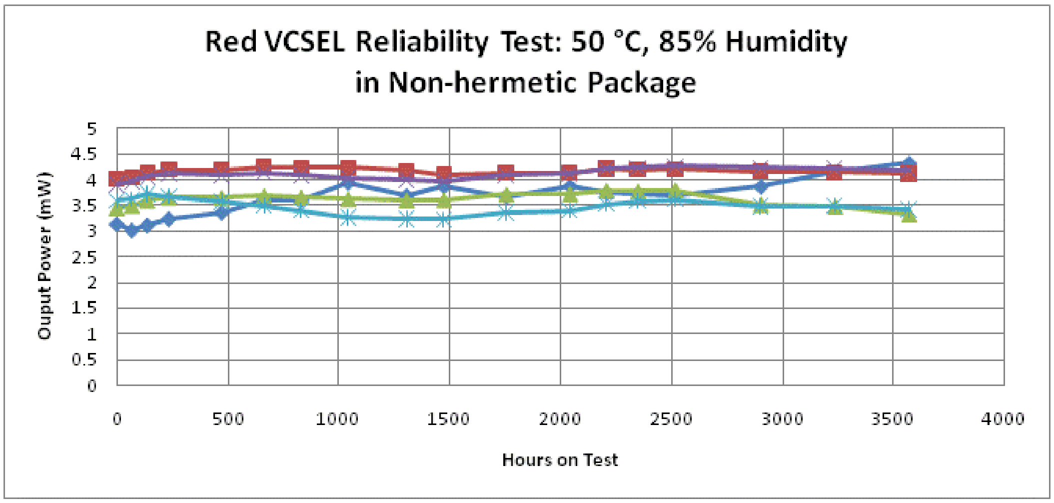

Figure 12: VIXAR's Red VCSEL Reliability

5 VCSEL Array Technology Satisfies Laser Printer Requirements Today

The laser light source requirements for each laser scanning unit design are different. While many high-end laser printer designer/manufacturer use a unique photoconductor material, the wavelength requirements for currently-used photoconductor materials are well-bounded and can be satisfied with currently available VCSEL technology (including wavelength requirements in the red region of the spectrum).

Historical concerns with using VCSEL technology, such as reliability at higher operating temperatures and/or humidity, have been solved for the printer environment by VCSEL designers at the forefront of the technology.

Large, monolithic VCSEL arrays are a primary means by which high-end laser printer designs will differentiate themselves in the immediate future.

6 References

[1] K. Kataoka, Y. Shibayama, and K. Doi, "Multiple Beam Scanning for Laser Printer: Application to Optical Fiber Array Method", Opt. Rev. vol. 8, pp.218-226, (2001).
[2] Naotaka Mukoyama, Hiromi Otoma, Jun Sakurai, Nobuaki Ueki, and Hideo Nakayama, "VCSEL array-based light exposure system for laser printing", Proc. of SPIE Vol. 6908, 69080H-11, (2008).
[3] "Operation of VCSELs Under Pulsed Conditions", Bill Hogan, 2010, http://www.vixarinc.com/pdf/PulsedPowerAppNote2.pdf.
[4] "Electrophotographic photoreceptor having a light-sensitive layer formed from titanyl phthalocyanine pigment dispersed in a branched ester or alcohol solvent", United States Patent 5114815.
[5] "Mineral Commodity Profiles, Selenium", by W.C. Butterman and R.D. Brown, Jr. , Open-File Report 03–018, U.S. DEPARTMENT OF THE INTERIOR, U.S. GEOLOGICAL SURVEY, 2004.
[6] "Electrophotography", Milan Stolka, Joseph Mort, OI: 10.1002/0471238961.0512050319201512, Published Online: 4 DEC 2000.
[7] Interview (3/31/2011) with David Weiss, Senior Scientist in the Department of Chemical Engineering at the University of Rochester, Rochester, NY, specializing in OPCs and how they interact with the various subsystems in the electrophotographic process.
[8] "Advances in Organic Photoconductor Technology", David S. Weiss, Martin Abkowitz, Chemical Reviews, 2010, Vol. 110, No. 1.