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The Development of Laser Diode Arrays for Printing Applications

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1. Introduction

Printing is one of the developed world's oldest industries, currently commanding worldwide annual revenues in excess of $700bn (Global Print, 2009). In many ways it can be regarded as a gauge of the health and development of local economies, as it serves a diverse spread of business sectors as well as local and national governments. Within the printing industry lasers are ubiquitous, from small desktop laser printers to large scale industrial printing presses. This chapter will provide a brief summary of the history of printing technology, concentrating on the development and implementation of lasers to accommodate specific needs within the printing sector.

There is a widespread and continually expanding use of laser diodes, and, in particular, laser diode arrays in printing applications. Laser diode arrays are enabling revolutionary developments in a range of printing applications which have generally been driven by the requirements to improve printing speed, reduce cost and increase quality. As a result of the growing demand from commercial printing suppliers, arrays of laser diodes have been developed for all areas of the printing market.

The printing market is expected to undergo continued growth in coming years, despite the global economic slowdown and growing competition from emerging multi-media technologies. This growth will largely be met by increasing demands from the emerging markets of developing nations in the Far-East and South America, and will provide a significant opportunity for printing press manufacturers. In particular, there will be a growing range of applications that can be successfully addressed by laser diode arrays, which provide a low-cost yet highly efficient means to improve print speeds and print resolution.

This chapter describes the development of novel laser diode arrays designed to meet specific requirements for state-of-the-art printing presses. The bulk of this work has been carried out by Intense, Inc., the world's leading supplier of laser diode array print products. Intense utilises a proprietary quantum well intermixing (QWI) process, which provides a means for post-growth band gap engineering. This can be used to develop a range of novel optoelectronic devices, including photonic integrated circuits. However, the company's main focus is the development of high power single and multimode lasers for a range of markets, including printing, defence, medical and industrial applications. Through the use of QWI and the development of high yielding wafer fabrication and assembly processes, the company has pioneered the development of a range of laser diode array products that exhibit market-leading performance and reliability. These arrays have been designed and manufactured to meet the demands of a range of diverse applications within the printing market. This chapter will address each of these applications, discussing the market needs and the solutions that have been engineered to fulfil these requirements.

The future generation of laser diode arrays will be enabled by the development of novel device designs and processing technologies which yield significant improvements over existing technologies. The use of one such technology, Quantum well intermixing (QWI) is discussed in Section 2. Section 3 will discuss the development of laser diode arrays in high quality commercial print applications with a print resolution of 3600 dots per inch (dpi). The emergence of new digital printing presses in variable printing applications with resolutions of 1000-2500 dpi will be discussed in section 4, in particular describing the development of ultra-fine pitch laser arrays for next generation printing presses. Section 5 will discuss the application of laser arrays in forming large size print-heads for a range of coding and marking applications, where lasers will provide improvements in cost, quality and versatility compared to incumbent technologies, such as inkjet, thermal and gas laser printers.

2. Quantum well intermixing in printing applications

Many of the modern printing applications in which lasers are deployed require a laser device with high output power, good beam quality, high reliability and a long lifetime. Achieving the output powers required in certain applications is not a trivial task, due to the occurrence of catastrophic optical damage (COD), the key failure mechanism in short wavelength single mode lasers.

COD occurs due to the predominance of surface states at the laser facet. These defects act as non-radiative recombination centres during operation and lead to an increase in temperature in the vicinity of the facet, and a commensurate reduction in band gap at the facet. This then results in additional optical absorption at the facet, and ultimately induces a thermal run-away cycle which culminates in the sudden failure of the facet.

Quantum well intermixing (QWI) provides a simple and inexpensive, yet powerful technique for the prevention of premature failure through COD. It has thus become a key enabling technology for the realization of high power laser devices that are required in many printing applications. The technology enables localized post-growth modulation in the band gap of III-V materials which can be applied to the facet regions of laser devices in order to suppress COD.

QWI generally involves the localized introduction of defects into the semiconductor crystal, followed by a high temperature anneal. The defects enable an increase in the atomic diffusion rate, resulting in enhanced inter-atomic diffusion, and a change in the composition of the quantum well, which is generally manifested as an increase in the quantum well band gap. By controlling the defect density it is thereby possible to control the rate of intermixing.

Spatially selective QWI can be achieved by patterning the surface of the semiconductor wafer with different dielectric caps and subjecting the wafer to a high temperature anneal (600-1000 ºC) (Kowalski et al., 1998). During the high temperature anneal, defects are generated within the semiconductor wafer, with the level of defect generation determined by the specific properties of the dielectric capping layer. By employing two different cap layers, one which enhances defect generation rate and one which suppresses defect generation, it is possible to locally increase the band gap in certain regions of the wafer whilst retaining the original band gap in other regions. This band-gap engineering process can be used advantageously to provide a non-absorbing mirror (NAM) function. This is achieved using QWI to locally increase the band gap in the facet region, thereby rendering the facets non-absorbing. In this way it is possible to prevent the thermal runaway process that stems from increased absorption at the facet and ultimately results in premature failure of the diode. This enables high power operation to be sustained with greater robustness.

This is demonstrated in Figure 1, which shows typical LI curves for 8xx nm lasers developed for printing applications. All laser configurations employ standard ridge waveguide geometry, using a double trench design for planarisation purposes. The ridge width is 2 µm, defined using an inductively coupled plasma (ICP) dry etch process, with a very simple device geometry as illustrated in Figure 1(a). Data is shown in Figure 1(b) for lasers with and without NAMs, where lasers with NAMs possess varying degrees of QWI band gap shift. All the lasers underwent an identical premature aging cycle prior to this LI measurement.

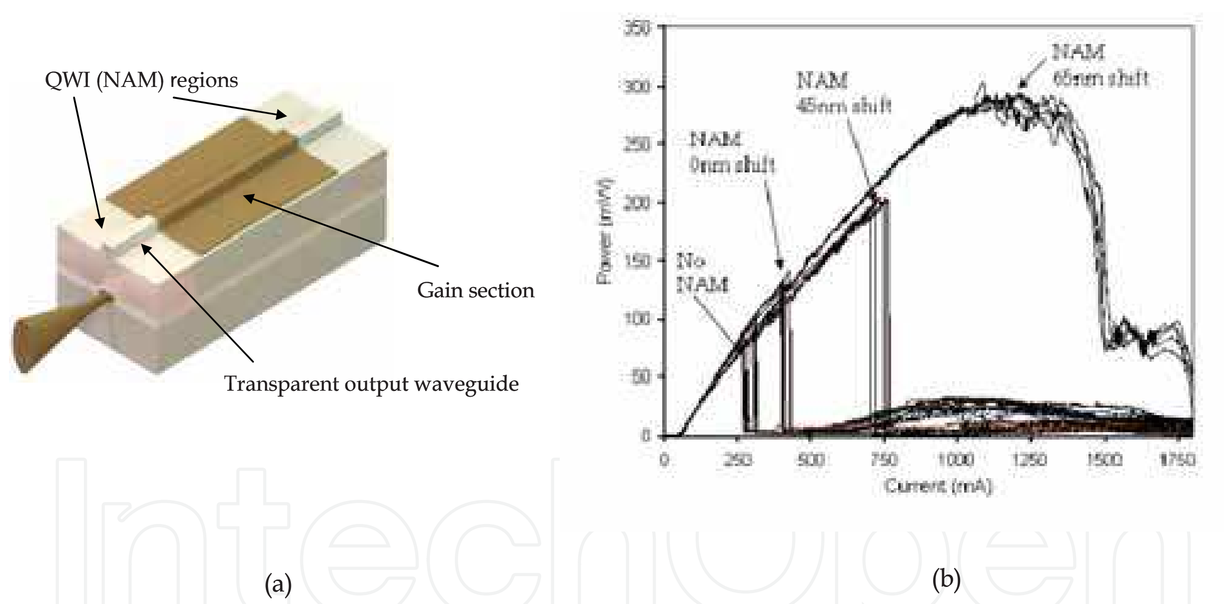


Fig. 1. (a) Schematic 3-D illustration of the chip layout used to produce high power single mode laser diodes using intermixed NAMs to suppress COD, and, (b) L-I curves for 8xxnm ridge waveguide lasers with and without NAMs, where devices with NAMs have undergone a range of QWI band gap shifts.

The laser without a NAM undergoes catastrophic failure at under 100 mW output power. For a laser with a long unpumped section, but without QWI shift in band gap, there is an approximate 50% increase in output power, simply due to the reduction in carrier diffusion from the active to passive sections. Using QWI to induce a 45 nm band gap shift in the NAM regions, a significant further increase in output power is observed, to 200mW, more than double the output power of the standard laser. By further increasing the QWI shift in the

NAM section to 65 nm, the laser does not fail. It instead undergoes thermal rollover, illustrating the significant improvement in high power operation that can be achieved by suppressing band-to-band absorption and carrier diffusion at the facet.

The manufacturing benefits enabled by NAMs are key to enabling the emergence of laser diode arrays for printing, by providing the technical means to achieve the requisite performance levels together with considerable improvement in manufacturability, as further described in section 3.

3. Computer to plate applications

3.1 Introduction

A key development within the printing industry has been provided by computer automation, in particular the development of desktop publishing software. This has led to substantial improvements in the efficiency and throughput of printing systems which has been complemented by the development of increasingly efficient printing presses, in particular the use of modern computer to plate (CtP) printing technology.

CtP printing is the unequivocal standard for high quality, high volume commercial printing applications. It superseded earlier computer to film and phototypesetting techniques, by using laser sources to directly image a photosensitive plate. This enabled the elimination of film preparation steps used in earlier technologies, providing substantial improvements in printing productivity and quality together with reductions in costs.

The printing process itself involves a procedure known as offset printing, in which a printing plate is wrapped around a rotating drum. The plate is first processed to create image areas which are ink-receptive and non-image areas that are ink-repellent. The plate is then coated with ink which adheres only to the pre-defined image areas. The overall image is then transferred via an offset drum with a rubber coating to the print medium, as illustrated in Figure 2. The printing plate is repeatedly coated with ink and used to typically

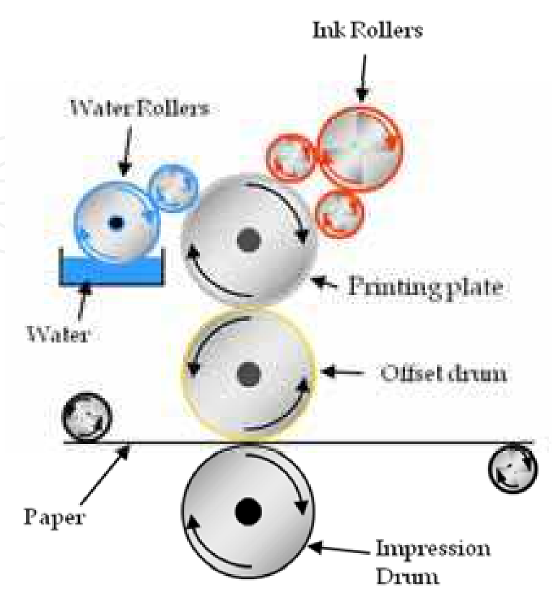


Fig. 2. Illustration of basic working principles employed in offset printing system.

reproduce many thousands of identical impressions. Originally the printing plate would be defined by hand, but in the late 20th century photographic techniques were developed to create film negatives which could be used to expose printing plates, inducing a chemical change in the plate coating, and thereby generate image and non-image areas. More recently, with the advent of computer automation, it became possible to carry out much of the editing and graphic design digitally, and thereby create computer-generated film negatives, in a process known as computer to film (CtF).

3.2 Modern developments

CtP technology has emerged since then, superseding CtF as the current state-of-the-art technique for high quality commercial printing. CtP has eliminated the film preparation stage and the associated plate exposure steps used in CtF. This has significantly improved the efficiency and quality of the printing process, as defects generated within the film are not transferred to the final print product and misalignment errors are eradicated. Instead the printing plate is directly exposed by illuminating its surface with a laser source which is scanned across the surface. In turn, the laser output is modulated by digital data output from the desktop publishing software to create image areas in-line with the finished product.

The first CtP systems employed a low power UV laser beam (300-450 nm) to expose the printing plate, compatible with the chemistry of existing plate coatings. Subsequently, a range of printing plate coatings has been developed to improve printing quality and efficiency, including the development of thermal printing plates.

Thermal CtP plates possess a thermally sensitive coating layer, the properties of which are altered by exposure to a near infra-red laser beam, enabling a laser with appropriate wavelength (800-1050 nm) to directly image the printing plate. This provides some significant advantages in reducing printing times and increasing print quality, however, a higher power laser source (~ 200 mW) is required to adequately expose the plate.

A key advantage of the thermal imaging system is that costs associated with the development of the printing plate can be significantly reduced. For UV systems the development process often requires specific lighting conditions, and a greater dependence on chemical development. With thermal printing, the demands on developing solutions and environment are significantly reduced, leading to more efficient, lower cost printing with reduced ecological impact. In addition, print quality can be significantly improved through the use of thermal systems, as the plate cannot be overexposed - providing it is subjected to a threshold energy exposure, increased exposure does not alter the plate properties. This leads to higher print quality with improved image clarity and sharpness.

A disadvantage of using a thermal imaging laser is the requirement for increased laser power in order to image the printing plate. For this reason it is necessary to use a multiple laser source to image a plate efficiently. The print-head comprising the multiple laser source is scanned across the surface of the printing plate as the plate is rotated in an orthogonal direction, as shown in Figure 3. The output of each laser element within the print-head is independently modulated to selectively expose the printing plate in designated image areas, as dictated by the output of the editing software.

Several approaches have been utilised in order to attain a printing system with multiple imaging sources. These include the use of:

- Discrete laser arrays comprising multiple laser sources, the output of which are combined through optical fibres to a single optical header comprising a bundled fibre-array
- Laser lightvalve technology to generate multiple beams from a single high power multi-mode laser.
- Monolithic single mode laser diode arrays comprising a single chip containing multiple individually addressable laser diode emitters, the output of which can be independently modulated to completely expose the printing plate.

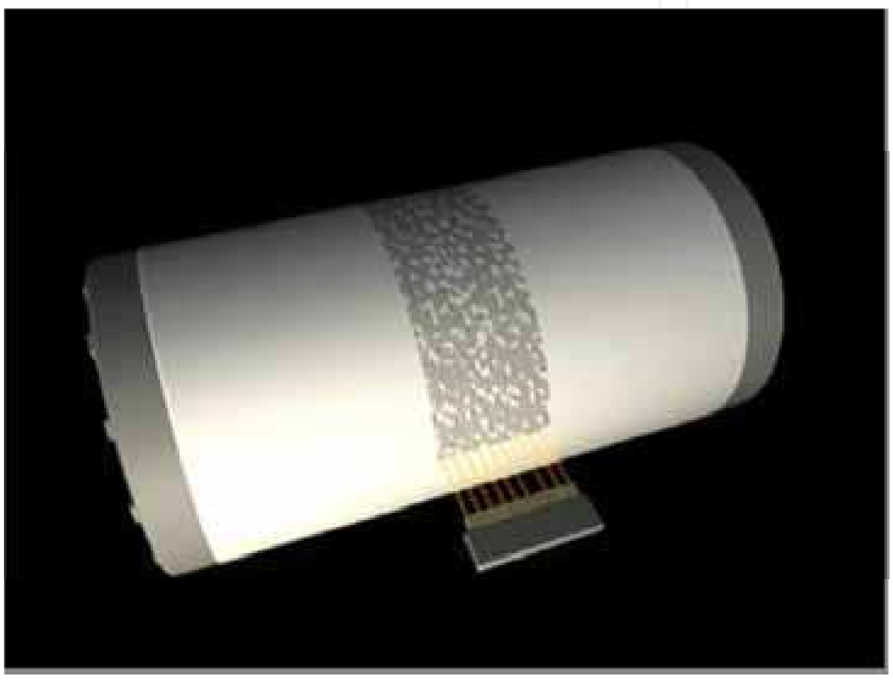


Fig. 3. Illustration of a laser array used to image a CtP printing plate.

Discrete laser arrays were first employed in laser printing systems in the mid 1990s. Generally such systems use a large number (up to 100) of fibre pig-tailed individual laser sources. The output of these are coupled together in a single optical head, in which each output fibre is accurately positioned to form a linear fibre array with a well defined pitch, of the order of 150-200 µm. This requires very accurate alignment of the individual fibres to form the optical head, often involving a v-groove submount. This can prove time-consuming and costly, and produces a relatively large and bulky laser array source, with added system complexity. In addition, the minimum pitch is determined by the fibre diameter, which precludes the use of fine-pitch arrays and limits system specifications.

A more recent development has involved the use of novel technology to modulate the output of a single high power laser source using laser light-valve technology (Tamaki et al. 2004). This involves the use of a high power, multi-mode laser diode source, either a single emitter or bar, the output of which is collimated to create a uniform line of light. This is then spatially modulated through the use of an array of modulators, to produce a multiple-beam output which is then used to image a printing plate. The modulator array tends to use either ferroelectric modulators or grating light-valve technology. This approach provides some advantages over discrete arrays, in particular, the fact that only one laser source is required, reducing costs and inventory control. In addition, the system can be designed to accommodate the failure of individual elements within the laser bar, and the pitch of output beamlets can be precisely controlled in the modulator array manufacturing process. However, a disadvantage is that significant light loss tends to occur due to inefficient coupling to the modulator array. In addition, the use of a multi-mode laser source introduces further complications and costs in terms of the high resolution imaging of the printing plate. The reduced depth of field available when imaging with a multi-mode source, combined with imperfections in the dynamic operation of a printing system means that an auto-focussing system is required to maintain high resolution imaging across the printing plate. Such a system, capable of responding at high speed, leads to considerable increase in overall costs. Utilising single mode laser sources, which provide a much higher depth of field, allows the self-focussing system to be dispensed with. This reduces system complexity, as well as cost.

By employing monolithic arrays of single mode lasers in CtP imaging over discrete laser arrays or systems using modulator arrays, numerous benefits can be realised. These include a reduction in form-factor, reduced inventory, improved print quality and reduced costs. The development of commercially deployed monolithic arrays is discussed in the following section.

3.3 Monolithic laser array development

This section describes the development of commercially available high power monolithic laser arrays for CtP, comprising x64 individually addressable elements, operating over the 800-840 nm (8xx nm) wavelength range. As described above, such arrays have distinct advantages over previously developed laser array solutions.

As these arrays do not provide any scope for failure during operation, their commercial development requires a very high yielding manufacturing process, with unheard of single emitter yields. The array yield itself is determined by the single emitter yield raised to the power N, where N is the number of array elements. Thus for an array comprising 64 elements, a single emitter yield greater than 99 % would be required to achieve an array yield in excess of 50%.

Such yields have been made possible through the use of QWI technology which provides an inexpensive and high-yielding process for the manufacture of laser diodes with NAM facet passivation. NAMs have proven critical for the manufacture of high power laser diode arrays for print applications. This is not only due to the improved power that can be attained through COD prevention but also due to the improved manufacturing tolerance that can be realized through the use of NAMs in laser diode array fabrication. The incorporation of a relatively long passive NAM section reduces the tolerance to processing pattern misalignment errors. During bar cleaving, such misalignment can result in a variation in the distance between the edge of the active region and the facet, which can lead to variable parametric performance across the bar. The NAM also provides a reduced tolerance to placement errors in die-bonding of the laser array. As the NAM region is not pumped and therefore remains cool during operation, it does not require heatsinking. This enables the packaging process to be simplified, as it is possible to deliberately overhang the NAM of a diode array with respect to the heatsink on which it is bonded. This allows for adequate heat-sinking, whilst simultaneously facilitating optimum optical access to the laser facet. This is required for optical alignment, for example to collimating optics, and also eliminates bonding issues such as solder overspill at the facets (Yanson et al., 2007).

In addition to providing high output power in a single mode, it is vitally important that the laser array provides a highly uniform spot size for each array element, in order to uniformly image the printing plate with high reproducibility. To achieve this, custom designed optical components are required, including micro-optic arrays. However it is also necessary that the laser output is consistent in terms of both vertical and horizontal far-field distributions. In order to control far-field, a novel epitaxial layer design has been developed which incorporates a 'V'-profile farfield reduction waveguide layer (Najda et al., 2005), and has been shown to reduce the vertical far-field divergence and suppress higher order mode oscillation with no reduction in the optical overlap factor. In addition, this epitaxial design has been shown to provide significantly improved tolerance to variations in epitaxial layer thickness and composition, plus variations in laser processing, e.g. etch depth variation.

Despite the advantages that are provided by QWI technology and customised epitaxial design, the achievement of the extraordinary yields required to realise commercially viable x64 array chips remains a substantial technical challenge. This necessitates a high level of attention to detail in manufacturing processes and concerted yield improvement activities. In particular, sources of defectivity in wafer growth, processing and assembly must be extremely low. By implementing such continuous process improvement activity along with a rigorous defect reduction philosophy, the levels of uniformity and performance required for a CtP laser array have been demonstrated, along with exceptionally high yield.

Figure 4 shows output power as a function of emitter number for a x64 element array, driven at 250mA CW, illustrating that there is little variation in output power across the array.

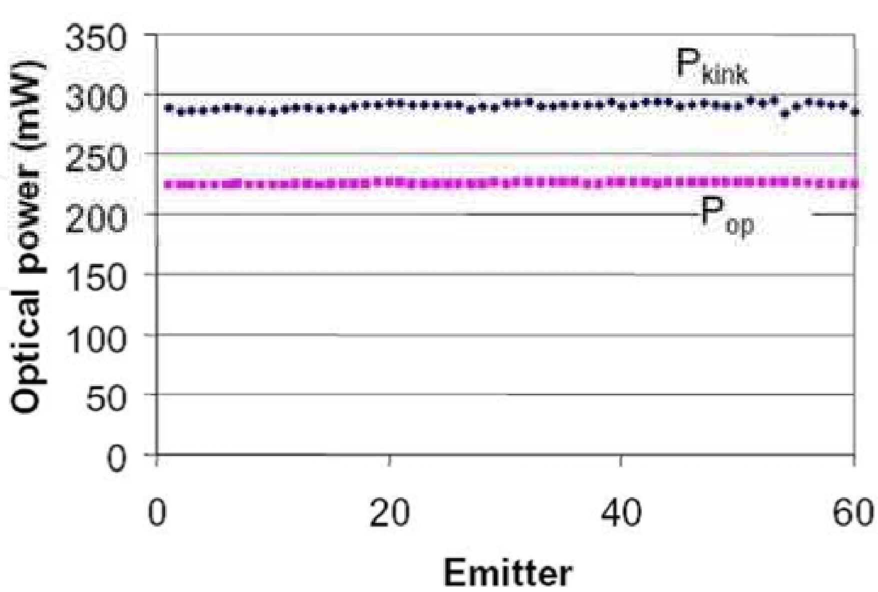


Fig. 4. Variation in output power at fixed drive current, and variation in kink power across a x64 array operating at 8xx nm.

Figure 5 illustrates the variation in far-field for both fast and slow divergence axes as a function of emitter position within the array.

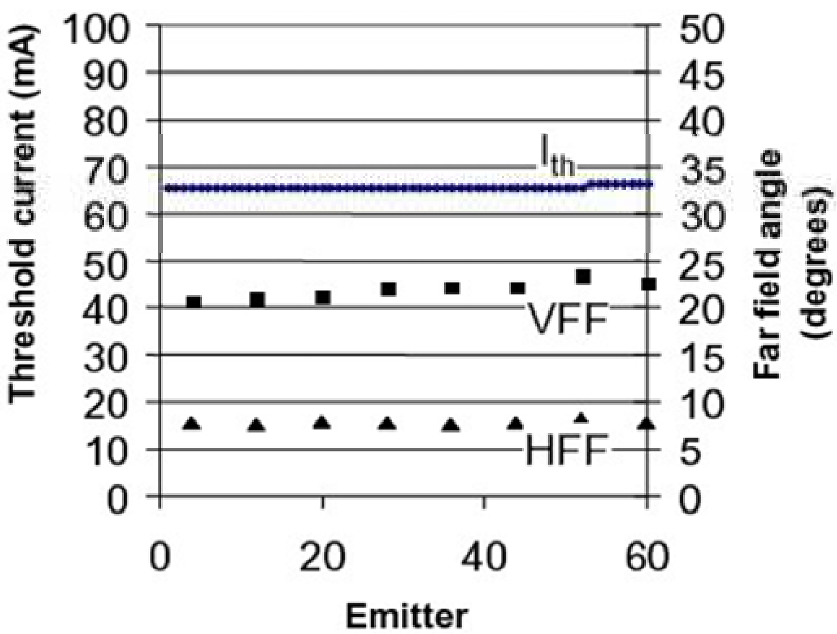


Fig. 5. Typical array uniformity in threshold current and far-field divergence (FWHM) for x64 monolithic 8xx nm laser diode array.

Although the laser array is a key part of the overall CtP system that determines the system's quality, speed and cost, it is only one component among many. The array chip itself must be integrated with the overall control system in order to effectively image print plates. The array chip in this case is integrated into a compact module that includes drive electronics and imaging optics. This is delivered in a compact and low cost platform using an ASIC to independently control the drive current to each array emitter and perform any necessary signal processing tasks. The output of the array is conditioned using custom optical components that control the image spot size on the printing plate. A single cylindrical lens optic is used to collimate the array output in the fast axis direction, while a micro-optic array having the same pitch as the laser array is used to control the output of each individual emitter in the slow divergence axis.

The packaging demands for such an array product are also extremely challenging, given the large number of arrays and high output powers required. As the laser performance is highly sensitive to any changes in the thermal environment, the packaging process must minimise local variations in heat generation and dissipation, e.g. hotspots, which would alter the array's uniformity and ultimately affect its lifetime. This requires careful packaging design in terms of the heatsink and solder materials (finishing, composition) and thorough control over the assembly process in order to ensure adequate heatsinking of the chip along with low electrical, optical and thermal crosstalk between individual array elements.

In addition to obtaining high output power in a single mode with well controlled beam divergence parameters, and high uniformity across the array, it is critical that any array deployed in CtP systems is robust and can withstand many thousands of hours of continuous operation. There is no scope for failure of any of the array channels during the lifetime of the array module, and extension of the lifetime is vital in order that monolithic arrays can compete with alternative technology. Each emitter in the array must perform within the tight system specifications throughout the long operational lifetime of the product.

Through the use of QWI, in addition to well controlled facet coating, the use of tailored epitaxial designs and tightly controlled manufacturing processes, excellent lifetime performance has been obtained for array devices operating at 8xx nm. Figure 6 shows monitored lifetest of fully-assembled array modules with each emitter operating at 200mW in a single mode over a 22,000 hour period. The data shows no catastrophic failure for any of the array channels and minimal degradation over the monitored lifetest period. Together with similar data accrued for many array modules, totalling more than 30 million device hours, the failure in time (FIT) rate is 118 (10^9 device hours), with a resultant mean-time to failure (MTTF) for an array module of > 17,000 hours. This represents an unheard of reliability for such a monolithic array, and illustrates the growing attraction for integrating monolithic arrays into next generation CtP systems.

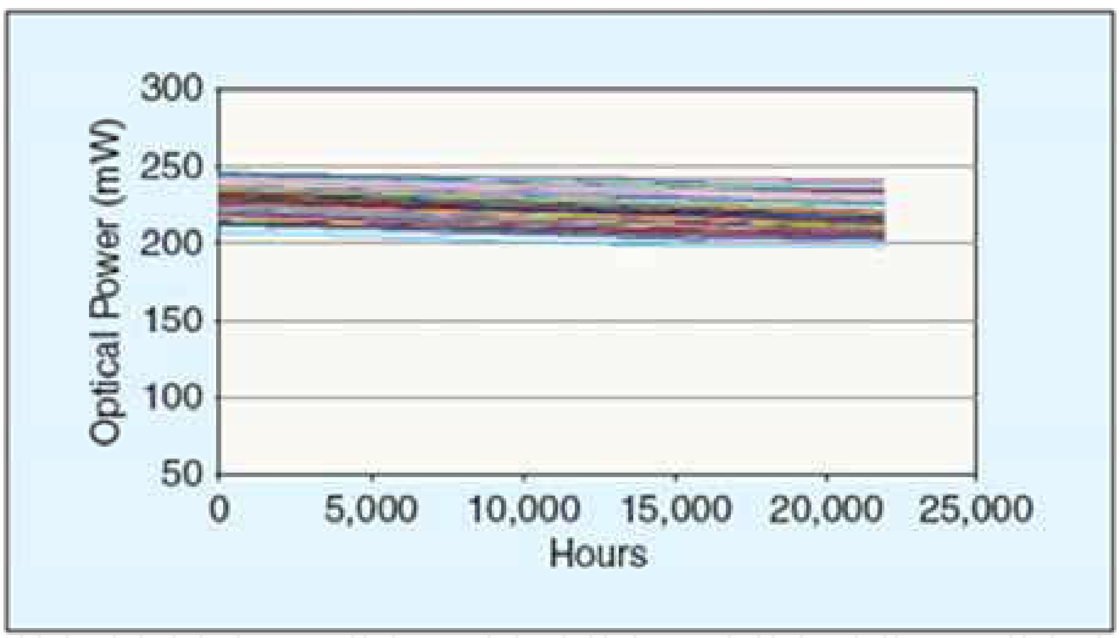


Fig. 6. Monitored lifetest data for a x64 element array operating at 8xx nm. The array module exhibits highly robust performance over 20, 00 hour CW operation.

While these devices are deployed in current CtP printing systems, the need for higher power to enhance printing speed will drive the development of next generation devices in which the output power is likely to be increased to 300 mW and beyond.

4. Digital printing applications

4.1 Introduction

Digital printing is a rapidly growing sector of the commercial print market, which until recently commanded only a small portion (~ 5-10%) of the total output of the global printing market. However recent rapid advances in the quality of digital printing presses have led to significant improvements in the speed, quality and operating costs. This means that modern digital printing presses are competitive with more traditional offset printing methods, at least for small to medium sized print jobs.

Due to the ongoing technical improvements, trends towards greater print-on-demand and variable printing, and increased ecological concerns (and associated legislation), it is anticipated that the flexibility offered by digital printing presses will lead to considerable growth within this area. Market analysts have predicted that the digital printing market will continue to grow over the next 5-10 years, by a 24% compound annual growth rate. The market accorded to digital printing might therefore be expected to reach ~30-50% market share by 2020 (Fleming, 2003).

The printing process utilised in digital printers is that of electrophotography, which is used in virtually all laser desktop printers. Figure 7 illustrates the key components used in electrophotographic printing systems.

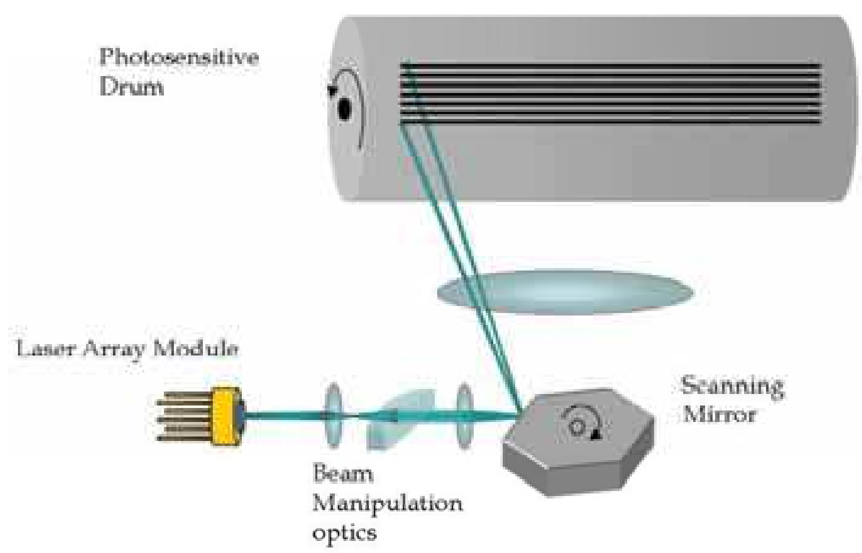


Fig. 7. Schematic illustration of the key elements of an electrophotographic printing press.

The key component in such systems is the photoreceptor, a revolving drum which is uniformly coated with a layer of charge as it rotates, via a corona wire. The charged drum is then irradiated with a laser (or LED) beam which is scanned across the drum as it rotates using a rotating polygonal mirror. The laser output is modulated so that certain areas are selectively exposed to the beam, as dictated by the data supplied to the laser drive circuit via the raster image processor. These areas are discharged, whereas areas on the drum that are not exposed remain charged, creating an electrostatic latent image corresponding to the data supplied from the editing software.

The rotating drum is then coated with positively charged toner, which adheres only to the discharged surfaces of the drum. As the drum rotates, a sheet of paper is brought into contact with it and a large negative charge is applied to the paper to transfer the charged toner particles to the paper. For colour prints, generally a composite image is formed from a combination of images produced in cyan, magenta, yellow and black. The photoreceptor must be imaged once for each of the four component colours.

Photoreceptor coatings are generally sensitive in the wavelength range from the visible to the short IR wavelengths, generally covering the spectral band 500-900 nm and therefore laser sources with this output range are used. There is an advantage in using shorter wavelength sources as the focussed spot size is smaller, allowing higher print resolutions to be achieved. However currently, cost-effective sources are only available from the red to the infra-red part of this wavelength band. The output powers required to successfully discharge a photoreceptor vary dependent on the type of photosensitive coating used, but is typically under 10 mW.

Key drivers in the development of modern digital printing presses are the desire for increased printing speed and increased printing quality.

The printing speed can be enhanced by scanning several independent laser sources across the drum simultaneously. In this way several lines of data can be written simultaneously, thereby reducing the time it takes to fully expose the drum and complete a given print job. Rather than utilising multiple discrete lasers with the complexity and cost that this would incur, the preferred approach is to employ a monolithic laser array to image the photoreceptor. In order to achieve a high resolution, and thereby improve print quality, the array pitch should be minimised. In conventional Fabry-Perot laser arrays the minimum pitch is controlled by the limitations of wire bonding. For standard wire bonding technology, a ball bond is formed that is roughly three times the wire diameter, setting a minimum wire-bond pad dimension of 45 µm. For conventional double-trench ridge waveguide devices, the minimum trench width is ~ 25 µm. Taking these dimensions into consideration, together with the expected accuracy of bond positioning, the minimum pitch that can generally be achieved using a p-side up individually addressable laser diode array is ~ 60-80 µm. Such laser diode arrays are commercially available and used in modern digital print systems.

The application requires very tight control over a number of device characteristics, including output power, resistance, crosstalk, farfield, polarisation and packaging smile. In order to produce a high quality image, it is necessary that there is minimal variation in any of these parameters across an array. This requires a very strict adherence to design and manufacturing tolerances, not only in the epitaxial growth and device fabrication stages, but also in any packaging processes, to ensure that effects of strain induced during chip bonding and any optics attach steps are minimised.

Despite the commercial deployment of fine pitch (~ 60-80 µm) laser diode arrays in digital printing applications, future generation presses will require improved printing speed and increased resolution. This has spurred the development of ultra-fine pitch laser arrays, (~ 20 µm pitch) requiring the development of novel components to ensure each array element can be independently driven. Such an array pitch is difficult to realize in an individually addressable array and requires the development of novel fabrication and/or laser bonding techniques.

A number of approaches have been conceived to produce an individually addressable ultra-fine pitch laser array, including the use of p-side up approaches, such as air bridge technology to provide individual electrical contacts, and specially designed contact pads. However these have certain disadvantages surrounding their uniformity, overall performance and manufacturability, and are unlikely to provide a highly scalable solution for developing a large element array. Until recently, commercially available array sources have been limited to x4 and x8 arrays emitting at 780 nm.

Recently, an ultra-fine pitch (20 μm) visible laser diode array has been demonstrated that utilises a p-side down flip-chip bonding approach to enable the individual array elements to be driven independently. This array incorporates 22 independent emitters housed within a custom designed butterfly package. Using a p-side down array provides increased scope for scaling the size of the array to a higher number of elements, but also provides additional benefits, in reducing thermal cross-talk between adjacent array channels.

4.2 Submount design and manufacture

The design and manufacture of suitable submounts to enable p-down bonding together with individual addressability has been key to achieving such a fine pitch laser array with many elements. In order for the array to be individually addressable, it is required that the ceramic submounts possess an electrical circuit that enables each individual array element to be bonded to a separate electrical track. This involves patterning the submount to provide independent current injection paths for each laser element, on the same 20 μm pitch as the laser array. A narrow track-and-gap arrangement (of the order of 10 μm) is required for such interconnects. Also, to enable the bonding process, it is required that the electrical tracks on the ceramic submounts are coated with a eutectic solder. The manufacture of such a complex submount with narrow solder/metal tracks (~10 μm) is beyond the current capability of most commercial suppliers. Therefore the realisation of a p-side down ultra-fine pitch array requires the custom design and development of a suitable submount.

This has been achieved using standard photolithography and etch processes on metal layers deposited on a BeO substrate. Design of the custom array submount is illustrated in Figure 8. This shows the conductive tracks with a width of 10 μm, laid out on a 20 μm pitch in the chip bonding region. In this region the electrical interconnects are coated with a AuSn layer to facilitate the flip-chip bonding of the laser to the submount. Away from the die-bond area at the rear of the submount, the conductive tracks fan-out, increasing their effective pitch, then terminate in a staggered array of wire-bond pads with a 70 μm pitch that is compatible with the limitations of the wire bonding process.

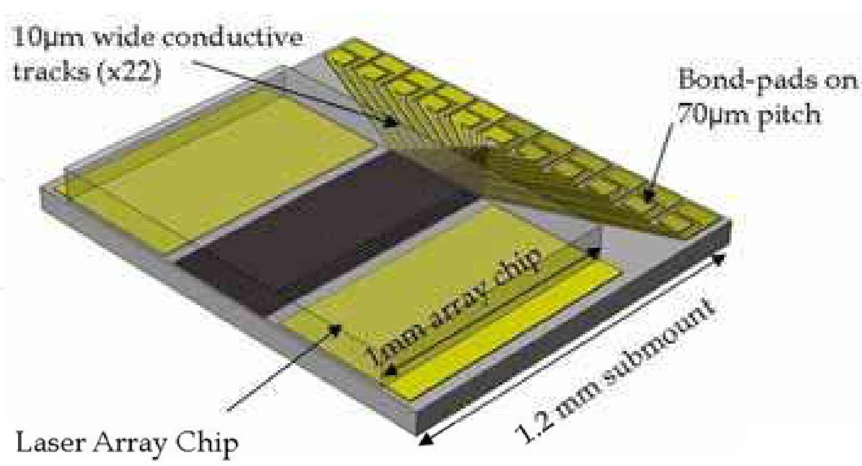


Fig. 8. Illustration of the submount design used to demonstrate p-side down ultra-fine pitch array performance.

The initial step in the submount manufacture involves the blanket deposition of a Ti/Pt/Au layer used to provide the electrical contact. Then, a novel jet vapour deposition™ (Gorski & Halpern, 2003) process is employed to deposit a layer of 4-5 μm thick AuSn solder on the metallised regions. Photolithography combined with ion milling is then used to define the 10 µm wide tracks with 10 µm separation.

4.3 Chip design

Figure 9 is a SEM image illustrating the array chip design. Each individual element is a single-mode ridge waveguide laser formed by dry etching, with a 2 µm ridge width. The array is fabricated in a 3″ wafer, employing a standard separate confinement heterostructure (SCH) GaInP-AlGaInP red laser design, operating in the wavelength range 630-680 nm. Between the array elements, deep isolation trenches are etched into the substrate to increase inter-element resistance and thereby reduce electrical crosstalk.

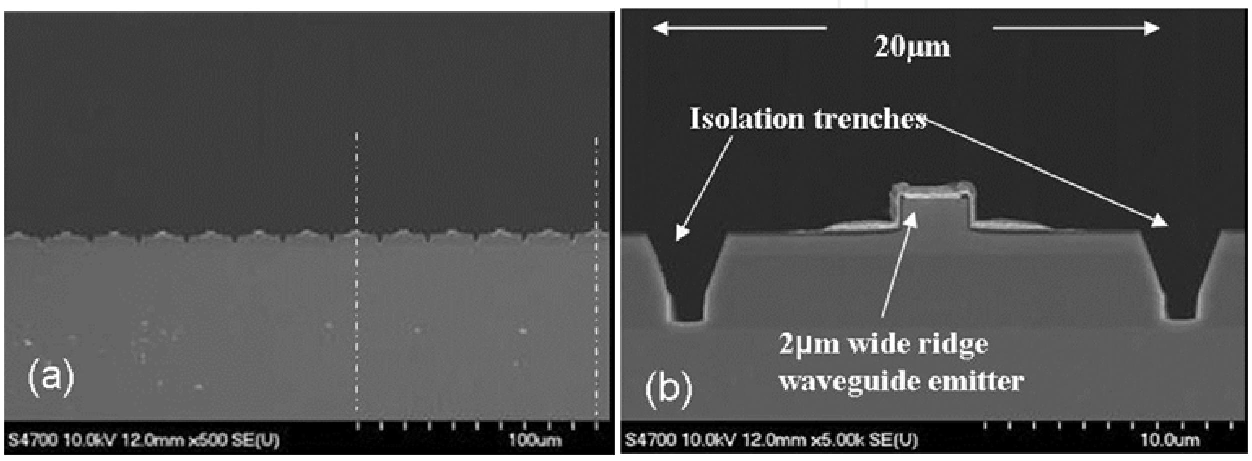


Fig. 9. SEM images of a 20µm pitch red laser array, showing (a) x500 magnification of half the array chip, (b) x5000 magnification of a single emitter within the array.

4.4 Array die bonding

The array chips were die bonded onto the customised submounts, by first carefully aligning each of the ridge waveguides with its associated submount track. The chip was then placed in contact with the submount and the assembly taken through a heating cycle up to ~ 320 ºC to reflow the solder and form a eutectic bond. Flip-chip bonding was performed using a Palomar 3500-II die-bond tool which enables precision alignment of the array chip to the submount. An illustration of the chip-carrier alignment prior to bonding is shown in Figure 10.

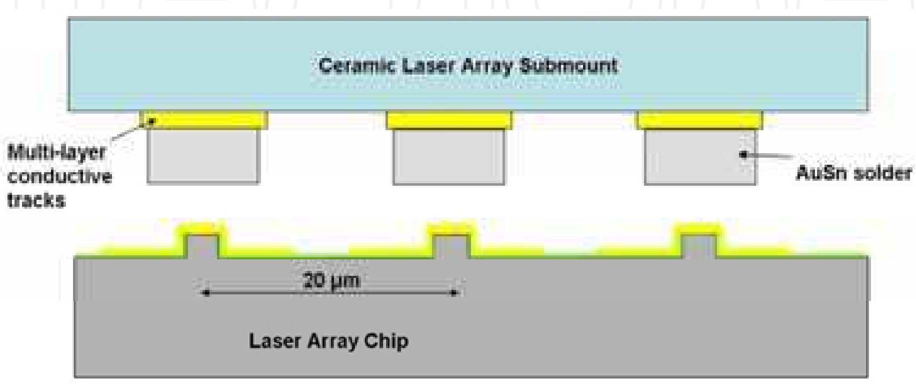


Fig. 10. Schematic illustration of the flip-chip die bonding process used to manufacture a 20 µm monolithic laser array.

The array on submount sub-assemblies were then bonded onto a second larger ceramic (commercially available) specifically designed for integration of p-side up array chips in a butterfly package. These were then integrated into the 26-pin butterfly package with a hermetically sealed sapphire window (Kowalski et al, 2008).

4.5 Array test

Bonded devices were tested CW to determine key characteristics for each emitter, including threshold current, slope efficiency, far-field, resistance, and uniformity across the array. Figure 11 shows LI curves for all 22 elements of a typical array module, illustrating the high level of uniformity in LI performance. The lasers exhibit far-field divergence angles of 8º in the slow (horizontal) axis and 40º in the fast (vertical) axis.

Although it is vital that a single laser emitter conforms to the system specifications in terms of its individual performance, the overall performance of the array is determined by how the different array elements interact with one another – the array crosstalk, which is a primary parameter determining the ultimate image quality. When a number of laser elements are operated simultaneously, their close proximity leads to significant alteration in output power characteristics, e.g. reduction in slope efficiency, due predominantly to the thermal crosstalk between devices. By utilising a p-side down approach described above, the junction temperature for a given emitter is reduced due to the improved heat dissipation. This leads to a significant drop in thermal crosstalk.

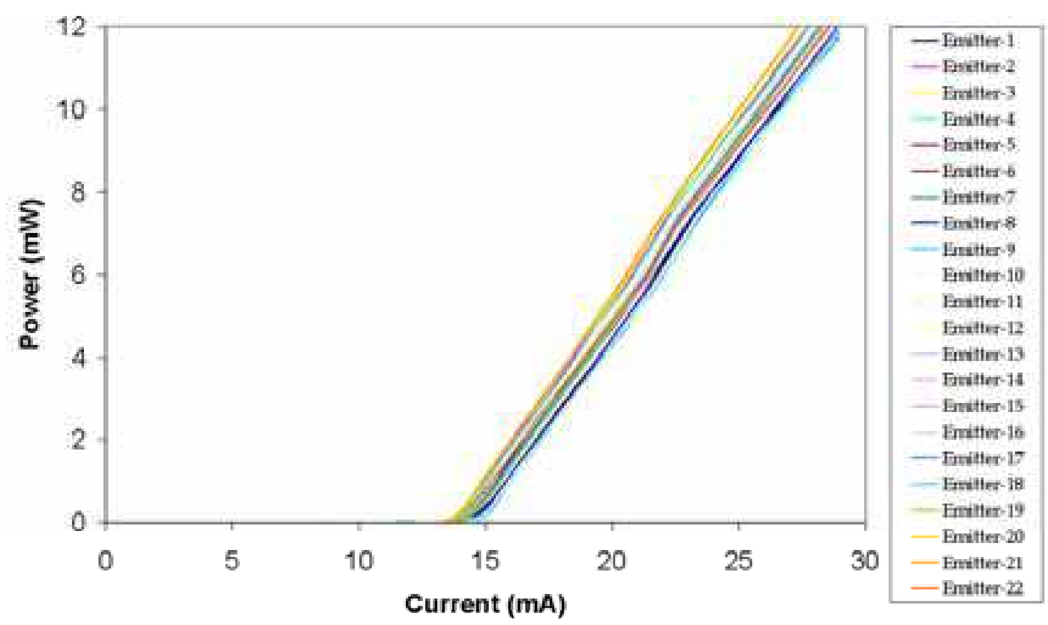


Fig. 11. LIV curves obtained for fully packaged 20 µm pitch x22 element laser array, illustrating high uniformity achieved in output power.

Crosstalk is determined by measuring the time-varying output from the array when all elements are initially powered up to their operational drive current.

Figure 12 shows a typical cross-talk measurement for a fine-pitch red laser array in which the integrated output power over all channels is measured as a function of time following initial power-up. The measured power droop after ~ 1s is 15%, in-line with application requirements.

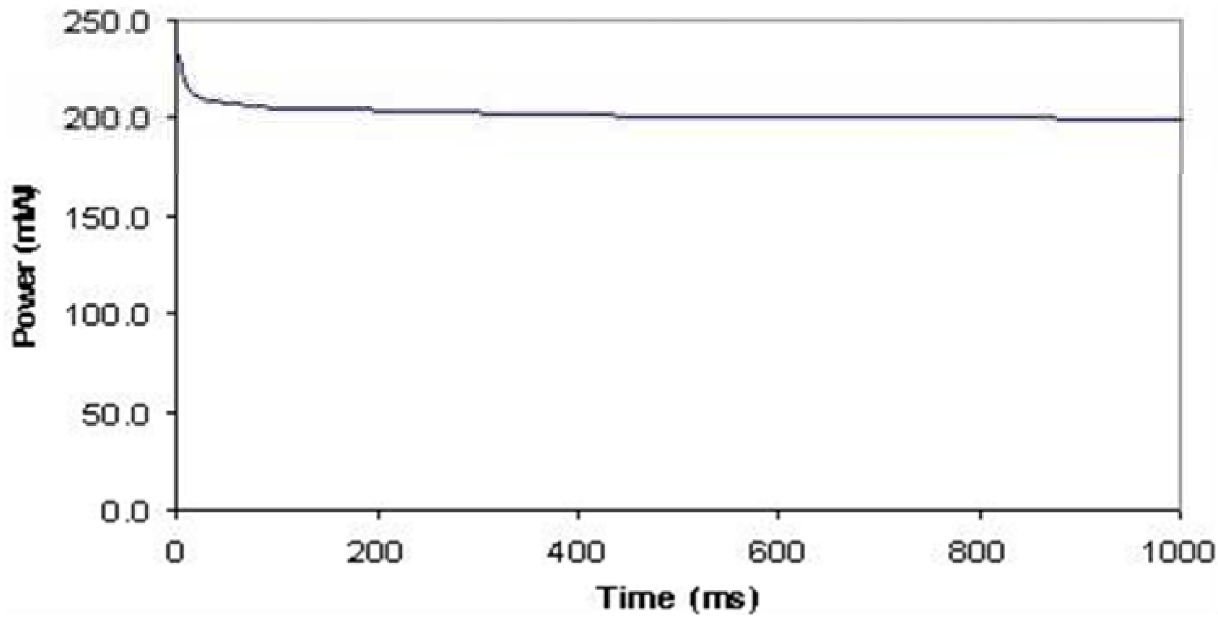


Fig. 12. Measured power-droop across fully packaged array module.

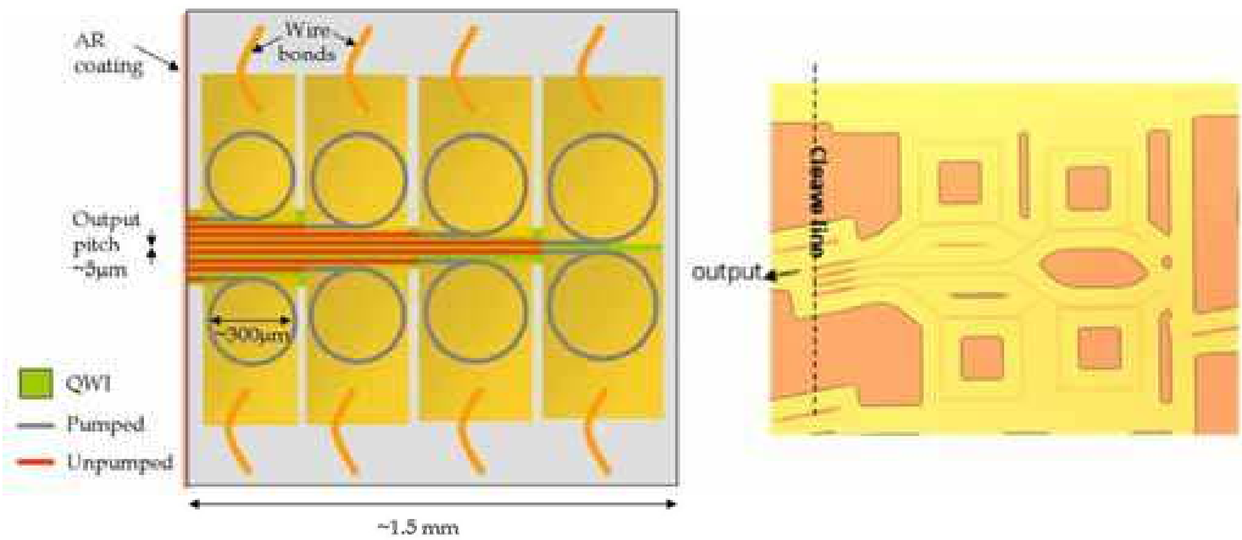
Reliability measurements for these ultra-fine pitch modules are currently limited to burn-in data accrued over 500 hrs operation in application mode. Over this time period no device failures were observed, whilst power degradation was negligible. Wider pitch red laser arrays produced in similar material and operated at higher drive currents (equivalent to greater thermal and optical stress than the finer pitch module) have been placed on monitored lifetest for several 1000 hrs with no sudden failures and a typical degradation of 2%. This illustrates that the product is robust and reliable at the operation levels likely to be required for future generation digital presses.

4.6 Alternative array designs

While the above approach has demonstrated excellent performance, a number of alternative means to produce ultra-fine pitch laser arrays have been proposed and partially demonstrated. An alternative approach to arraying the active laser elements close together can be achieved using ring laser technology, in which a series of ring lasers are arrayed such that their output waveguides are arranged in parallel with close proximity to each other.

The device architecture is illustrated in Fig. 13 (a). This has a number of potential advantages in that the effective pitch size can be further reduced to the order of 5 μm or less. As the output waveguides are passive, the inter-element crosstalk should be significantly reduced. The only notable disadvantage may be the need to significantly increase the size of the chip in order to accommodate the array of active ring elements, and this may ultimately limit the number of array elements that can be integrated into a single fine-pitch array.

Work on such a device has been carried out through the IOLOS program, a sixth framework program funded by the EU to explore various physical phenomena occurring in ring lasers and their applications. Work on ring laser arrays has been limited, but initial attempts to realise a x4 element array have been successful. Fig. 13 (b) shows a microscope image of a x4 ring laser array. Further work is required to improve the design and processing in order to reduce bending losses in the ring elements, which will then be used to determine the performance compared to a similar Fabry-Perot array chip and assess potential for further pitch reduction and scalability.



(a) (b)

Fig. 13. (a) Illustration of chip layout for ultra-fine pitch array of ring lasers and (b) microscope image of actual chip, using square rings with etched turning mirrors.

Another approach towards providing laser array solutions for future generation digital print systems is to use VCSEL arrays. Using VCSEL elements it is possible to construct 2-D arrays and thereby enable higher printing speeds to be attained. Such lasers have been demonstrated operating at ~ 780 nm, but although relatively large arrays of 32 elements have been fabricated, their output power is curently limited to 3 mW with array pitch of 30 μm (Mukoyama et al. 2008). Nevertheless, VCSEL arrays do provide another route towards fulfilling the requirements of future generation digital print presses.

5. Coding and marking applications

5.1 Introduction

Coding and marking is a relatively low-resolution application, which generally implements low-technology and low-cost solutions. However, within this sector, laser sources are becoming more desirable compared to existing solutions, e.g. thermal and inkjet printers. The emergence of laser sources has been driven in response to the requirements of customers within this market who require more flexible printing systems, including a print-on-demand capability, together with lower running costs. This is led by a number of factors, including increasingly stringent health and safety regulations, and the need for improved traceability of product, optical identification of goods at the point of sale and counterfeit security measures. Marking systems, by definition, require a high printing speed together with high reliability; whilst, in addition, there is a strong desire to reduce costs through a reduction in downtime and maintenance, and a decrease in consumable expenditure.

Within certain markets there is a recognised need to introduce print-on-demand technology – the ability to instantaneously alter the content of any labelling to reflect changes in product look-up-codes, bar codes, and packing date. In addition, within the food production market, following a number of highly publicised food scares, there is increasing demand for implementing greater detail in product traceability and tracking. A print-on-demand capability provides significant advantages to the producer and retailer in reducing label inventory and consumables cost, whilst also providing improvements in operating efficiency.

At present there are a number of competing technologies within the coding and marking sector, including:

- Inkjet printing
- Thermal transfer
- Scanning laser marking

Each printing solution possesses their own relative advantages and disadvantages relating to the need for rapid printing with high quality and low running costs.

Inkjet solutions are widely available and relatively low cost. However, although there is no direct contact between the print-head and the print medium, there is a tendency for the inkjets to become clogged by dirt and debris, particularly in poorly controlled environments such as packing houses. Such blockages can lead to incomplete printing, which, e.g. in the case of bar-code scanning, is unacceptable. Also, although inkjets are capable of sustaining a high printing rate there are associated restrictions relating to drying time, in order that the ink is not smudged and made illegible. Ink usage is also unsuitable in many production environments, e.g. food packing, due to potential cross-contamination with product. In addition, many inks are solvent based, and can therefore be considered as atmospheric pollutants, whilst spillages can lead to ground water contamination. As a result, there is increasing restriction placed on the ink usage in certain environments.

Thermal transfer systems use a consumable ribbon, which is heated to transfer wax or resin to the substrate. The ribbon itself is relatively expensive and the process requires a finite cooling time, which can significantly reduce print quality at higher printing speeds. However the key disadvantage of thermal printing systems is the direct contact required between the thermal printhead and the marking substrate, which tends to reduce the reliability of the printing components, requiring frequent maintenance together with associated costs and management.

Both solutions rely on heavy use of consumables, which are undesirable on the production line and which require careful inventory and cost control. Neither solution is well-suited to applications requiring non-planar surfaces.

In contrast, laser marking overcomes many of these disadvantages, allowing consumables to be removed from the production environment, simplifying consumable management and providing a high speed solution with low contamination risks. One of the main advantages is the non-contact nature of laser marking, which brings increased printing speed together with improved reliability, as mechanical wear-and-tear is eliminated. Another advantage is that laser marking presses are effectively ink-free; reducing consumable costs and relaxing many environmental and contamination concerns.

Single beam solutions are widely used in laser marking applications, and until recently have utilised a single high power (~10-30 W) laser source, e.g. CO_2 or solid-state laser, which is scanned across the substrate using galvanometer mirrors. The combined system can be cumbersome and expensive and the requirement for scanning a single source tends to limit the ultimate printing speed that can be attained. Also, CO_2 lasers are electrically inefficient, which raises running costs, and in many applications the marking is performed using an ablation approach, which can lead to particulate generation, a particularly undesirable feature in production environments.

A more recent development, which provides a more elegant solution, has again involved the use of laser diode arrays. In this case the laser diode arrays act as a source for direct, single-pass marking, which does not require scanning of the laser source. Instead, by using a laser array, multiple lines of data can be written simultaneously using a marking medium which incorporates a light sensitive coating. This generally utilises pre-existing thermochroic coatings in which a colour change is induced in the print media by the heat generated through absorption of laser energy, usually at infra-red wavelengths (~700-1500 nm). Figure 14 illustrates the basic mechanisms involved in this method of laser marking.

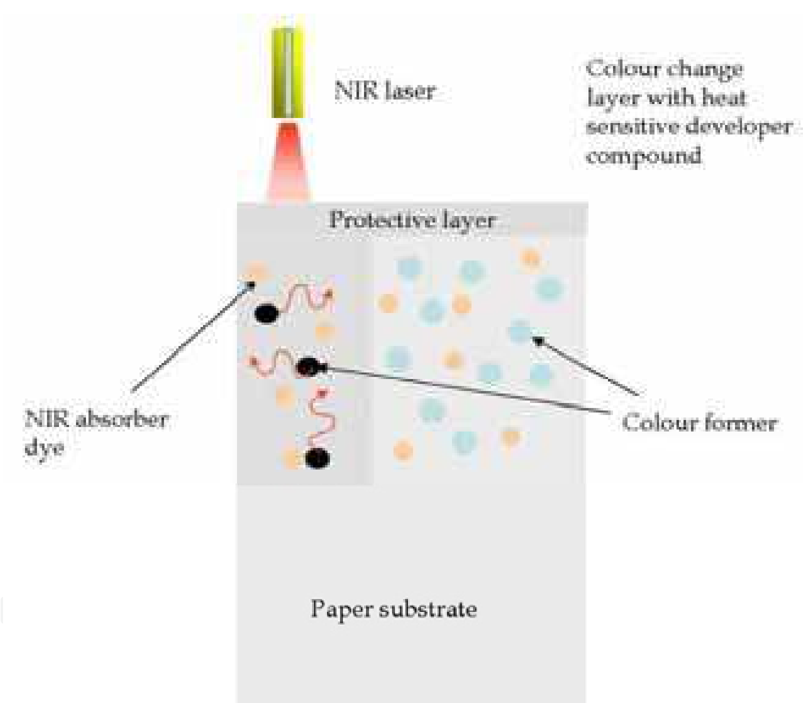


Fig. 14. Thermally driven colour change induced by laser absorption in thermochroic print media.

This provides a high speed, low cost approach, with high print quality, no consumable costs and high reliability, as there is no contact between the print media and the marking laser. This solution is particularly suited to clean environment production lines, as required in food and pharmaceutical industries, where potential contaminants, such as ink, are highly undesirable.

Laser diode arrays can also address emerging trends to develop secure coding and marking capabilities for brand protection and counterfeit prevention measures. In these applications, they can be used to encode data which is concealed in sub-surface layers, for example as a layer embedded within a laminated package. In this way it is possible to add further tamperproof coding, providing additional protection to forgery.

The following section will describe the commercial development of a direct laser marking system which provides a print head with a width of up to 75 mm with 203 dpi resolution. This consists of ~ 300 individually addressable laser elements, on a constant pitch of 125 µm, comprising a number of separate array chips, each containing ~ 100 laser elements.

5.2 Laser diode array solutions in coding and marking

Achieving such a laser diode array cost effectively represents a significant technical challenge. The print width needed for a single pass marking system requires widths of several cm. Print speeds required are of the order of 1.5 m/s, determined by the sensitivity of the print medium and the output fluence of the laser.

In order to provide a laser diode array solution for this market place, it is essential to understand the physical interaction of the laser source with the print medium. This requires accurate knowledge of the physical properties of the print medium so that an appropriate imaging laser can be designed. A good understanding of the absorption coefficient for the imaging laser, the thermal properties of the coating and its thickness is also necessary.

However the key technical challenge is the construction of an array with a pitch of the order of 100 µm which comprises up to several hundred individually addressable elements. This is a considerable challenge to meet with current manufacturing capabilities. Forming a single monolithic laser diode array of several cm width is not practically feasible with currently available wafer processing capabilities. It would require the growth of large diameter III-V substrates together with compatible processing equipment and unrealistic device yields.

Nevertheless, it is possible to manufacture a print-head in which the laser diode array comprises a number of separate monolithic array chips. In this case, each array chip can be fully tested and screened prior to subsequent packaging steps. Using this approach, large (75 mm) print heads have been demonstrated, comprising up to 300 emitters, each producing up to 500 mW output at 980 nm, with an inter-element pitch of 125 um, equivalent to 203 dpi. The product, known as a DLAM (Direct Laser Array Marking®) has been developed by Intense Inc. to meet specific needs within the food labelling market. Similar technology has also been used to realise super-arrays comprising up to 800 elements for a range of print and other applications.

For this product, the benefits of QWI technology are again essential in enabling the requisite output power to be sustained with the necessary levels of reliability. The additional benefits provided by incorporating long NAM sections into the laser cavity, in relaxing processing and packaging tolerances, are also an important contributor to the success of this approach. Again, successful development of a cost-competitive multiple-array product requires an extremely high single chip yield to be sustained throughout the wafer fabrication process. This requires high uniformity and conformity to specifications through all process steps and a rigorous effort to minimise wafer defectivity levels throughout the manufacturing line.

The primary engineering challenge, however, is in constructing a 'super-array' comprising several discrete monolithic array chips, aligned in such a way that the inter-element array pitch is maintained from one array chip to another. This requires extremely accurate alignment between chips before and during the die-bonding step, to ensure that the edge emitters of all adjacent array chips maintain the same pitch as that within each monolithic array, as illustrated in Figure 15.

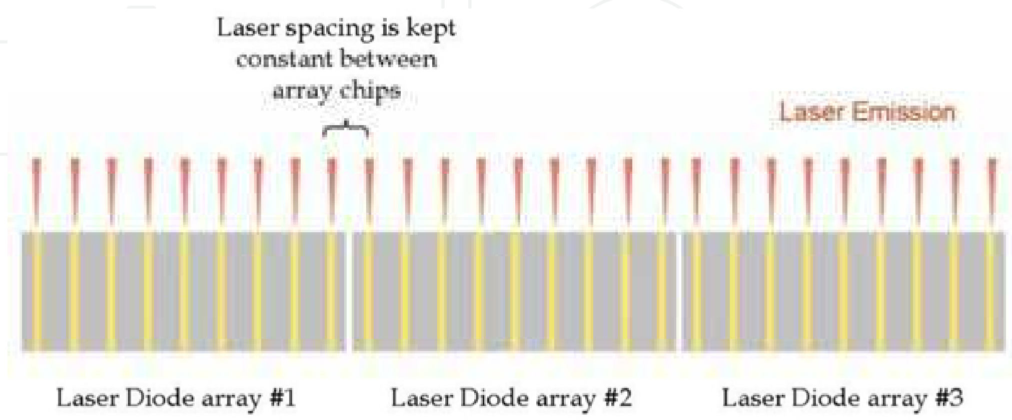


Fig. 15. Schematic layout of super-array comprising 3 monolithic array chips.

In order to achieve this, the edge emitters on each array chip are arranged close to the cleaved edge, providing improved tolerance to cleave variations. New high-precision die-bonding techniques have been developed to enable multiple chips to be bonded in close proximity (+/- 3 um) to one another as illustrated in Figure 16. The bonds are formed using hard eutectic solder, without compromising the bond characteristics, enabling optimum thermal performance and reliability to be achieved. A novel chip layout is also required to ensure separate wire bond pads are provided for each individual emitter within the array, including the edge emitters.

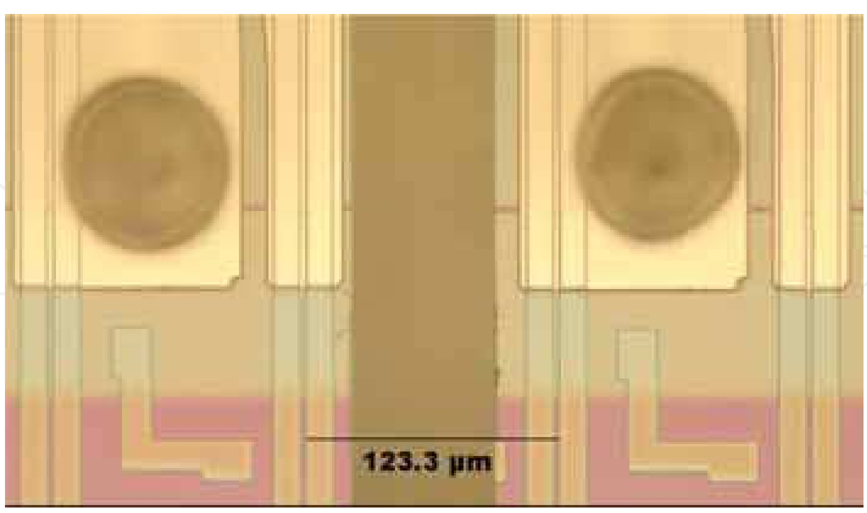


Fig. 16. Microscope image showing the precision alignment between two neighbouring array chips within a DLAM array.

Figure 17 is a photograph image of a laser print-head comprising a number of arrays 'stitched together' to form a 'super-array'.

Fig. 17. Photograph of a DLAM 'super-array' comprising a number of monolithic array chips bonded on a common carrier, with the pitch between arrays maintained across the entire print head.

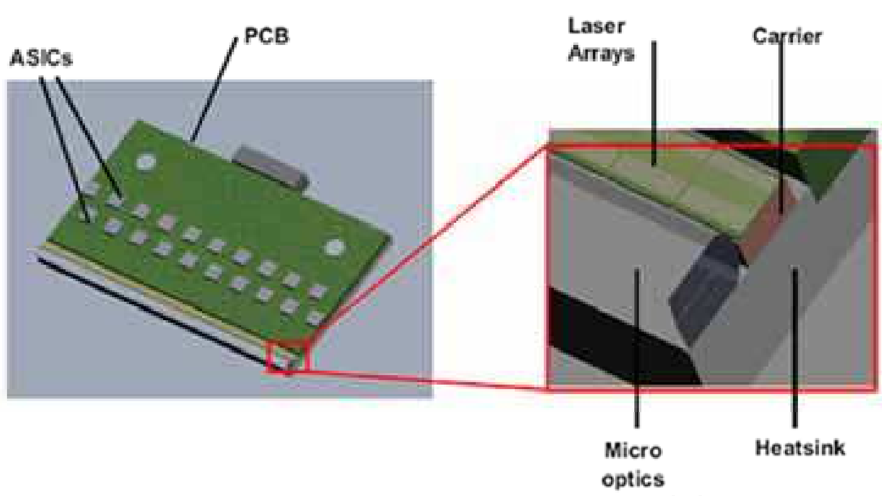


Fig. 18. Illustration of a DLAM module with 'super-array' chip bonded to a carrier and mounted on a heatsink with ASIC and micro-optic array.

In order to minimise packaging induced strain, the laser chips are mounted onto a thermally conductive substrate fabricated from material with a closely matching thermal expansion coefficient. This is integrated into a custom designed submount as shown in Figure 18. This provides a heatsink and integrated ASIC which controls the current supply to each individual array element. In addition, a custom designed micro-lens is incorporated to provide adequate beam manipulation in line with system specifications. The alignment, in particular of the micro-optics to each laser element is critical, placing stringent demands upon the flatness of the substrate and the overall assembled module. This has required extensive process development and refinement to enable highly precise alignment between the system components. Additional imaging optics are incorporated into the package to provide the required spot size characteristics at the imaging plane. The optics themselves are designed to provide a high depth of focus, producing good image quality over a range of relative displacements to the print media. They also impart added flexibility to the overall print-head characteristics, allowing different application requirements to be addressed by tuning the print-width, resolution and power density.

Figure 19 shows the measured L-I curves for each of the 270 elements of an entire DLAM array, illustrating the high uniformity achieved in output power across the array.

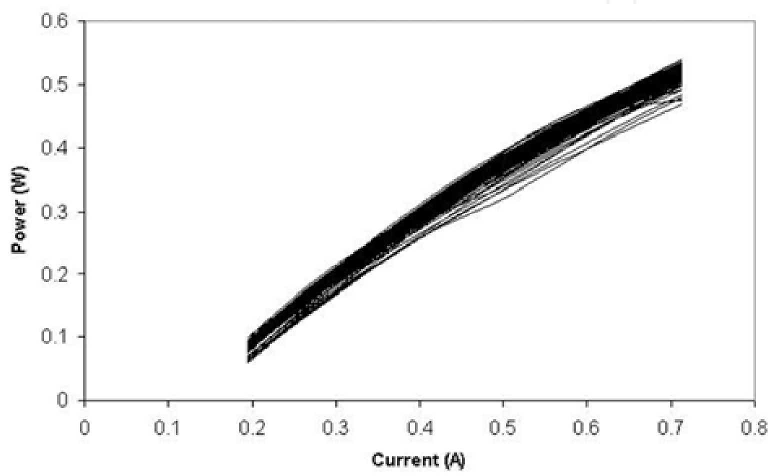


Fig. 19. L-I curves for 270 elements comprising a super-array operating at 980 nm for coding and marking applications.

DLAM array products have undergone successful application trials and are currently deployed in food labelling applications. Given the advantages provided, there is likely to be a growing market for laser array products within coding and marking, however one where the demands on the product are likely to grow in order to increase printing speed and quality whilst reducing overall system cost.

6. Conclusions

Laser diode arrays provide an increasingly attractive solution for a range of technical issues that have to be overcome in existing and future generation printing presses. As a result of the advantages they provide over existing non-laser and single laser solutions, their use within commercial printing is continuing to grow and expand into different areas of the commercial printing market. Laser arrays are now widely used in high resolution CtP applications, and their deployment in highly versatile variable printing applications, e.g. digital printing and coding and marking is becoming more widespread.

QWI has proven an essential tool in the development of high power laser devices for printing applications. It has provided the technological breakthrough that has made large monolithic laser diode arrays a commercially viable product by enabling the required yields and reliability to be realised.

As the demand for laser diode arrays expands, the demands placed on the technical performance and pricing will continue to grow, requiring the development of increasingly inventive and novel diode array solutions. The expected growth will nevertheless provide a substantial business opportunity for laser diode manufacturers and spur competition between suppliers to provide technically superior and cost effective products.

7. Acknowledgement

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8. References

Fleming, M. (2003), "Armed with competitive technology and a more mature sense of the market, suppliers and print providers are turning digital printing into a high-volume business", Digital Output, May 2010, Available from: <http://www.digitaloutput.net/content/contentct.asp?p=101.>

Global Print (2009), Available from: http://www.global-print.org/gpmarket/

Gorski, M. (2003). Halpern, B., "Jet vapor deposition for Au/Sn solder applications" Advanced Packaging. Vol. 12, no. 2, pp. 31-32,34.

Kowalski, O. P. (1998). Hamilton, C. J., McDougall, S. D., Marsh, J. H., Bryce, A. C., De La Rue, R. M., Vögele, B., Stanley, C. R., Button, C. C. & Roberts, J. S. "A universal damage induced technique for quantum well intermixing" *Applied Physics Letters* vol.72 no.5 1998 pp.581-3

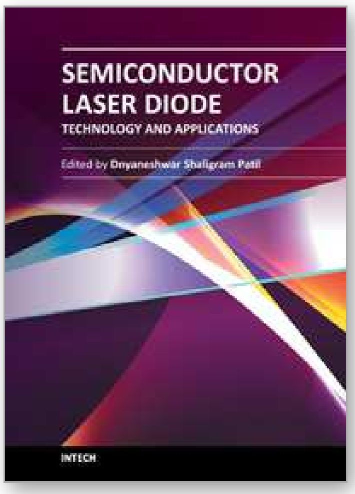
Kowalski, O. P. (2008). McDougall, S. D., Qui, B., Masterton, G. H., Armstrong, M. L., Robertson, S., Caldecott, S. & Marsh, J. H. "Ultra-fine pitch individually addressable visible laser arrays for high speed digital printing applications", *Proceedings of the SPIE*, vol.7230, pp. 72301J-08, 2009

Mukoyama N. (2008). Otoma, H., Sakurai, J., Ueki, N. & Nakayama, H. "*VCSEL array- based light exposure system for laser printing*", *Proc of SPIE* Vol.6908, 6908H-11 (2008)

Najda, S. P. (2005). Bacchin, G., Qiu, B., Smith, C. J. M., Vassalli, O., Toury, M., McDougall, S. D., Hamilton, C. J. & Marsh, J. H. "Very large arrays of individually addressable, high power, single mode laser arrays in the 800-1000nm wavelength range obtained by quantum well intermixing techniques", *Proceedings of SPIE*, Vol. 5738, pp 33-39

Tamaki E. (2004). Hashimoto, Y. & Leung, O. "Computer-to-plate printing using the Grating Light ValveTM device" *Proceedings of SPIE*, vol. 5348, 5348-08, p. 89

Yanson, D. (2007). Marsh, J. H., Najda, S. P., McDougall, S. D., Fadli, H., Masterton, G., Qiu, B., Kowalski, O. P., Bacchin, G. & McKinnon, G., (2007) "High-power, high-brightness, high-reliability laser diodes emitting at 800-1000 nm", *Proceedings of SPIE* Vol.6456, 64560L



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