Photonic Integration: the other wavelengths, the other material systems, the other applications

Richard M. De La Rue

Optoelectronics Research Group, Department of Electronics and Electrical Engineering,
University of Glasgow, Glasgow G12 8QQ, Scotland U.K.

Abstract: Recognising the importance of hybrid integration, alongside the prospects offered by the use of monolithic integration, this presentation will range widely over the topic of photonic integration. It will also range widely over the optical spectrum, as implied by the title of this paper. While the words 'other wavelengths' may suffice for some purposes, the recognition that these words also automatically suggest other material systems (than silicon or indium phosphide) and other applications – than fibre telecomm – will shape the presentation.

Introduction

Because of the importance of fibre-optical telecommunications for the infra-structure of the world, it is often assumed by those working in the corresponding parts of integrated photonics research and development that the most important activity is oriented towards telecommunications. It is certainly of great interest to observe how both silicon photonics and indium-phosphide based photonic integration have progressed in recent years. We may also believe that, despite the current wave of financial incompetence that has struck some of the leading economies in the world, there will be a serious revival in fibre-based telecoms development, particularly at the LAN, MAN and FTTH levels.

Working to a title that includes 'the other wavelengths' has the primary problem that the territory is embarrassingly rich. We have the whole of the visible spectrum to consider – and can now legitimately include a substantial part of the ultra-violet spectrum in our territory of interest. Likewise, going only a short way beyond the fibre telecom wavelength bands around 1.55 μm opens up the longer wavelength parts of the near infra-red spectrum, before we proceed to consider the mid- and far- infra-red.

Hybrid Integration: Display Devices and Laser Pointers

Taking a broad view of the meaning of photonic integration, and allowing for various levels of hybridity, opens up, for example, the vastly important area of display devices - and the much less important territory of the laser pointer.

The liquid crystal display (LCD) is now all-pervasive. Although the plasma-display provides significant competition, it is primarily the LCD that is now used in place of the cathode-ray tube for displays in consumer optoelectronics such as televisions and computer monitors. The LCD, on all size-scales, is intrinsically a strongly hybrid photonic/optoelectronic component. Although molecularly oriented liquid crystal films lie at the heart of the display, the active layer must be sandwiched between transparent plates of glass, which additionally support patterned conductive layers, colour selective and polarising films - and arrays of driver transistors in thin-film (i.e. amorphous silicon) format. Furthermore, the approximately white light source required for the LCD must be provided separately – and distributed as evenly as possible across the entire active display region. Edge-mounted sources that distribute light via leaky/scattering waveguide layers provide one route to LCD illumination. A possible alternative approach uses back-lighting from an array of discretely distributed high-brightness white or UV light-emitting diodes (LEDs). The latter approach offers an interesting opportunity for the application of photonic crystal or photonic quasi-crystal light extraction structures integrated into the LEDs, with the multiple objectives of enhancing the extraction efficiency and the overall 'wallplug' (conversion) efficiency of electric power into useful light – and of controlling the shape of the emitted beam of low-coherency light.

The blue semiconductor diode laser, as exemplified by its application in Blu-ray disc consumer electronics, has become the pre-dominant species of laser - in terms of absolute numbers manufactured and sold, being produced annually in quantities measured in hundreds of millions. It is by no means certain that optical disc-based memory technology will prevail, because of trends in purely electronic storage, magnetic disc memory and direct (streaming) production of audio and video information via the internet, but it seems likely that the blue semiconductor diode laser, followed fairly closely by the ultra-violet semiconductor diode laser will be used in a progressively wider range of applications. Integration of grating structures to realise DFB and DBR lasers in the blue and ultra-violet spectrum will make it possible to have accurately controlled emission wavelengths, together with a measure of tunability.

The laser pointer provides an interesting example of a mass-produced device that makes use of clever hybrid integration techniques at the miniature/micro-optics level. We may characterise the laser pointer as being a compact device that produces coherent light in the visible part of the electromagnetic spectrum, has good beam quality - and low enough electrical power consumption and sufficiently high efficiency to be conveniently operated in hand-held mode.

While currently available red laser pointers use direct conversion of electron flow into photons, i.e. injection electroluminescence, in red light emitting semiconductor diode lasers, green laser pointers use a more complex combination of components. For green laser pointers, the process begins with light generation at approximately 850 nm in an infra-red emitting semiconductor diode laser, followed by (frequency) down-conversion to 1.06 μm through pumping of a neodymium-doped (Nd-doped) crystal chip and then second harmonic generation (SHG) of green light at 530 nm, via a chip of potassium titanyl phosphate (KTP). The greater complexity involved in the green laser pointer does indeed imply greater intrinsic cost, perhaps by as much as an order of magnitude in comparison with the red laser pointer.

Laser pointers for light at other, longer, wavelengths than the green, such as the yellow at 577 nm or 593 nm, also use wavelength conversion, but the process involves optical pumping (again starting from an infra-red semiconductor diode laser) in a disc of semiconductor gain medium, with the intermediate step of second harmonic generation of the light from the infra-red semiconductor laser. Finally, in currently available and (quite probably) all future manifestations, the blue laser pointer goes back to being simply an edge-emitting semiconductor diode laser, together with collimating/patterning optics. Post-finally, it seems plausible to suggest that there will soon be ultra-violet laser pointers that will take advantage of the intrinsic invisibility of the ultra-violet light beam, even when propagating through scattering media, and that will rely on the fluorescence of many materials for visibility where required. Safety and ethical issues are likely to impact on the availability of ultra-violet laser pointers to the general public, but legitimate applications of the same kind of technology, with suitable operating restrictions, will surely be found.

Projection TV and Coherence Issues

An application that is fairly closely related to both laser pointers and to displays is the topic of scanning laser-based projection TV – and cinema. The development of compact and efficient lasers with the appropriate combinations of semiconductor diode lasers and solid-state (typically single-crystal) gain and frequency conversion components for specific colours in the red-green-blue (RGB) parts of the visible spectrum will make it possible to create high quality images that are generated by rapid scanning (and switching) of the constituent laser beams.

An important issue in the use of intrinsically coherent light sources such as lasers for display and optical memory applications is the generation of speckle. Speckle is the direct result of random scattering of coherent light from typical more-or-less rough surfaces. Because of coherence the scattered laser light has strong interference effects that degrade image quality in a visually unacceptable manner. To overcome the speckle problem it becomes necessary to destroy the coherence of the laser light in an appropriate way. For the possible use of lasers in display back-lighting, specific forms of integrated screen that have the right combination of transparency and diffusivity are required. For semiconductor diode lasers used in reading compact discs, saturable absorption is typically integrated with the laser stripe – in order to produce fluctuating (and therefore functionally less coherent) light via Q-switching behaviour.

OLEDs: a possible alternative display technology

Returning to the issue of basic approaches to display technology, we now turn briefly to consideration of the organic light-emitting diode (OLED) based display. In contrast to the LCD approach, OLED displays involve intrinsically light emitting semiconductors that are based on electron and hole injection and recombination in layers of electrically conducting organic chemicals. These chemicals may take the form of oriented molecules, of polymers or dendrimers. Different molecules emit light at different colours. OLED displays offer significant potential advantages, by comparison with LCDs, in terms of substantially simpler construction, mechanical flexibility and ruggedness – and even in terms of overall efficiency. Although the issue of reliability has not yet been definitively dealt with, it is now reasonably likely that OLED displays will push into the territory of LCDs, beginning at the bottom end.

Compact Tunable Lasers in the Visible/Ultra-Violet spectral range

The various examples of photonic integration that have been described and discussed above certainly have a largely hybrid nature – and definitely conform to the ‘other wavelengths’ definition through being mostly concerned with light in the visible part of the spectrum. One plausible direction for future work is the extension of the micro-chip laser approach through the use of a wider range of materials, both classical ‘solid-state’ (often single crystal) media for gain and frequency conversion and semiconductors diodes or optically-pumped semiconductor structures. 1D and 2D Photonic crystal structures integrated into microchip lasers that use broad-spectrum gain media, such as titanium doped sapphire (Ti:Al2O3), offer the opportunity to produce widely tunable (many tens of nanometres of wavelength range) visible-wavelength coherent light sources - through second harmonic generation selected by careful matching between the fundamental and second-harmonic band-structures of the photonic crystal [1]. Arguably there is a 'crying need' for such lasers, which could reduce the costs and size of tunable coherent light sources by several orders of magnitude – in comparison with the current generation of lasers that consume large amounts of electrical power and occupy a substantial fraction of a large optical table. With integrated saturable absorption, peak powers could be usefully large, e.g. one Watt – and many potential applications, e.g. in molecular spectroscopy, should not require more than a few milliWatts of tunable coherent light.

DFB and DBR lasers at other wavelengths – and further levels of integration complexity

Up to this point, our discussion has deliberately emphasized the use of hybrid approaches to photonic integration – and it has also not made any attempt to restrict the definition of integration to the use of planar optical waveguides in 'integrated optical circuits. Let us now take on board the recent large advances in essentially monolithic waveguide device integration based on silicon VLSI technology and the complex, monolithically integrated structures that have been realised in epitaxial heterostructures based on indium phosphide. Recent progress towards low cost integrated components for telecomm applications - at levels from chip interconnect, via LAN and FTTH and on up to long-haul - has been most impressive. The issue of the 'silicon laser' seems likely to be solved within a few years – and is not a central problem, because it can already be solved through hybrid integration with a III-V semiconductor gain chip. Alternatively the primary light source for a circuit may be an off-chip 'conventional' semiconductor laser that provides enough power to drive the whole integrated photonic chip.

Even if we generalise the definition of (fibre) telecomm wavelengths to cover all of the plausible wavelength ranges – such as those around 850 nm, 980 nm, 1300 nm and 1550 nm – there remain large areas of the optical spectrum that will or must be exploited for applications other than telecomm ones. If we select the blue/ultra violet spectral region, the need for monolithic integration arises from the desire to have efficient blue light sources with controlled coherence, including narrow emission lines that can be tuned over several nanometres. The integrated waveguide photonic component required for this functionality is a multi-section DFB or DBR laser based on large band-gap nitride semiconductor diodes. Basic large band-gap nitride laser diodes are typically (in-plane) edge-emitters and can be produced on intrinsically semi-conducting substrates that include single crystal gallium nitride platelets or thick layers of hydride vapour phase grown material. But such nitride lasers may also use the insulating (single-crystal) sapphire substrates that have largely been used in blue LEDs. A degree of justifiable additional, opto-electronic, complexity could then come from the use of similar epitaxial material as the medium for electronic components such as drive transistors linked to the laser. An arguably more interesting extension of this degree of complexity might come from the monolithic integration of micro-fluidic structures on the same substrate, with applications such as integrated bio-sensor chips being addressed.

Going away from the telecomm wavelength bands, but now moving to longer wavelengths, bring us to the quantum cascade (QC) laser. It is of some interest to note that successful introduction of the QC laser concept was based on epitaxially grown III-V semiconductor structures with many hundreds of thin layers. An important point is that, because only electron-transport between sub-band states is involved, it has been possible to use a larger range of semiconductors for QC lasers than would be considered for lasers based on electron-hole pair recombination across the electronic band-gap. Tunable DFB and DBR versions of QC lasers will surely find a range of applications at wavelengths in the range from 2 to 20 μm. Etch and re-growth of local regions on the same substrate as the QC laser could again allow electronic drive transistors to be monolithically integrated. Enclosed channels for flowing gases to be probed spectrally, through the in-plane emitted mid-IR radiation, would add further to the complexity of the monolithic integration that was achieved. The European Community FP6 project Nitwave has explored the use of large band-gap nitride semiconductors for inter-sub-band transition based devices over a range of infra-red wavelengths [2].

Conclusions

This summary has unavoidably been shaped by the need to understand developments in, and the possibilities generated, by light sources based on semiconductor diodes. For many purposes, the semiconductor diode is the primary light generator of choice, being typically the most efficient and compact way of performing the task of converting electric power into optical power. This superior performance holds good for light sources over a large range of optical spectrum – from the deep ultra-violet, through the visible and near infra-red - and well on into the mid-IR. But the summary has also endeavoured to explore some of the possibilities for integration, of both a hybrid nature and a monolithic nature, across this range of wavelengths.

References

[1] J. Torres, D. Coquillat, R. Legros, J.P. Lascaray, F. Teppe, D. Scalbert, D. Peyrade, 'Giant second-harmonic generation in a one-dimensional GaN photonic crystal', *Phys. Rev. B*, **69**, 085105 1-8, (2004).

[2] L. Nevou, N. Kheirodin, M. Tchernycheva, L. Meignien, P. Crozat, A. Lupu, E. Warde, F.H. Julien, G. Pozzovivo, S. Golka, G. Strasser, F. Guillot, E. Monroy, T. Remmele, M. Albrecht , "Short-wavelength electro-absorption modulation based on electron tunneling between GaN/AlN coupled quantum wells", *Appl. Phys. Lett.*, **90**, 223511, (2007).