ECIO-08: Polymer Devices in Integrated Optics

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1 Abstract

Polymers have many applications in Photonics. Over the last 20-30years they have provided revolutions in the base technology (e.g. polymer coatings for silica fibres and plastic optical fibre) and in advanced applications (e.g. liquid crystal based filters and switching devices). This presentation offers a vision of the future

2 Polymers and Molecular Materials in Photonics

For a polymer to find application in optical systems it is essential to understand what physical form the polymer will take and what best fits the application. In contrast to most crystalline systems or oxide glasses, the naming of a polymer, for example polyethylene, is no guide to its physical nature nor its full property set. To understand the full gamut of its properties it is necessary to know, for illustration,

- Molecular size as specified by the molecular weight and molecular weight distribution of the polymer
- Polymer topology – is the polymer cross-linked (covalently bonded), branched, or are the molecules separable,
- Mechanical and Thermal phase behavior - is it glassy, elastomeric or crystalline (or a mixture of many "phases"), and if so its relevant thermal parameters,
- Chemical composition - is it a single monomer,
- a co-polymer,
- Monomer distribution – is it random, blocky, etc.,
- etceteras.

This list is many pages long and not readily answered except in a few highly studied systems and each parameter may be subject to change within any single embodiment, from batch-to-batch or from different manufacturers of notionally the 'same' material.

Thus, the down-selection of an individual material is not trivial and should properly be done via an exacting specification and verification exercise. Sadly many market deployments of polymeric materials failed to grasp this issue, or perhaps took expedience before good engineering! Unfortunately this has seriously damaged the credibility of these materials and they have had a troubled history, and now carry a baggage of suspicion as to their "fitness-for-purpose" in critical applications.

For most applications in optical technology, especially integrated optics, the principle requirements are for a baseline performance as an optical material (low loss at the wave-band of interest; preferably a suitable refractive index of low dispersion; good thermal performance; good process-ability) and additionally engineering quality assurance. This latter has been the most substantial challenge for optical quality polymers.

3 Contemporary Developments

Plastic optical fibres have had a long gestation, struggling for many years to demonstrate value against an incumbent glass fibre of mostly superior metrics, lower cost and greater supporting technology. However, with an improved specification, and the emergence of volume optical system deployment wherein ease of termination and flexibility, linked to easy alignment and a non-exacting application specification, has opened many new opportunities; plastic optical fibre has definitely found volume applications suited to the performance it offers.

Typically based on acrylates or perfluoro polymers, there are now several vendors of plastic optical fibre. This is supported by the emergence of cost effective VCSEL based transceiver technology, and RCLED. Plastic fibre for intra-office equipment and automotive applications (e.g. MOST) seem likely to continue to expand the opportunities for POF. From the perspective of integrated optics this is driving new developments for integrated optic modules and components and these will continue to grow the ECU50 Billion photonics market in Europe. (See ref.1 and ibid)

Cambridge University and Dow Corning have been developing planar waveguide technology using siloxane based polymers. A key target market is board level optical interconnect. The expectation is that optical technology will penetrate to every level of electronics systems and be the back-bone for all high data-rate channels for signalling. A recognition that siloxanes provide a preferred materials class for waveguide developments had been advanced for some years but the development of acceptable polymers, and proving the full-spectrum of process and performance specifications for circuit-board deployment has taken skill and persistence. This work provides an excellent example of the required program of research required if a polymer based optical interconnects is to be fit for commercial deployment.

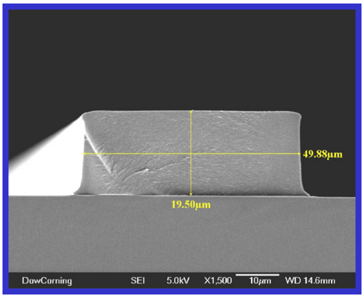
The requirements of this application illustrate the technical complexity of the problem The material has to be deployable into manufacturing of boards with complex metallic interconnects; quite possibly needing to be processed via large area patterning; it must certainly survive lead-free solder reflow temperatures (>250°C); it must provide low enough loss for low-cost transceiver link budgets in realistic systems scenarios; it must be agnostic with respect to wavelength selected.

The challenge is to select hierarchical classes of device element that can be combined effectively to demonstrate functions that might then be integrated as single devices similar to the "Spice" models for the functional elements in electronics. Foundry practice can then permits exchange of design rules and the designer can then parameterise the selected design against a target foundry.

Additionally the various waveguide geometries required by differing applications must be explored. The companion proofs of process variables, process methods and quality engineering (reliability in service and tolerances to manufacturing of total systems, for example thermal excursions in solder re-flow etceteras) are also demonstrated.

To begin an emulation of this design practice the polymer wave-guide program within Dow Corning and CAPE has taken a step-wise approach to the full technology expression of optical waveguide components and systems. The first parts made were simple traces rendered as short straight sections and longer spirals. Later devices, typical of standard needs (such as splitters, combiners and couplers), were fabricated in multi-mode and single mode designs. Thus the demonstration of the technology allows a level of abstraction sufficient to allow end-users clear paths to realise designs of merit in a variety of applications. (Refs: 2,3).

Adoption of a polymer waveguide technology for optical interconnect applications on circuit boards requires that every facet of the design and deployment is plausibly enabled to future proof the developments. Thus adherance to the design framework above coupled with verification engineering and quality engineering disciplines is vital. In Dow Corning’s development we see a very clear demonstration of the conjoining of the materials science with process engineering that has enabled market relevant proofs of fitness-for-purpose.



The development of electro-optic devices based on polymeric and/or molecular materials is not new. In more recent times many have recognised the potential of molecular engineering to provide superior electro-optic coefficients and faster operational performance than is possible from the traditional materials. The difficulty has always been that any real application of such devices has deployment specifications and operational demands which the highly specialised molecules have thus far proven unable to survive. This does not detract from their potential and has not stopped researchers from continuing to seek improved systems, but even the best-in-class have yet to prove their fitness-for-purpose.

It is worth noting that inorganic, electro-optic crystals typically have a rising dielectric loss as the frequency operation increases. They may or may not have inconvenient damage thresholds (for optical flux or electric field). For the vast majority of available crystals the relevant electro-optic coefficient will lie in a range between 25 and 50pm/V. This contrasts with the best in class polymeric, or dye guest-host systems which have shown peak electro-optic coefficients greater than 200pm/V (see L. Dalton e.g. ref.11). Furthermore, typical molecular design targets utilise a non-resonant electro-optic response dependent on "Chi2" which is determined by the transition dipole moment magnitude in the aromatic charge transfer system. This means that contrary to their metal oxide or semiconductor crystalline competitors these materials have a lower dielectric constant and low dielectric loss which may be low to extremely high frequency, greatly in-excess of 100GHz.

Liquid crystal materials in integrated optics have also been studied, designs from the planar waveguide community for electric field driven phase control in Mach-Zehnder (MZ) devices are typical (ref. 12). Herein the relatively slow but either analogue or digital response of the LC is used to introduce a field initiated phase shift in one arm of a MZ structure and thus cause switching of optical power from one branch of the device to the other. In principle such optical elements can then be combined in parallel and in series to produce filter structures of arbitrary complexity. As yet the optical integration offered out of such elements has yet to be exploited widely, but the feasibility proofs have shown the promise.

Thus there are still opportunities for these materials but the technical and scientific challenge should not be underestimated.

The development of low cost CMOS back-planes for projection display applications has driven commodity costing of so-called liquid-crystal-on-silicon technology. Several groups world-wide have seen the potential herein to produce a new class of integrated optical system.

In principle, since an LC can control phase, the pixel circuitry of an LCoS back-plane can address upwards of 4Million phase controllers. This array of controllers thus becomes an arbitrarily programmable phased array (or holographic optical element). These have been shown to allow not only beam steering, but also point-to-point interconnection, multi-cast and broad-cast array switching capability. Using the intrinsic capability to write gratings then extends this capability to dispersive devices and LCoS has been adopted by several groups to demonstrate wavelength selective add-drop devices suitable for deployment in telecommunications as Reconfigurable Optical Add-Drop Multiplexers (ROADM).

This technology is still in its infancy but the direct coupling of the power of CMOS, with capability to place over a billion gates of processor power, with the power of computer generated holograms, via the liquid crystal phase control, is a staggering example of integrated optics far exceeding the previous generations of study.

4 Conclusions: The Potential Future

It is clear that polymers and molecular materials will play an every increasing role in integrated optics. Their complexity brings with them challenges as well as exciting opportunities. We believe to be the most exciting opportunities for advancement are

Self Assembly - the ability of molecular materials to self assemble and, either as polymers or as mesoscopic supramolecular systems, it is this capability which suggests manifold photonic integration applications. The future is for device structures to be created wherein the assembly of the photonics crystal or ordered array is entirely pre-determined by molecular design and process environment control. Example applications are: Polymer Modulators; Quantum Information Processing; Ubiquitous Integrated Optics. For high performance polymer modulators and, conceptual nano-scale gain devices, the ability to create polar order and thus have exceptional hyper-polarisability tensor values is already being demonstrated. Taking the next steps to create these effects in systems which replicate nature's ability to sequester and protect the reactive, functional, molecular entities is being attempted and will surely occur in the next decades. Having mastered polar order the next challenge beyond this is to control the spin environment and manipulate directly the quantum density of states. This leads one to contemplate the next great revolution... that of Quantum Information Processing, wherein we will finally see the complete fusion of "electronics" and "optical physics". The concept of ubiquitous integrated optics has been a currency of our community for many years. Even today this is true to a degree un-imaginable when Charlie Kao and George Hokham invented the optical fibre in the latter half of the 1960s. However, the process has a long way to run still.

5 References

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