# Fabrication and design of micro-optical interconnect systems with fanout

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In the last decades, optical interconnects have been envisioned to replace electrical copper wires at the different levels in the interconnect hierarchy. One of the possibilities to bring the advantages of micro-optics telecommunications to the computer backplane, the printed circuit board and the inter- and even on-chip interconnect level, is to use plastic free-space micro-optical interconnect modules. Such modules can offer high aggregate communication bandwidth through thousands of point-to-point optical links on a footprint of a square centimeter. Such micro-photonics modules have been a topic of interest and have been investigated extensively in the recent years at the Department of Applied Physics and Photonics at the Vrije Universiteit Brussel.

To make optical interconnects even more attractive, during this PhD work we have investigated wether the possibility of performing passive optical signal broadcast could be implemented in such micro-optical interconnect systems with using passive beamsplitting diffractive phase-only elements (DPEs). Such diffractive optical elements can be modelled as a surface texture only, and can be integrated directly onto the surfaces of the optical interconnect module. The choice of such a passive approach has the advantage that the surface texture of the prototype module can be replicated in a few hundred of low-cost monolithic plastic replica components. In this way, the high prototyping costs of the necessary highly accurate micron-sized diffractive and refractive micro-optics can be spread over the total number of replicas. Furthermore, the design for manufacturability allows for compatibility with present-day mass-replication techniques such as injection moulding or hot embossing.

In this PhD work, we have modelled the aforementioned millimeter sized micro-optical interconnect modules featured with optical beam fanout for every input channel and this for two distinct applications.

In a first application at the board-to-board interconnect level, our module can perform a selective optical signal broadcast when used in an optical fibre based reconfigurable optical interconnect multi-processor network. In this distributed shared memory multi-processor simulation environment, every processing node has the availability of a wavelength tuneable laser to emit its data optically via an optical fibre into the network. The optical fibres of all nodes are then gathered in a 2D fibre ribbon, which then leads to the input and output side of our selective optical broadcast module (SOB). In here, for every input channel, the optical data is splitted to a selected number of receiving processor nodes. The actual optical links can be reconfigured when the sending node laser is changed to emit at another colour. As every receiving node in the network is sensitive to a unique colour, changing the emitted colour thus results in establishing a new different optical link between other pairs of processing nodes.

Fellow researchers at the department have shown in architectural simulations that significant program execution speed-ups can be obtained with reconfigurable optical interconnects in DSM networks, even when taking into account the limited fanout count in our SOB module (due to dimensional modelling restrictions), the limited number of available wavelength channels (colours) per node and the limited wavelength tuning speed of the micro-lasers (in the order of 100 microseconds).

At the more debateable on-chip optical interconnect level, we have been able to model the concept of a selective optical broadcast in a micro-photonics module for a future implementation of an 81 x 81 port fully non-blocking optical cross-connect system. Here our 1 $cm^3$ plastic micro-optical module with fanout is placed above a smartpixel opto-electronic chip. This chip contains clusters of vertical-cavity surface-emitting micro-lasers (VCSELs) and arrays of optical detectors with some underlying CMOS circuitry for performing the smart function in the smartpixels. The reconfigurable cross connection between the electrical input and output channels happens in two intermediate consecutive stages through optical 3 x 3 beam fanout.

The second part of our PhD research has focused on the prototyping and replication of the necessary refractive and diffractive micro-optical subcomponents, to come to an actual implementation of the micro-photonics modules with selective fanout. Our main contribution consisted in the establishing and adaptation of a commercial available elastomeric moulding and vacuum casting technology, but in this case applied on optical components with micron sized features. We have successfully replicated a myriad of different prototype subcomponents – ranging from 2D refractive microlens arrays, 2D micro-hole arrays in connectors for precise optical fibre positioning, towards diffractive gratings and diffractive Fresnel microlenses with 2 micrometer sized features. Moreover, several of these subcomponents have been assembled together in more intricate micro-optical modules which have then been replicated into poly-urethane plastic monolithic replica copies. In this way, we have shown that it is possible to integrate both diffractive and refractive micro-optics into the same micro-optical system. As a result, we were able to fully implement a fibre-based module which can perform an optical coarse wavelength division demultiplexing function. In this fabricated and replicated module, the light emitted of an incoming fibre is collimated and then splitted via a linear diffraction grating towards a number of different receiving fibres at the output. According to the input wavelength (colour), the optical beam is diffracted to other output fibres. Such a module can be used as a low-cost all-optical wavelength routing element in for instance fibre-to-the-home networks.

We also demonstrated the possibilities of the vacuum casting replication technique on other types of prototype optical interconnect components: stand-alone out-of-plane couplers with micron-sized mirrors which can be plugged into PCB optical waveguides, and 2D arrays of polymer micro-pillars for establishing compliant optical interconnects between flip-chipped opto-electronic chips and printed circuit board embedded optical waveguides.

Finally, we could also change the elastomeric moulding in the replication process to obtain the geometrical inverse pattern of a planar surface with sub-millimeter sized optical features. Here we were able to fabricate 2D arrays of concave micro-lenses which can find imaging application as gold-coated spherical micro-mirrors in a range of biophotonics applications.

**Lieven Desmet** was born in Kortrijk, Belgium, in 1975. He graduated as Industrial Electrical Engineer with majors in micro-electronics at the BME department of the University College Ghent in 1997. In September 2000, after a three-year abridged Masters in Engineering training at the Vrije Universiteit Brussel (VUB), he obtained his degree in Electrotechnical Engineering with majors in Photonics. He continued working at the Applied Physics and Photonics department of the VUB, where he pursued research on the integration of refractive and diffractive micro-optics in micro-optical interconnect systems. He contributed to the modelling, the prototyping and the replication of several micro-photonics modules using the department's Deep Proton Writing, elastomeric moulding and vacuum casting technologies.