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Integrated-Optics versus Micro-Optics - a Comparison

E.C.M. Pennings*, M.K. Smit#, A.A.M. Staring*, and G.-D. Khoe&

* Philips Optoelectronics Centre, WY-61, Prof. Holstlaan 4, 5656 AA Eindhoven, The Netherlands
Phone: +31-40-2743037 / Fax: +31-40-2743859 / E-mail: epenning@natlab.research.philips.com

Delft University of Technology, Fac. of Electr. Eng., Mekelweg 4, 2628 CD Delft, The Netherlands
Phone: +31-15-2782438 / Fax: +31-15-2784046 / E-mail: M.K.Smit@ET.TUdelft.NL

& Technical University of Eindhoven, EH-12, PO Box 513, 5600 MB Eindhoven, The Netherlands
Phone: +31-40-2473452 / Fax: +31-40-2455197 / E-mail: G.D.Khoe@ele.tue.nl

Introduction

It is the purpose of this paper to assess the relative merits and prospects of integrated-optic versus micro-optic devices for fiber-optic telecommunication systems. Firstly, this comparison is made from a market perspective. Then, the analogy between electronic and photonic integrated circuits is investigated. Finally, a specific comparison is made for wavelength demultiplexers for dense WDM applications. A comparison similar to this one but also including polarization-diversity hybrids can be found in Ref. 1.

In this paper, the following classification is used:

- *Fiber-based* devices, such as couplers, which are exclusively made from fiber.
- *Integrated-optic* devices, where light is guided in planar waveguides.
 - *Single-component* devices, such as lasers, laser amplifiers, and phase-modulators.
 - *Photonic integrated circuits*, where a number of optical devices are monolithically integrated.
- *Micro-optic* devices, which rely on diffractive or reflective bulk elements such as lenses or mirrors.
- *Modules*, which are assembled from any of the above elements.

The fiber-optic component market

Figure 1 shows the fiber-optic component market for 1992 and 1997 in the US. A direct comparison between integrated-optic and micro-optic techniques can only be made for passive components and Fig. 1 shows that the comparison therefore applies to the smaller part of the market (15%), since the larger part consists of active devices such as lasers and photodiodes. For passive components, the largest market segment is formed by couplers (11%) which are almost exclusively fiber-based. This shows that the market segments captured by integrated-optic and micro-optic products are both quite small (of the order of 1% - 2%). The micro-optic segment consists of products such as switches, isolators/circulators, attenuators, and filters. The integrated-optic segment mainly consists of LiNbO₃ switches and modulators. Another proven integrated-optic product (though active) is the DFB laser with integrated electro-absorption modulator.

Figure 1: The 1997 US fiber-optic component market forecast (source: ElectroniCast'92).

The market analysis shows that the demand for components with a larger degree of optical functionality has been negligible so far. This is important because the competitive edge for PIC's is precisely in integrating complex optical functionality. This situation, however, is likely to change: the market is not only *growing* fast (more than 25% a year), but also *changing* due to the rapid commercialization of WDM systems. However, the first WDM transmission systems will merely require optical devices with a single functionality, so that the demand for complex optical functionality will only increase *later on*, i.e. when the wavelength domain is used to realize add-drop multiplexing and cross-connecting functions.

Technological considerations

It has been argued many times that the competitive edge of photonic IC's comes from increased scale of integration plus the corresponding cost reduction. This argument is in fact based on an implicit analogy between photonic and electronic IC's. This analogy, however, has to be treated with care. Firstly, the markets for photonic and electronic IC's are very different: as was argued in the previous section, the demand for complex optical functionality is still in its infancy. Secondly, there are several technical reasons why photonic and electronic IC's are quite different:

Packaging is much more difficult for photonic than for electronic IC's. Packaging related issues are the fiber-chip coupling problem which leads to the use of tapers and lenses, the influence of reflections and the accompanying use of isolators, and temperature sensitivity which can necessitate Peltier coolers and thermistors. It is important to notice that these packaging issues form, on one hand, the major *economic* incentive for integration, but that they, at the same time, form a *technical* obstacle against integration.

The scale of integration seen in electronic IC's is directly related to intrinsic on chip amplification and feedback which allow for accurate performance control and thus for the ability to cascade a large number of components. So far, optical feedback is not feasible in photonic IC's and integrated optical amplifiers are in their infancy. Even more important is that the characteristic size of the building blocks for photonic and electronic IC's differ by at least two to three orders of magnitude. Lastly, whereas electronic IC's contain many duplicates of a small set of building blocks, most photonic IC's integrate a number of very different elements. The accompanying problem of optimizing the performance of each individual sub-element complicates the design and leads to compromises in performance.

As a result, photonic IC's will follow their own rule of economy, different from electronic IC's, and will reach a more limited scale of integration. In order to reach that limit and speed up commercialization, additional effort will be required to reduce packaging costs, incorporate on-chip amplification, reduce component size, and to develop improved processes and fabrication-tolerant components.

Wavelength demultiplexers for dense WDM applications: a comparison

In this section, a specific comparison is made for a key component in OFDM networks, i.e. the wavelength demultiplexer for dense WDM applications. The development of these demultiplexers is shown in Fig. 2.

Fiber-based: The lack of fiber-based demultiplexers in Fig. 2 illustrates the unsuitability of fibers to demultiplex many closely spaced wavelengths *simultaneously*. Fibers are, on the other hand, very suitable to demultiplex two widely spaced wavelengths (i.e. duplexers), which are typically used for two-channel transmission systems (e.g. 1.31/1.55 μ m), or in EDFA's (0.98/1.55 μ m and 1.48/1.55 μ m). It is important to notice that duplexers form more than 90% of the demultiplexer market and are almost entirely fiber-based.

Modules: Fibers can, of course, be used in combination with *filters* to realize wavelength demultiplexers for dense WDM. These filters can be placed in series (cascaded) or in parallel by using a fiber splitter. Popular filters are the (fixed) interference filter² and the tunable (fiber) Fabry-Pérot filter.

Micro-optics: Fig. 2 shows that much of the work on micro-optical demultiplexers was already published in the early eighties³⁻⁶ when MM fibers were used with wavelengths of $\lambda=700-900$ nm. The subsequent reduction of interest was due to the shift of focus to coherent detection schemes. In the late eighties, when interest in WDM revived, work on micro-optical demultiplexers continued⁷⁻¹¹ and several earlier designs were commercialized. Micro-optical wavelength demultiplexers can be divided into the cascaded interference filter type and the grating-based type. Recently, the phased array design, which is typical for integrated optics, has also been realized in micro-optics¹².

Figure 2. Overview of reported wavelength demultiplexers and their development in time.

Integrated optic: The first integrated optic demultiplexers appeared in the late eighties and relied on cascaded duplexers¹³⁻¹⁴. Soon afterward, planar versions of the micro-optic grating based demultiplexer were reported^{15-20,21-22}. An alternative design is the phased array (PHASAR) or arrayed waveguide grating (AWG)²³⁻³⁰. This design has recently gained in importance due to superior performance and ease of processing. Fig. 2 shows how integrated-optic demultiplexers have subsequently been integrated into more complex PIC's (such as lasers³¹⁻³³, receivers^{34-37,38}, and an add/drop multiplexer³⁹) and how they have been used in various system experiments^{40,41-45}. It seems that this development is accelerating which is, for example, demonstrated by the rapid commercialization⁴⁶ of the Si-based demultiplexers.

Discussion and conclusion. The performance of a variety of commercial demultiplexers is compared in Table 1. The splitter plus filter configuration is rather popular due to its simplicity and tunability, but it poses an intrinsic splitter loss of $10 \cdot \log(N)$ and may show unwanted back-reflections. *Fixed* demultiplexers will gain in importance, as soon as WDM channels have been *standardized*. For cascaded filters, the loss increases proportional to number of channels, which limits its suitability to 4-8 channels. Micro-optic demultiplexers offer proven reliability in addition to excellent performance in terms of number of

Table 1: Overview of performance of commercial wavelength demultiplexers.

Technique	Type	N	$\Delta\lambda$ (nm)	Ins.Loss (dB)	Ret.Loss (dB)	X-talk (- dB)	Drift (nm/°C)	Pol.Dep. (dB)	Vendor
Module	Splitter + FFP-filter			<1.5-2.5	?	?	Act. tuning	<0.5	Micron Optics
				<4	>22-40	?	Act. tuning	?	Queensgate
	Cascaded filters			<1.5	>40-55	>15	0.004	?	OCA
Micro- Optic	Cascaded filter	4-8	1.6	<3-4	>40-55	>30	0.004	<0.1	OCA
	Grating	4-41	1-16	<3-5	?	>30-55	0.02-0.004	?	Jobin-Yvon
Integr.- Optic	PHASAR (passive)	8	?	<10	>25	>20	?	<1	Hitachi
		8	1.61	<10	>30	>20	0.01(tuning)	?	AT&T
		4-32	0.8-2	<6-7	>40	>20-22	Peltier/NTC	<0.3	NTT

channels, insertion loss, cross-talk, polarization-dependence and thermal stability⁴⁷. Integrated optic demultiplexers, especially the phased array type, have seen an enormous development and the recently commercialized Si-based demultiplexers show a very competitive performance. The performance of these commercial versions can, however, not yet match that of micro-optic versions. This leads us to conclude that the real breakthrough for integrated optics has to be expected when both technology and market are ready for photonic IC's with increased functionality due to a larger scale of integration.

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