Micro-optics versus integrated-optic devices : a comparison

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Micro-Optic versus Integrated-Optic Devices - A Comparison

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Summary

Integrated optics has, ever since its inception in 1969 [1], held the promise that the success of integrated electronics could be transferred to the realm of optics. So far, this promise has fallen short of expectations and the market for photonic integrated circuits is still in its infancy. It is the purpose of this paper to investigate the current status of integrated optics in comparison with micro-optic and fiber-based techniques, and to generate possible explanations for the slow commercialization of integrated-optics. First of all, the market for fiber-optic components is analyzed. Secondly, the technological issues which make integrated optics quite different from integrated electronics will be investigated. Thirdly, a specific comparison between the potential of these competing technologies will be made for two optical devices used in networks based on optical frequency division multiplexing (OFDM), i.e. the polarization-diversity hybrid and the optical wavelength (de)multiplexer.

Introduction

In order to limit the scope, the discussion will be confined to optical components for lightwave telecommunication systems, i.e. to components that have at least one single-mode fiber pigtail.

The single-mode character of the glass fiber is rather important in this context, because it directly affects the viability of waveguide optics. Although single-mode fibers were originally proposed in 1966 [2], attention soon focussed on the graded-index fiber [3]. As it was very difficult to realize integrated optics employing large multimode waveguides, almost all device work concentrated on micro-optics at the time. When the use of the graded-index fiber was discontinued due to modal noise problems [4], the come-back of the single-mode fiber thus also reinvigorated the interest in integrated optics.

In this paper we have distinguished fiber-optic components into the following categories:

- *fiber-based*: components made from fiber, such as couplers, filters, polarizers and filters. Fiber-based components are predominantly fabricated using either the fused-fiber or the side-polishing technique.
- *integrated-optic*:
  - single-component devices, such as lasers, laser amplifiers, phase-modulators, etc.
  - photonic integrated circuits, where a number of optical elements are monolithically integrated on a single substrate.
- *micro-optic*: techniques where light is not guided, but which rely on diffractive or reflective elements such as lenses or mirrors.
- *hybrid modules*: assemblies from any of the above components.

Note that it is the purpose of this paper to investigate the potential of photonic integrated circuits, rather than integrated-optic components with a single functionality. We thus exclude most lasers and OEIC's, such as PIN/FET combinations from the comparison, but include advanced lasers such as DFB lasers with integrated modulator.

When making the analogy between integrated electronics and integrated optics, one has to bear in mind that there is a large difference in time-frame: whereas the starting point for integrated electronics is the invention of the transistor in 1947, the equivalent starting point for integrated optics is the invention of the semiconductor laser diode in 1962, i.e. fifteen years later. The development of integrated electronics continues with the integrated circuit which was patented in 1959, the first microprocessor which was reported in 1971, and the widescale deployment of the microprocessor in PC's during the 80's. For optics, the first OEIC was reported in 1978 [5] and complex photonic integrated circuits were reported from 1990 onwards [26]: the time difference in development between integrated electronics and integrated optics thus has increased to about twenty years. Based on this analogy, widescale deployment of photonic integrated circuits is not likely to happen before the turn of the century.

The fiber-optic component market place

When comparing integrated optics and micro-optics, it is a good starting point for the discussion to first identify which components have already established a place in the fiber-optic component market. Fig. 1 shows the 1997 market forecast for active and passive fiber-optic components for North-America. By far the largest part of the market consists of lasers and photodiodes for active components and of fiber-optic components such as fused 2x2 couplers and star couplers for passive components. The market for OEIC's shows a very strong growth, but consists of the integration of optics with electronics such as laser/driver and PIN/FET combinations rather than of an integration of optical elements. Laser amplifier modules show a strong growth as well and contain pump lasers, fiber WDM's and micro-optic isolators. Micro-optical components have a small but well-established presence in the form of isolators, fiber FP filters, opto-mechanical switches, and demultiplexers for three or more wavelengths (91% of the demultiplexers involve two wavelengths only and are fiber-based). For advanced photonic integrated circuits, the market is still small at the moment. One area, where integrated optics seems to have a competitive edge, is in lithiumniobate modulators and in tree couplers, such as 1 x 32 couplers, where integrated optic couplers are smaller, cheaper and show better port-to-port reproducibility. At the same time, the market for single-function components is very large, consisting of lasers and transceivers. It is likely that these devices will function as "enablers" for more advanced PIC's. Lasers become more advanced leading to three-section DFB or DBR lasers, and DFB lasers with integrated modulators. The success of lithiumniobate modulators allows lithiumniobate foundries to be set up that can also fabricate customized PIC's.

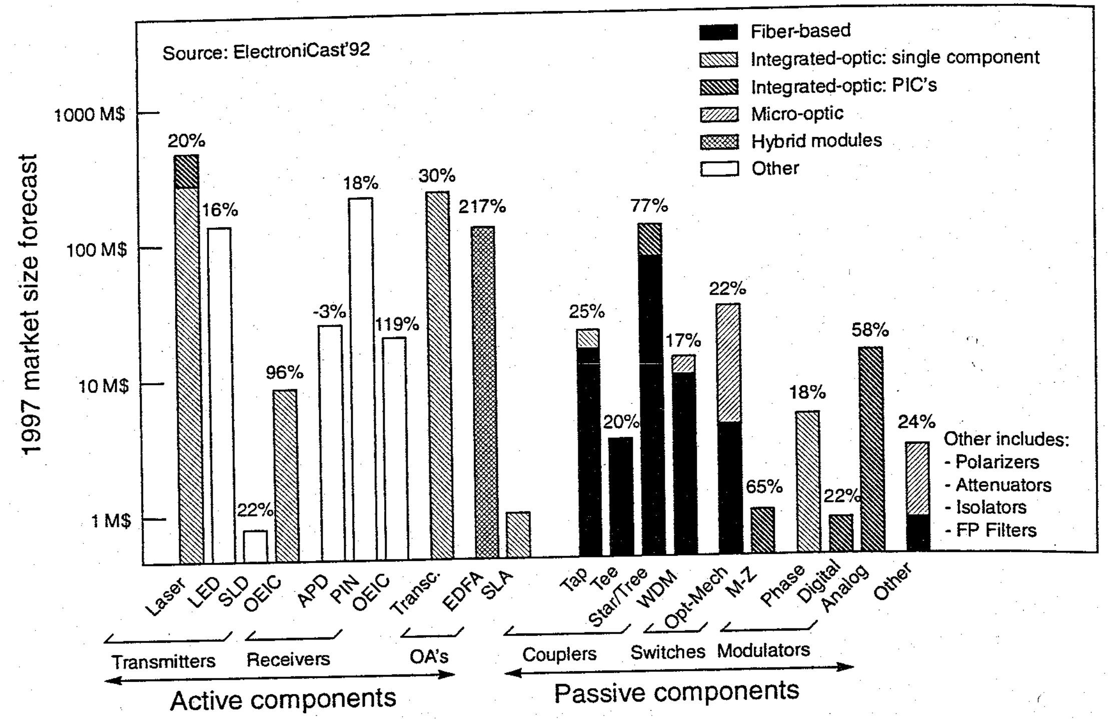

Figure 1: The 1997 market forecast for fiber-optic components for North-America. The percentages express compound annual growth rates for 1992-1997.

One reason for the fact that integrated optics has, up to now, not been able to match the speed of development of integrated electronics is the fact that the market for photonic integrated circuits is still in its infancy, but it is also true that the telecommunication industry is, by tradition, not very market oriented. For example, many of the companies and institutes performing integrated-optics research do not have a direct commercial interest in the component market. In the coming years, big changes are expected due to the deregulation of the telecommunication market and the gradual global break-up of PNO monopolies. As a result from the deregulation process and increasing competition, integrated-optics research will to an increasing extent be performed by component manufacturers and as a consequence become more market driven.

Technological considerations

In this section, we want to identify the technological factors that make integrated optics differ from integrated electronics. It is these differences that cause the development of photonic integrated circuits to take longer than the corresponding development for integrated electronics.

The fiber-connection problem. Whereas in electronics input and output connections are simple (unless the signal frequency becomes very high) the optical fiber connection problem is complicated. In fiber-pigtailed lasers, for example, the packaging costs are usually a multitude of the chip costs. Packaging costs are very different for (i) *fiber-matched waveguides* such as those based on lithiumniobate or silica, when compared to (ii) *compact waveguides* as used in semiconductor optical chips. Fiber-matched waveguides can be coupled relatively easy to fibers (butt-coupling). Commercially available integrated optic couplers, switches and modulators are, therefore, almost exclusively realized with fiber-matched waveguides. Fiber coupling of compact waveguides is much more complicated due to the large difference between the fiber and the semiconductor waveguide dimensions. The temporary success of multimode fibers was partly due to the fact that it strongly relaxed the coupling problem to the laser. Presently the coupling problem to single-mode fibers has been solved technically, but fiber coupling to lasers is still expensive and until recently communication lasers were the only semiconductor components which possess sufficient functionality to justify the coupling costs economically. Semiconductor optical amplifiers (SOA's) are the next class of components to take this hurdle. Due to difficulties in reducing packaging costs it will take a long time, however, before integrated optic components with a limited functionality can compete with micro-optic or fiber-optic alternatives. The best way to offset packaging costs is to increase the functionality of the chip by integration of multiple components on a single chip.

The lack of (on-chip) optical amplification: in electronic IC's compensation of losses is no problem due to the active character of the transistor. Until recently there were no means for loss compensation in optical circuits. As component losses are considerable (in semiconductor switching matrices 2-5 dB per switch is not exceptional) the integration scale is strongly restricted by the component losses. In fiber matched waveguide systems component losses are usually much lower.

The relatively large size of integrated-optic components: modern transistors have dimensions of only a few microns. Optical couplers or switches in fiber-matched waveguide systems have lengths ranging from many millimeters to several centimeters, so that only a few components can be cascaded on a single wafer. Semiconductor components are usually smaller, but suffer from higher losses.

The lack of an optical feedback-principle: both in optical and electronic IC's it is difficult to control the component parameters very accurate. In electronic IC's the feedback principle is used to reduce the sensitivity of the circuit performance to the spread in component performance. In photonic IC's such a principle is not (yet) available. The requirements on process technology are, therefore, much more severe, which is doubly complicating because integrated-optic technology is a young technology and the variety in integrated-optic components which have to be integrated is considerably larger than the variety of components in electronic IC's.

The influence of reflections: many fiber-optic communication systems are extremely sensitive to reflections, which can cause power fluctuations, noise, non-linearity, and dispersion. In coherent transmission systems and CATV applications, for example, reflections should be kept below -50 dB. Many components such as narrow linewidth lasers and laser amplifiers, therefore, require the use of optical isolators which complicates packaging and increases costs.

The wave character of light: dealing with optical waveguides leads to issues similar to those encountered in microwave electronics. Optical waveguides can radiate light, which leads to loss of power and can cause cross-talk. Similarly, single-mode operation of waveguides is usually desirable, which can complicate PIC design and leads to strict tolerances on waveguide dimensions. Recent work, however, has shown that the single-mode condition can, in many cases, be relaxed by employing the imaging properties of multimode waveguides [50].

In conclusion, one might be tempted to think that integrated-optic components are and will remain futuristic. We do not adhere to that opinion and believe that there is a future for integrated-optic components, but that the following issues deserve attention in order to speed up the commercialization of photonic integrated circuits:

i) Reduction of packaging costs (e.g. by automation).
ii) Incorporation of on-chip optical amplification.
iii) Reduction of component size.
iv) Improvement of process technology and development of fabrication-tolerant components.

The last five years have shown tremendous progress. The gradual reduction of packaging costs will broaden the class of components where integrated-optics can compete with micro-optic and fiber-based components. The major breakthrough for integrated optics, however, can be expected when both technology and market are ready for photonic integrated circuits with an increased functionality due to larger-scale integration.

Polarization-diversity optics for coherent lightwave receivers: a comparison

In this section, a specific comparison will be made between the potential of integrated-optic, fiber-based and micro-optic polarization-diversity hybrids. Polarization-diversity hybrids are key components in coherent lightwave receivers, whose wavelength tunability can be used to construct flexible photonic networks based on optical frequency division multiplexing (OFDM). For such applications, coherent receivers could provide a cost-effective alternative to direct-detection systems, where the cost and performance of the coherent receiver need to be compared to that of a direct-detection receiver in combination with an EDFA preamplifier and a narrow tunable filter [47]. Optical front-ends for coherent polarization-diversity receivers have been regarded as prime candidates for monolithic integration and are thus very suitable for a comparison with micro-optic and fiber-optic solutions. Fig. 2 lists all polarization-diversity hybrids that have to our knowledge been reported in the literature for different competing technologies, tracing their development in time in the form of sub-components, complete hybrids, packaged versions, systems experiment, and commercial availability.

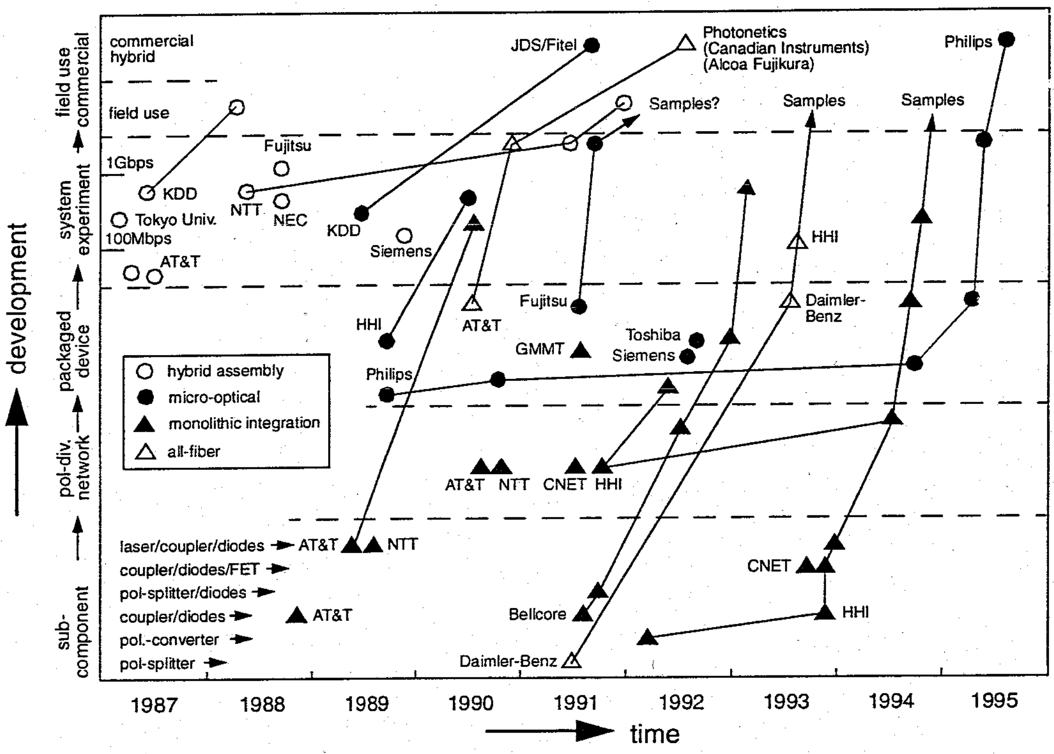

Figure 2. Overview of reported polarization-diversity networks, and their development in time.

Assembly of polarization-diversity hybrids from separate components has been used in the first polarization-diversity system experiments which were reported from 1987 onwards (Tokyo Univ. [6], AT&T [7][8], KDD [9], and others [13][14][15][17]). Although assembly can produce a reliable polarization-diversity hybrid ready for field use (KDD [10], NTT [16]), assembly procedures are cumbersome, and produce rather bulky polarization-diversity hybrids with increased losses, reduced polarization extinction, and reduced robustness when compared to a single component. This soon initiated a trend towards completely fiber-based, micro-optic or integrated polarization-diversity hybrids.

All-fiber polarization-diversity hybrids have been fabricated using side-polishing techniques (AT&T [18]) and fused-fiber technology (Daimler-Benz [20]). All-fiber hybrids offer excellent insertion losses of 0.2-0.7 dB and ultralow reflection, but they show weak polarization-extinction ratios of around 15 dB. It is illustrative for fiber-optics, that both reported hybrids were immediately used in system experiments [18][21], and were available either as samples or as a product by Photonetics. The critical component in the fused-fiber hybrid is the polarization splitter [19]. Usable bandwidths are 17 nm for the fused-fiber technology [20] and over 100nm for the side-polishing technique [18]. The side polishing technique, however, shows serious reliability problems due to aging of the glue which forms the coupling layer between both fibers.

Micro-optical polarization-diversity hybrids, in principle, can offer low insertion losses, excellent polarization-handling and ultralow reflection (Fujitsu [37], and HHI [33]). The main disadvantages of micro-optics are the strict tolerances on fabrication and alignment procedures. This affects cost, performance and robustness and as a result several micro-optical hybrids were reported without subsequent system experiments or commercialization [39][40]. A different approach minimizing both fabrication and alignment procedures was reported by Philips [46]. This resulted in a high performance hybrid (compact size, insertion loss of 0.7 dB, polarization extinction ratio of 25-42 dB, balancing 50±3%, reflection of less than -58 dB, and usable bandwidth of over 90 nm), which is now commercially available. Although micro-optics requires high-precision manual operations, this does in no way prevent low-cost mass-fabrication as demonstrated by the micro-optical recording heads used in CD players.

Monolithically integrated polarization-diversity hybrids were quite promising, but required much more research. The very first device was reported by AT&T [25] and was also immediately used in a system experiment [26], though not polarization-diversity. Much research was still required on sub-components such as integration of the polarization-rotator (HHI [34]), photodiodes (e.g. AT&T [11]), polarization splitter (Bellcore [31]), FET (CNET [41] and HHI [42]) and laser (AT&T [25], NTT [24], and HHI [45]). In addition, the packaging of such a PIC is far from trivial. If the laser is not integrated, both a SMF fiber and a PMF fiber need to be coupled to the PIC simultaneously using a Si V-groove (GMMT [28]). If photodetectors are not integrated (AT&T [22], NTT [23], CNET [27], HHI [29]), then the output waveguides must be coupled to four fibers, which has not been reported so far, or quad photodetectors need to be packaged together with the hybrid (HHI [35]). But even if photodetectors are integrated with the hybrid, the high-frequency behavior will still be limited by the electrical connection between the photodetectors and the front-end electronics. If SMA connectors are used between the photodetectors and the electronic front-end, a cut-off frequency of 6 GHz is still achievable (Bellcore [30]), but optimum high-frequency behavior actually requires that either the electronic front-end is placed inside the package (5 GHz, GMMT [28]) or that FET's are integrated as well (1GHz, HHI [42]). Given technological difficulties that needed to be overcome, it is not surprising that only very recently the first system results were reported employing a polarization-diversity receiver PIC (HHI [48]), yielding a best receiver sensitivity of -33.5 dBm for a 140 Mbit/s FSK system.

Despite of quite impressive achievements in the field of monolithic integration, PIC's are still not competitive with fiber-based or micro-optic polarization-diversity hybrids for a number of reasons. Firstly insertion losses are considerably larger for integrated-optic than for either fiber-based or micro-optic solutions. Secondly, coherent systems are extremely sensitive to reflections, which are required to be smaller than -50 dB. So far, the influence of reflections by photonic integrated circuits has been little studied and often neglected, but there is growing evidence that PIC's cause non-negligible reflections, not only by the facets, but also by integrated-optic elements and by active/passive transitions [49][51]. Also, monolithic integration of many different optical functions on a single chip constitutes a compromise on the performance of each single element, so that overall system performance does not match the system performance achieved when using separate components. It is, therefore, questionable whether there will be a market for coherent PIC's: since they have to outperform their fiber-based or micro-optic counterparts, or they have to be much cheaper which, however, will put serious constraints on the total PIC size.

(De)multiplexers for dense WDM applications: a comparison

In this section, a specific comparison will be made between the potential of integrated-optic and micro-optic wavelength demultiplexers. The total market for WDM couplers can be divided in two categories, i.e. (de)multiplexers (i) for two wavelengths and (ii) for three or more wavelengths. Two-wavelength demultiplexers are mainly used as duplexers for two-channel communication (1.3/1.5µm), or are employed in EDFA's (0.98/1.55µm and 1.48/1.55µm). The market for WDM couplers consists for about 90% of duplexers and is completely dominated by fiber-couplers. It is, therefore, unsuitable for a comparison between micro-optics and integrated-optics. For dense WDM applications (DWDM), on the other hand, fiber-based WDM couplers are less suitable because they need to be cascaded [90][91]. This market relies entirely on micro-optics or integrated optics, as can be seen in Fig. 3. The comparison will, for these reasons, be confined to the rapidly expanding field of DWDM components.

Micro-optic devices. In the early eighties a large number of micro-optical (de)multiplexers were published. This focus was due to the fact that micro-optics is the natural solution for multimode fiber-based systems, which were dominant in the early eighties as explained in the introduction. Although some demultiplexer designs employ dichroic or interference filters (NTT [88], JDS), most micro-optical WDM designs use collimating optics and a reflecting grating (Jobin-Yvon [89], STC [94], NEC [84], AT&T [86][93], BTRL [85] and Physical Optics Corporation [87]). Such a WDM configuration can commercially yield 20 channels with a spacing of $\Delta\lambda = 1$ nm, an insertion loss of 4 dB, cross-talk below -30 dB and a thermal drift better than 0.02 nm/°C. Despite the availability of good components only a few publications on WDM transmission experiments explicitly mention the use of wavelength demultiplexers (STC [94] and GMMT [95]): most WDM system experiments use ordinary couplers and filters to perform the (de)multiplexing function. Obviously the emergence of WDM transmission systems does not automatically create a market for demultiplexers!

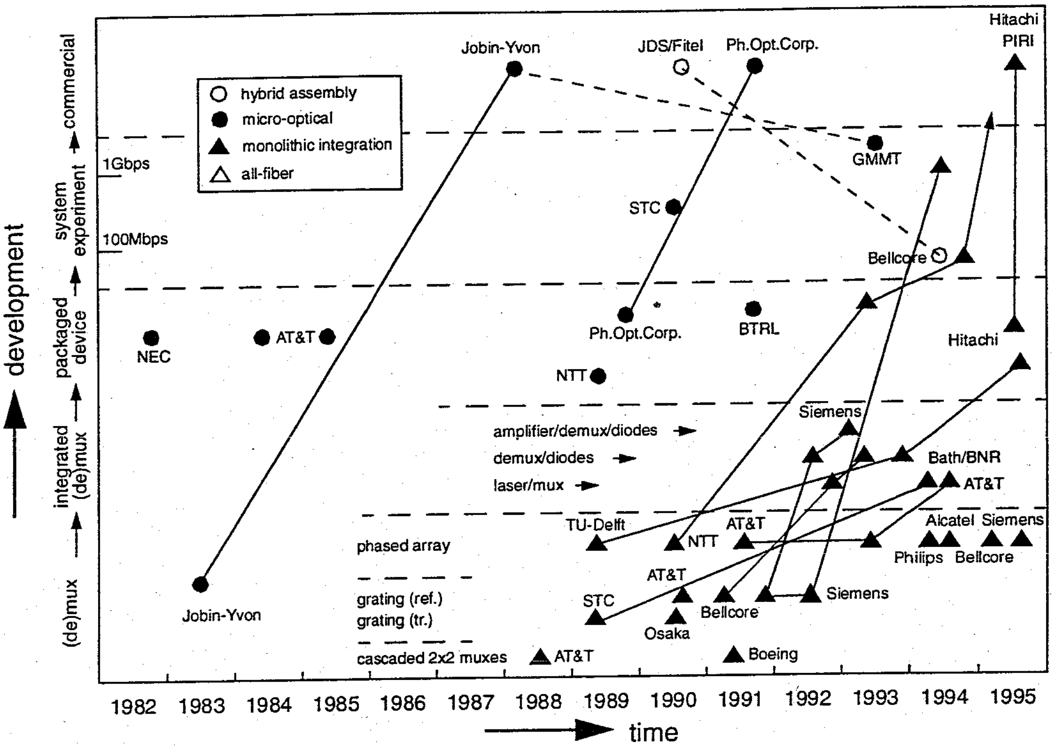

Figure 2. Overview of reported dense wavelength division multiplexers (D-WDM's), and their development in time.

In the second half of the eighties, research on micro-optic WDM's slowed down due to the advent of the monomode fiber and a shift of interest to coherent systems. When the interest in WDM returned in the early nineties, previously developed micro-optic (de)multiplexers were conveniently introduced on the market.

Integrated-optic devices. Starting at the end of the eighties an increasing number of integrated-optic devices is reported. Early planar demultiplexers applied well known techniques such as cascading Mach-Zehnder filters (AT&T [52]) or using focusing elements and dispersive gratings (STC/BNR [79][80]), thus creating a planar equivalent of the micro-optical design. Later devices combined dispersive and focusing properties in a single (curved) reflecting grating (Bellcore [66]-[68], Siemens [70]-[74]). A problem for grating-based devices is formed by the reflection loss of the grating (>6 dB), which is extremely sensitive to the steepness of the reflecting sidewall. This problem is avoided by applying an optical phased array as the focusing and dispersive element (TU Delft [54]), a concept which has found widespread application (TU Delft [55]-[58], NTT [59]-[62], AT&T [63]-[65], Philips [76], Alcatel [77][78], Bellcore [69], Hitachi [83], and Siemens [75]).

Since 1992 an increasing number of integrated devices combining (de)multiplexers with detectors (Siemens [72], Bellcore [68], TU Delft [57]) and lasers (Bellcore [67], AT&T [65]) has been reported. Recently first system experiments were reported using an add-drop filter (NTT [61][62]) and a multiwavelength receiver (Siemens [74]). These first experiments apply silicon-based components. First system experiments with InP-based components can be expected on a short term.

Right now, high-performance micro-optic (de)multiplexers are commercially available. However, integrated optical components are rapidly approaching the commercial stage: Hitachi and PIRI recently introduced the first integrated-optic demultiplexers. The performance of these (de)multiplexers compares well with their micro-optic counterparts. In addition, WDM systems, employing direct detection schemes, combine modest component requirements with the level of integration (e.g. in add-drop filters or optical cross-connects) where scaling effects might provide integrated optics with a competitive edge over other techniques.

Conclusion

In this paper, the status of integrated-optics has been reviewed in comparison with micro-optic and fiber-based technology. Early expectations of integrated optics based on the analogy with the success of integrated electronics, were found to be ill-based considering the many differences between integrated optics and integrated electronics.

For two components in OFDM networks, a specific comparison has been made between integrated-optic, micro-optic and fiber-optic solutions. Presently, integrated-optic polarization-diversity solutions cannot compete with fiber-optic or micro-optic solutions, and it seems unlikely that they will in the future. For dense WDM, competitive micro-optical wavelength-demultiplexers are commercially available, but market developments, technological considerations and scale of integration seem to be advantageous for integrated-optic solutions, as indicated by recent introductions of integrated-optic demultiplexers. Although these developments are promising, we do not expect a major breakthrough of integrated-optic components before the turn of the century.

Finally it should be noted that the different optical technologies cannot be too sharply distinguished. A butterfly-packaged digital telecommunication laser, for example, incorporates, apart from the laser, a Peltier cooler, a monitor photodiode, an NTC element, an isolator, fiber-chip coupling optics, and an internal bias and impedance matching network, so that it is more appropriate to view the laser as a hybrid module than as a planar waveguide component. As different technologies become more mature, the best solution for each individual application very likely consists of combining the best fiber-based, micro-optic or integrated-optic sub-components in a single module.

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