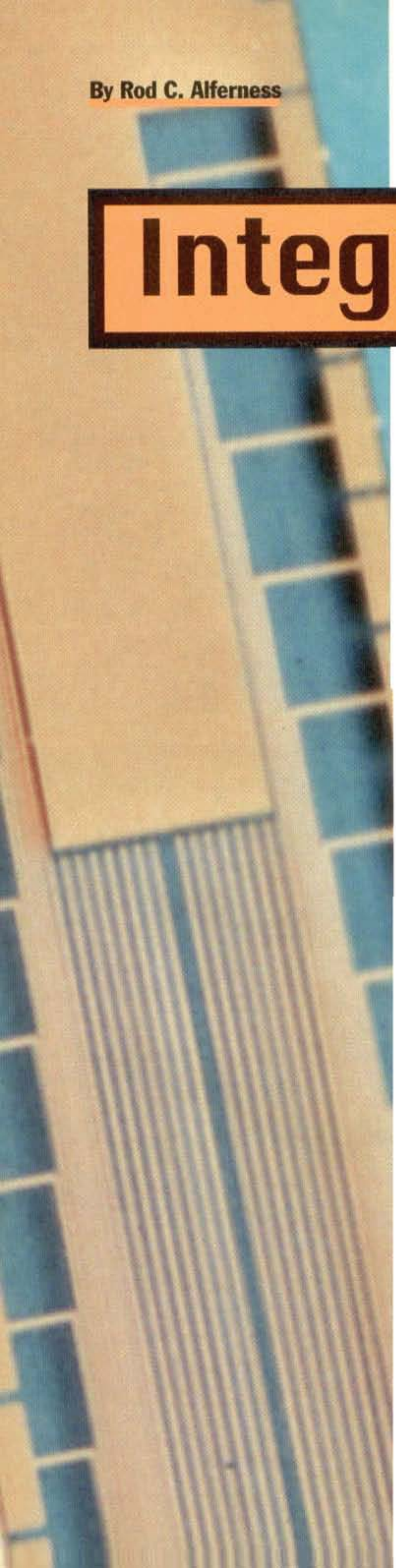
By Rod C. Alferness

Integrated Optics:

Technology and System Applications Converge



For many years, integrated optics was driven by technology and limited by applications; today, applications are driving the field and the growth potential is limited by only the performance and cost of integrated optics components. Using the history of integrated optics research as a backdrop, Alferness explores this critical technology.

The concept of integrated optics (IO) was proposed in the late 1960s. The vision of optical components—sources, modulators, switches, filters, and detectors fabricated on a chip and interconnected with on-chip waveguides to form an integrated optical circuit (IOC) providing a highly functional optical subsystem and manufactured by low-cost, mass-producible photolithographic techniques—captured the imagination of a generation of researchers that included traditional optics people and those migrating from the microwave area. It was an exciting but embryonic time for what would turn out to be the beginning of the information age revolution—the birth of ultrawideband optical communications.

The feasibility of both low loss fiber and semiconductor lasers had just recently been demonstrated. The vision of IOCs used to build sophisticated optical subsystems for communication and signal processing applications seemed to make the picture complete. A sense of the perceived potential for IO in those early days is evidenced by the naming of the first international conference on fiber communications—the Integrated Optics and Optical Communication Conference (IOOC), organized in Japan in 1977. Slowly at first, then rapidly, fiber evolved from multi-mode to higher capacity single-mode and semiconductor lasers matured to robust, stable, single-frequency, distributed feedback (DFB) lasers. As a result, optical communications systems first deployed in long haul applications over multi-mode fiber at bit-rates of 45 Mb/sec in 1980, rapidly advanced to single-mode systems at ~500 Mb/sec rates in the mid-1980s, and to gigabit/sec systems in the late 1980s. During that time, and through the early 1990s, while much work had been done, a lot of excellent technology had been demonstrated, and several commercial ventures attempted, IOCs had made very little impact in deployed commercial systems. Initially proposed as a technology of the future, integrated optics seemed to be in danger of remaining exactly that—a technology of the future!

Optical amplifiers

All that has dramatically changed. Real applications now critically depend upon the functionality of integrated optic components and subsystems. For many years, the IO field was driven by technology and limited by applications; today, applications are driving the field and the growth potential is limited only by the performance and cost that can be achieved by IO technology. A key to this radical change in the role of IO has been the development and rapid deployment of the optical fiber amplifier, which has had a profound impact on the design and implementation of optical communication systems. Prior to the use of fiber amplifiers, optical transmission spans were loss-limited to a distance of ~50 km, after which electrical regeneration was required to restore signal strength. In this case, the only optical components required are a semiconductor laser, which can also provide data encoding through direct modulation by turning the drive current on and off, and a high-speed photodetector. With optical amplifiers replacing electrical amplifiers as repeaters, signals remain in the optical domain over longer distances, without the need to be converted to electrical signals. A direct result is that over these longer distances, other impairments—notably fiber dispersion—become the limiting factor. But fiber dispersion can be overcome by using optical components with increased functionality, namely low-chirp waveguide optical modulators at the transmitter. An indication of the importance of integrated optical devices is that a majority of the traffic from the U.S. to both Europe and Asia via undersea fiber-amplified lightwave systems is now launched using high-speed waveguide modulators. These fiber amplified systems also use IO polarization scramblers to overcome otherwise limiting, polarization-dependent impairments.

Perhaps more significantly as a driver for IO subsystems is that optical amplifiers, because of their ability to simultaneously amplify multiple wavelength channels, make wavelength-division-multiplexing (WDM) a cost-effective way to upgrade the transmission capacity of existing fiber. The aggressive deployment of WDM point-to-point transmission systems has driven the need for wavelength multiplexer/demultiplexer circuits. Commercial WDM systems currently being deployed in the U.S., for example, make extensive use of waveguide grating routers to demultiplex multiple wavelengths on the fiber into separate wavelength channels. These terrestrial WDM systems, first deployed in 1995, also use waveguide modulators—both external lithium niobate ($LiNbO_3$) waveguide devices (see "What Integrated Optics is Really Used For," page 23) and InP-based integrated laser/modulators—to overcome fiber dispersion effects.

Furthermore, current WDM point-to-point systems represent only the first step in a potential evolution or migration to optical networks in which optical wavelength channels are dropped, added, and routed in the network by optical equivalents of today's electrical add/drop multiplexers and cross-connects (see Fig. 1). To build these optical network elements—a current area of active research—requires a host of highly functional optical subsystems for which IO modules, such as wavelength

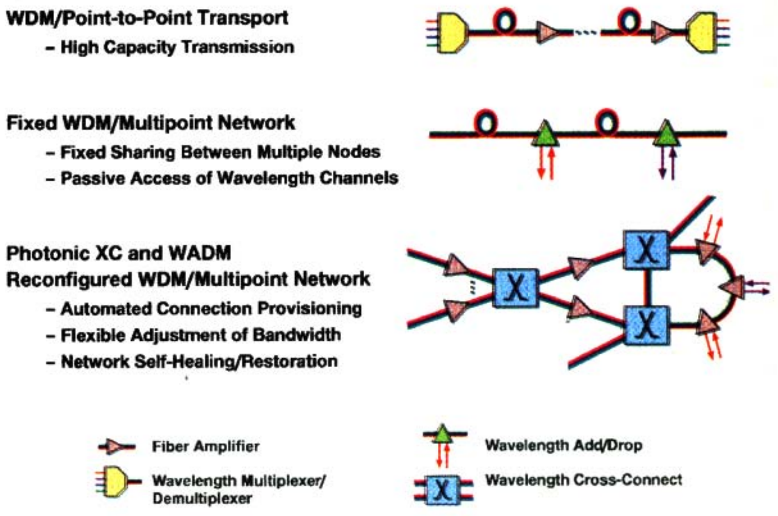


Figure 1. The evolution from optical WDM point-to-point transmission systems to reconfigurable multipoint networks.

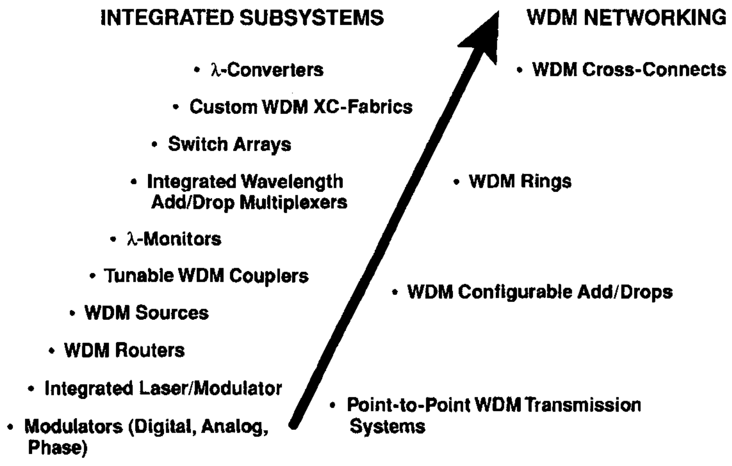


Figure 2. Advancing WDM systems and networks will require optical subsystems with higher levels of functionality and integration.

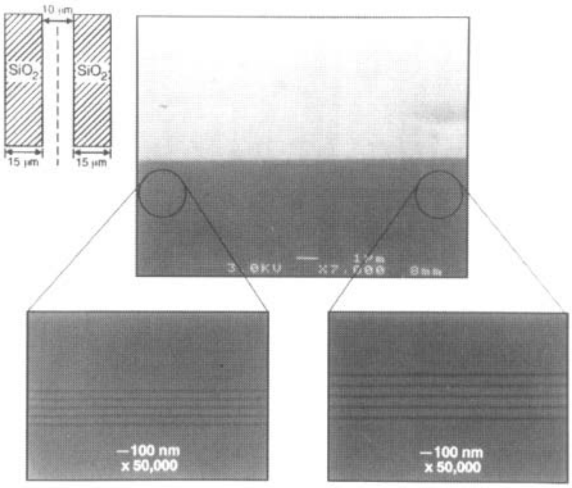


Figure 3. Electron micrograph of multiple quantum wells grown by selective area epitaxy.

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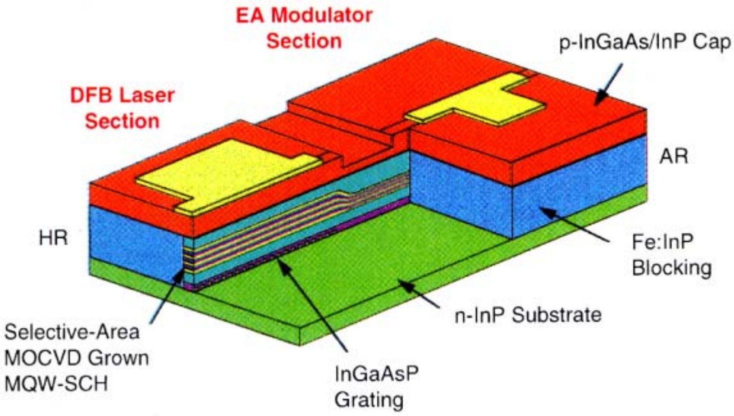


Figure 4. An integrated laser/modulator realized using selective area growth. The modulator is of the electro-absorptive type, *i.e.*, a voltage-controlled attenuator, based upon the quantum-confined Stark effect (QCSE). Similar to the classical Franz-Keldysh effect in bulk material, application of an applied field in the multiple quantum well modulator shifts the bandgap to higher values to reduce its transparency.The QCSE is very strong, allowing high extinction over short modulator lengths (~150 μm) with only a few volts.

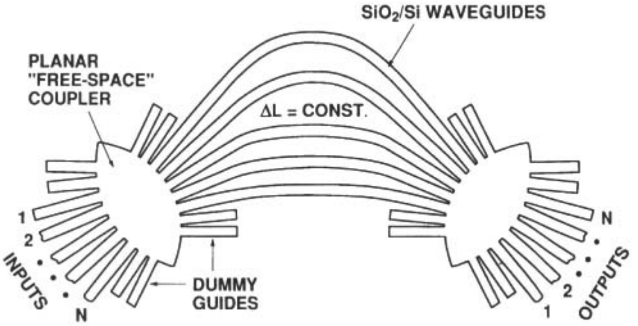


Figure 5. Waveguide grating router to provide wavelength multiplexing and demultiplexing commercial components offer eight wavelength channels with 200 GHz frequency spacing with a loss of 6-8 dB. Devices with larger numbers of channels will soon be available commercially.

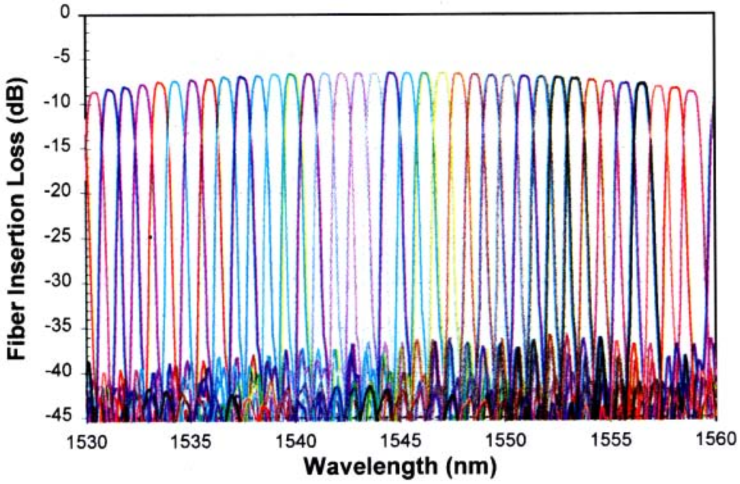


Figure 6. Measured wavelength response from a research model 36 port waveguide grating router using silica on silicon waveguides.

demultiplexers, tunable filters, optical switch arrays, wavelength, converter arrays, etc. will be key (see Fig. 2, page 17).

The optical amplifier has extended the reach and domain of optics. However, to fully exploit this expanded optical domain requires increased optical functionality in compact, cost-effective modules. This is what IO provides. After giving a brief history of IO research, this article discusses current technology and applications and offers some vision of the future.

A brief history of IO research

The original proposal for integrated optics was just that, a proposal—or a challenge, really. The technology did not exist for either the waveguide components or even the waveguides to interconnect them on a planar substrate. Not surprisingly, the early days of IO research were dominated by a pursuit of promising techniques to form low-loss waveguides on interesting planar substrates. To achieve optical waveguides, a region of high refractive index must be formed between two lower index regions. The required thickness of this area of higher index, along which the guided light propagates, depends upon the index difference between the high and low regions. Smaller index difference waveguides and longer wavelength operations require larger lateral waveguide dimensions. While planar waveguides (one-dimensional waveguiding) provided early feasibility demonstrations, strip or channel waveguides are necessary for most practical circuits and for coupling to fiber.

Not surprisingly, some of the earliest planar waveguides used glass technology. For example, by sputtering Corning 7059 glass onto substrates of the same glass, planar waveguides were formed in which the sputtered films had a higher index than the original material. Just coupling light into these early planar waveguides was an important practical and theoretical issue. Grating couplers and, especially, prisms were used to couple light in and out of the waveguides. They could also be used to observe and evaluate the optical modes of the waveguide. A mainstay of every IO research laboratory was a gigantic toolman's rotary table, used to provide the angular alignment necessary for coupling light into the waveguide. Waveguide Bragg reflection gratings that provide highly selective wavelength filters and are a key building block of today's DFB lasers were first demonstrated in 7059 glass waveguides.

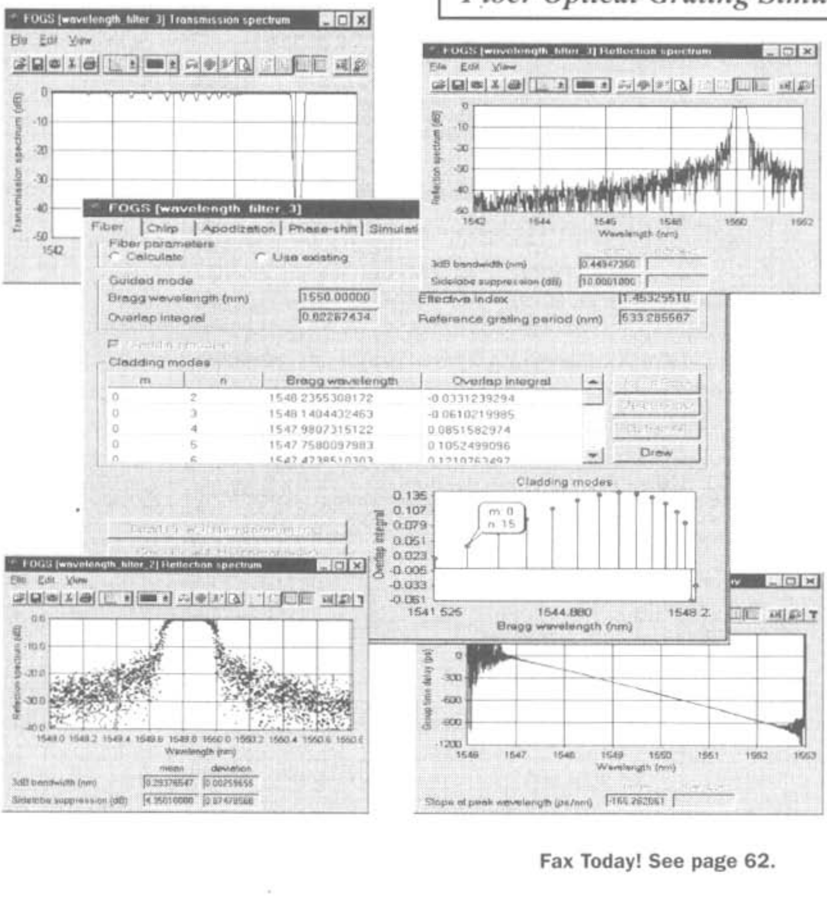
Continuing the search for better waveguide technology, ion-exchange waveguides were demonstrated in the early 1970s. This rather simple but flexible technique uses the exchange of silver ions in a molten silver nitrate solution with sodium ions in a sodium-based glass. The silver substitution provides an increased refractive index region. Strip waveguides are readily made by masking off all but the desired channel regions. Easy to fabricate and providing relatively low-loss performance, ion-exchange glass waveguide technology was a workhorse of research material system. It was used to demonstrate a family of passive components, including couplers, splitters, and filters during the 1970s and early 80s. This technology was also one of the first to be commercialized, although waveguides based on deposited silica films on silicon (as described below) is the more dominant commercial technology for passive IO components today.

While passive materials provided an early learning ground for IO research, much of the allure of IO is the promise of active subsystems. Consequently, intense efforts focused on finding ways to make waveguides in electro- and acousto-optic materials, as well as those in which lasers and detectors could be fabricated. By building on the gallium arsenide (GaAs) laser technology—waveguides formed using refractive index differences due to doping levels and material differences created by growing thin (sub-µm) material layers using epitaxial growth techniques—GaAs waveguide modulators and switches were demonstrated as early as the mid-1970s. However, growth techniques—mostly liquid phase epitaxy—were still immature, making reproducibility and propagation losses an issue.

$LiNbO_3$, a ferroelectric crystal that had been researched for bulk electro- and acousto-optic modulators, was another natural material candidate. The demonstration that waveguides could be conveniently formed by diffusing titanium (and other metals) into the crystal, provided a convenient, low capital-cost technology platform from which to explore active waveguide devices and IOCs. $LiNbO_3$ has excellent electro- and acousto-optic coefficients. Furthermore, by changing the diffusion temperature (typically ~1000°C), time, and titanium metal thicknesses and width, the waveguide properties can be flexibly and reproducibly controlled.

Concurrently, other key IO technology elements were also beginning to evolve. New electron beam mask generation techniques used to write the few microns wide waveguide patterns over the required centimeter lengths were developed. Additionally, new fabrication techniques—deposition, etching, and photolithography—were established. Indeed, IO and its special needs—large aspect ratios and curved structures, for example—provided motivation for processing technology research during this period.

Underpinned by the above waveguide and fabrication technologies, researchers demonstrated a wide variety of novel and interesting, but still not particularly practical, waveguide device candidates for future circuits. It was a time to flex the technology muscles. The list of new waveguide devices and simple circuits included modulators and switches of many varieties: acousto-optic (AO) deflectors, AO and electro-optically tunable wavelength selective couplers and filters, polarization splitters and converters, polarizers, and short pulse generators. With rather simple theories like coupled-mode, borrowed from the microwave domain as a guide, it seemed as though almost any new waveguide structure conceived, whether it used closely spaced coupled waveguides (directional coupler), Y branch splitters, Mach-Zehnder interferometer, sign-reversed phase



mismatch, periodic structures, asymmetric structures, adiabatically tapered structures, or grating lens could be designed and fabricated. And they usually worked!

At the Integrated and Guided Wave Optics (IGWO) Topical Meeting—first organized by OSA in 1972 and now called the Integrated Photonics Research Conference—and IOOC, one could always expect several really new devices or simple circuits. For the moment, it didn't matter that losses and control voltages were high or that the devices didn't work over a wide temperature range and were neither fiber-pigtailed nor robustly packaged.

Driving applications

In addition to optical communications, applications that have driven IO technology include signal processing for military systems, sensing, and consumer products. During the 1970s, the goal of a compact, robust, low-cost RF frequency signal analyzer strongly drove the technology. This sophisticated subsystem required integration of an acousto-optic deflector between two planar lenses and potentially an integrated source and receiver array—a challenging technical goal (and limited volume application) that was never commercially realized. IO chips for fiber gyroscopes—basically a Sagnac interferometer—were, on the other hand, a long time research goal and are now a commercial reality.

Lessons learned

During this period of research activity, several points became evident. First, it became quite clear that only single-mode devices would be realizable and potentially practical. While some work on multi-mode elements was pursued, trying to get all the modes to behave as designed proved untenable. At the time, this single-mode limitation was viewed as a potential roadblock, since early fiber optic systems used only multi-mode fiber. Fortunately for IO technology, the quest for ever higher capacity communication systems has driven the industry to deploy single-mode fiber.

A second conclusion was that, while the goal of integration remained important, if allusive, even individual devices implemented as waveguide (or guided wave) components offer tremendous advantage over their bulk counterparts. The small lateral and vertical dimensions (~μms) and corresponding electrode gap provide very large electrical field intensities that produce electro-optically induced index changes (Δn) with even modest applied voltage. In addition, the interaction length (L) can be made arbitrarily long (limited by loss, practical issues, and by required modulation bandwidth) so that electro-optically induced phase $\Delta\phi = \Delta nL/\lambda$, of order π necessary for typical active devices such as modulators, for example, can be achieved with voltages <5 V. By comparison, bulk modulators typically require at least a factor of 10 higher voltage. Furthermore, waveguide devices offered the advantage over their bulk counterparts of compatibility with single-mode fiber.

While compatibility is a plus, to achieve low coupling loss between an IO device and a fiber, the optical modes profile of the two should be matched. The typical mode diameter of single-mode fiber (~5–8 μm) is somewhat to substantially larger than that which one would choose for active devices to minimize control voltages, especially for semiconductor waveguide devices. Thus there are generally tradeoffs between fiber-device coupling loss and device modulation efficiency (drive voltage). With improved technology, tapered waveguides that provide a large optical mode at the end of the IO chip and a small mode in the active device region can be employed to offset these tradeoffs.

Polarization

During these earlier years, it also became apparent that polarization dependent effects would be a nagging thorn in the side of integrated optics. Waveguide characteristics depend upon polarization both through material index and the boundary condition to the wave equation. Furthermore, the electro-optics coefficients that determine the index change achieved for a given applied electric field depend on both the crystal orientation and the direction of polarization of the optical signal. Thus the so-called effective index of the waveguide mode depends upon polarization. This waveguide birefringence ultimately produces polarization dependence in devices such as couplers and filters. Also, and even more dramatic, the on/off ratio of modulators and the switching state of switches is strongly polarization dependent.

Polarization is not maintained as light propagates down a fiber. Launched linearly, polarized light emerges arbitrarily elliptical. Its polarization axes change with temperature, mechanical stress, etc. Therefore, except at the transmitter, IO devices and circuits must have substantially equivalent performance regardless of polarization. Over the years, a great deal of effort has gone into achieving effective polarization-independent operation. Solutions have included both very novel material engineering and device designs.

Integrated optics matures

In the 1980s, the field of IO entered a new phase. In the more mature technologies, like $LiNbO_3$ and ion-exchange glass, attention increasingly focused on solving issues critical to practical application. Chief among those issues were low insertion loss, fiber alignment and attachment, and robust packaging. To prove their value, these component/subsystems had to be demonstrated in system experiments for which fiber-pigtailed modules were essential. To provide low fiber waveguide coupling losses, extensive work was devoted to implementing good mode-matching waveguides to typical single-mode fiber. IO element-based system demonstrations also demanded excellent overall performance rather than optimization of a single parameter, *i.e.*, high modulation bandwidth in a modulator.

In the case of the waveguide modulator, system experiments and theoretical work in the mid-1980s began to suggest that the real system-enabling value of waveguide modulators would not come from their higher speed relative to direct modulation of semiconductor lasers. Rather, their principal advantage is their flexible waveguide circuit structures. The Mach-Zehnder interferometer, for example, can provide zero or generally adjustable chirp modulation. This means that the modulator provides the on/off modulation of intensity required for data encoding without producing any wavelength shifts during the transitions. In directly modulated semiconductor lasers, even single frequency DFB lasers, small frequency shifts are unavoidable as the laser is modulated between its low and high intensity states by changing the drive current. For operation at wavelengths of 1.3 μm where standard fiber, which represents most of the embedded fiber in the United States, has zero dispersion, the small chirp in DFB lasers was not a problem. However, when the fiber amplifier emerged with compelling advantages that convinced system designers to move to 1.5 μm to allow their use, this chirp, together with the dispersion of standard fiber at this wavelength, proved to be very limiting. This is especially true given the much longer loss-limited distances made possible by the amplifier. For example, at the bit rate of 2.5 Gb/sec, external waveguide modulators provide a two- to three-fold advantage in dispersion-limited transmission distances in standard fiber at a wavelength of 1.5 μm, compared to optimized directly modulated lasers. This means that dispersion-limited distances of ~700 km are possible with waveguide modulators.

Maturing technologies

The late 1980s also witnessed the maturing of two IO technologies—indium phosphide (InP) based semiconductors and deposited silica. These, together with titanium diffused $LiNbO_3$, are the three pillars of today's commercial products. IOCs made from the same materials as lasers and detectors offer increased levels of integration. When fiber systems migrated to the 1.3 μm and 1.5 μm wavelength windows to take advantage of the low dispersion and low loss windows of standard single-mode fiber, respectively, the InP material system replaced GaAs as the critical one. To take full advantage of the available bandwidth, single spatial mode and single frequency lasers had to been developed. In response, improved growth techniques that carefully controlled the refractive index and thickness of grown lattice-matched films on InP were developed. Metal organic vapor-phase-epitaxy (MOVPE), in particular, has proven indispensable to growing lattice matched films, including multiple quantum well structures (MQW) composed of alternating ultra-thin (~75 Å) layers of InGaAs and InP. In addition, there was much progress in semiconductor processing techniques, including high resolution wet and dry etching to define the relatively narrow strip widths (~2 μm) needed to make single-mode waveguides and allow for overgrowth of a low index cladding layer. With improved growth and processing techniques, the propagation losses, waveguide uniformity, and wafer-to-wafer reproducibility—all issues that had hindered earlier progress with semiconductor based integrated optics—improved substantially to make InP based IO a viable technology.

The improving InP technology was tested and further improved in the late 1980s when coherent transmission systems were an active research area. Such systems require tunable lasers that allow the local oscillator laser to be matched to the source laser. Furthermore, coherent receivers that require the local oscillator—a passive combiner to mix the received signal and the cw local oscillator and a photodetector—offered an excellent goal as a single chip IOC or photonic integrated circuit (a term now used interchangeably with integrated optics). The tunable laser alone forced researchers to deal with a longstanding issue for IO—the challenge of building waveguide circuits that include gain elements for lasers, as well as low-loss passive waveguide regions. The former requires a material composition whose characteristic bandgap wavelength is longer than the desired source wavelength. When current pumped and with appropriate feedback, such material forms a laser. However, even a short length of the same material, unpumped, is essentially opaque to light of that same wavelength. Consequently, a change in the waveguide material composition longitudinally along the waveguide length, to separate active and passive regions, is required. In the case of a tunable laser, such as the distributed Bragg reflector laser, the passive waveguide includes a tunable wavelength selective Bragg reflector. Early solutions to active/passive problems included the brute force approach of etching away the waveguide in all but the desired active region, and regrowing shorter bandgap material for the passive regions. While the method can be made to work, it is complicated and requires excellent etching and regrowth, and it can suffer from unwanted reflection at the active/passive interface.

Selective area epitaxy

In the early 1990s, a significantly more elegant solution, using selective area epitaxy to create active/passive IOCs on InP was demonstrated. This technique, which allows the effective bandgap of a MQW stack to be controlled across a grown wafer by appropriately designed silicon dioxide masking prior to growth, is a significant breakthrough in the potential of InP integrated optic circuit.

This powerful technique is seen in Figure 3 (page 17), which shows a scanning electron micrograph of the vertically grown MQW stacks both in the gap region between the SiO_2 mask (inset) and in the field region (gap $\rightarrow\infty$). The result is quite remarkable. By growing over the photolithographically controlled surface SiO_2 mask, the thickness and composition and, therefore, the effective bandgap wavelength of the grown material can be controlled across the wafer. The thicker quantum wells (right) grown in the gap region have a longer bandgap wavelength appropriate to gain (laser) elements. The quantum wells grown in the region outside the gap have a shorter bandgap, allowing optical transparency.

Selective area epitaxy is very well suited to fabricate IOCs that include a laser and modulator. As indicated earlier, low-chirp external modulation is essential to overcome dispersion limitations. Using integration to include both the stable single frequency DFB laser and low-chirp modulator on the same chip (see Fig. 4, page 18) offers the required functionality in a single package—a realization of the original IO vision. Integrated laser/modulators useful at modulation rates of 2.5 Gb/sec have been available commercially for several years. They are a critical enabling subsystem in the ongoing deployment of terrestrial WDM lightwave systems.

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Silica waveguides

Deposited silica waveguides, where very low loss waveguides are formed by depositing doped silica (typically phosphor doped) on a silica layer that can be on a silicon or quartz substrate, is another technology that has blossomed. Currently it is capable of producing very low loss (<.1 dB/cm), highly uniform waveguides over large areas (5" silicon wafers, for example). Furthermore, these waveguides are well matched to the fiber mode profile allowing low loss fiber-waveguide coupling.

While silica-based IO [also called planar lightwave circuit (PLC) technology] has been used by researchers to demonstrate a wide variety of passive circuits and some active (thermo-optic) components, currently its most important component is the waveguide grating router (WGR) (see Fig. 5, page 18). This elegant, highly functional waveguide circuit combines a passive $N \times N$ splitter, an array of waveguides with carefully designed path length differences, and an $N \times N$ combiner. By appropriate design of the path length differences in the waveguide array, the effective dispersion of the array is controlled so that when light from the array waveguide is mixed by the second combiner, the wavelength components are spatially separated and emerge sequentially out the waveguide output ports. In the $1 \times N$ wavelength demultiplexer mode of operation, for multiple wavelength input to one waveguide on the input side, this device acts like a "digital" prism to demultiplex the wavelength components whose wavelength spacing (actually, frequency spacing) is matched to that set by the waveguide array design. As indicated earlier, this waveguide grating router circuit is a key enabler for currently deployed WDM transmission systems. Results for a 36 channel demultiplexer are shown in Figure 6 (page 18). As an N input $\times$ N output device the circuit provides a potentially powerful periodic wavelength routing function. This IO component, as well as the InP based integrated laser/modulator and $LiNbO_3$ waveguide modulator, is commercially available from multiple vendors.

The commercial advantages

The commercial IO components market has given new life to the field in several ways. First, a real revenue stream is essential for continued R&D investment. As a result, each of the major IO technologies continues to be improved and new components are being developed. Continued research is particularly important for InP where the technology is more complex and there is significant opportunity for increased system-enabling value and an overall packaging cost reduction offered by higher levels of integration, including the monolithic integration of electronics. Second, through customer feedback, development efforts can be focused to solve real system problems. This is a mixed blessing, of course. As system builders design IO components for new networks, performance requirements continue to be pushed, placing stringent demands on the technology. For example, shaping or apodizing filters to achieve a more flat-top, step side response has long been an interesting, but academic research activity. For evolving WDM networks, such response is critically important and has, in fact, been incorporated in filters like the waveguide grating router (see Fig. 6, page 18). In another example, the potential application of configurable wavelength add/drop multiplexers and cross-connects (see Fig. 1, page 17) places very high crosstalk requirements on waveguide switch arrays. In response, highly complex $LiNbO_3$ switch arrays (with more than 150 integrated switch elements) that include crosstalk reduction stages have demonstrated –40 dB crosstalk levels. Such switches have been used in the wavelength cross-connect built to demonstrate WDM optical networks as part of the DARPA funded MONET program (see Fig. 7). Finally, the commercial success of IO will help to stimulate other technologies—for example, polymer waveguides are looking more promising—and new application areas such as sensors and consumer products.

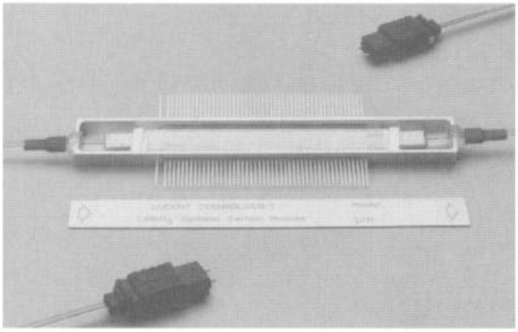

Figure 7. Low crosstalk $LiNbO_3$ waveguide switch array chip for optical cross-connects.

Future

How about the future? Research activity to address modules required for optical networking (see Fig. 2, page 17) is very active. Several approaches to WDM sources that can produce the comb of wavelengths required for WDM systems—including DFB laser arrays and a multi-wavelength source that integrates the waveguide grating router with optical gain elements on an InP substrate. First demonstration of integrated wavelength add/drop multiplexer—both on InP and using silica thermo-optic switches—has occurred. Exciting results on wavelength converter circuits have been reported. If photonic systems continue to grow, all of these elements could become key building blocks. So the future of IO looks bright; just as important, so does the present.

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