Optical Integrated Circuits: A Personal Perspective

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Invited Paper

***Abstract*—The remarkable early success and current explosive growth of electronic integrated circuits have fascinated photonics researchers since 1969 with the prospect of similar success in optical integrated circuits. Alas, physical and economic factors have stymied their efforts. Two recent commercial optical integrated circuits may be the first points on a photonic Moore's law curve. The author presents his view of the progress of optical integrated circuits since S. E. Miller's proposal in the 1969 *Bell Systems Technical Journal*.**

***Index Terms*—Optical communications, photonic devices.**

I. Introduction

The transistor was invented at Bell Labs in 1947. The first devices were based on germanium and had a clumsy point contact configuration. Later structures had a more practical field effect design. The initial yields were very poor for a single-transistor chip so that it seemed foolhardy to reduce the yield exponentially by placing N transistors on a chip. Nevertheless, in 1954, an inexperienced researcher, J. Kilby, at Texas Instruments went ahead and made a chip with a four-transistor circuit, including some passive circuit elements, all connected by external wire bonds. Some six months later, R. Noyce at Fairchild Semiconductor, which was to evolve into Intel, made a small-scale silicon integrated circuit (IC) that comprised planar transistors connected by on-chip aluminum wiring and silicon dioxide insulation.

Since 1954, the number of transistors on a chip has grown exponentially, doubling every one and a half to two years, according to Moore's Law, to approximately a billion today; a span of about 10^9 in 54 years! See Fig. 1. This remarkable growth can be attributed to several technical and economical factors:

1) the physical design of the planar field effect transistor;
2) ideal compatible materials: single-element silicon substrate, silica insulator, and aluminum wiring;
3) scalable circuit design based on low power complementary metal oxide semiconductor (CMOS) architecture; the cost per transistor drops inversely as the number N of transistors per chip increases;
4) real applications (e.g., memory and microprocessors) that require large-scale arrays of identical elements, which can be scaled down in size, seemingly without limit, as the processing technology advances;
5) progressively complex and successful applications that provide the funds to invest in the processing technology required for the next generation of reduced gate length.

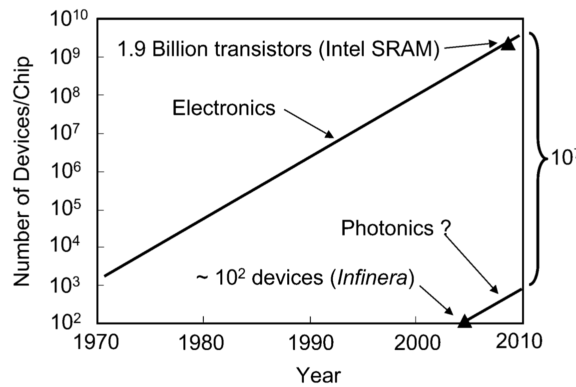

Fig. 1. Moore's Law for CMOS ICs and maybe for PICs. [MT = million transistors]. Created by Rod Tucker.

We will see in the following that photonic integrated circuits (PICs) have progressed much more slowly than electronic ICs (EICs). The PIC was first proposed, as far as I know, in 1969 and the first commercial application, requiring about 10^2 devices, occurred in about 2005, some 36 years later. The reasons for this lag generally follow the list above in a negative fashion:

1) active photonic devices are based on binary, ternary and quaternary materials that are much harder to control than Si;
2) photonic device sizes are determined by the optical wavelength, which is much larger than the electron size limit in EICs;
3) PICs require a wide variety of different devices (e.g., lasers, detectors, modulators, multiplexers, attenuators);
4) few applications that require both large-scale integration and high volume, with attendant low cost, have been identified.

In our taxonomy of integrated optics, PICs contain only optical components, not electronic devices. As the capabilities of PICs and EICs advance, it is clear that it would be advantageous to combine on the same substrate both PIC functions and high-speed electronic data processing. If the PIC and EIC functions are provided on the same substrate, or chip, we will call this an optoelectronic IC (OEIC). If two or more substrates of different composition are needed, we will designate the IC as a hybrid IC. Hybrid examples to be discussed later include:

1) InP-based PIC wire bonded to a Si EIC;
2) InP-based laser optically coupled to Si CMOS OEIC.

Manuscript received January 14, 2008.

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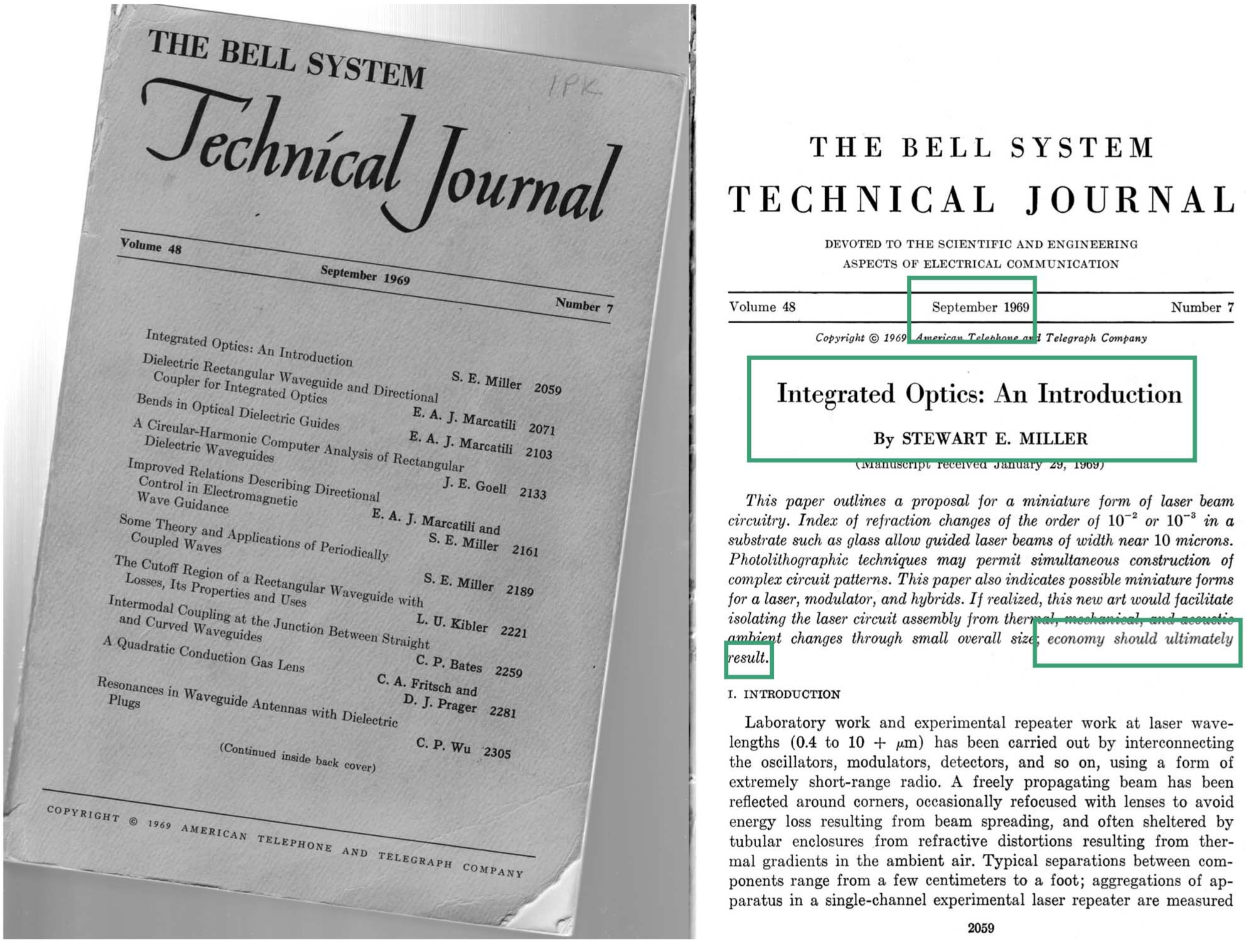
Digital Object Identifier 10.1109/JLT.2008.922149



THE BELL SYSTEM
Technical Journal

Volume 48 September 1969 Number 7

Integrated Optics: An Introduction — S. E. Miller 2059
Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics — E. A. J. Marcatili 2071
Bends in Optical Dielectric Guides — E. A. J. Marcatili 2103
A Circular-Harmonic Computer Analysis of Rectangular Dielectric Waveguides — J. E. Goell 2133
Improved Relations Describing Directional Control in Electromagnetic Wave Guidance — E. A. J. Marcatili and S. E. Miller 2161
Some Theory and Applications of Periodically Coupled Waves — S. E. Miller 2189
The Cutoff Region of a Rectangular Waveguide with Losses, Its Properties and Uses — L. U. Kibler 2221
Intermodal Coupling at the Junction Between Straight and Curved Waveguides — C. P. Bates 2259
A Quadratic Conduction Gas Lens — C. A. Fritsch and D. J. Prager 2281
Resonances in Waveguide Antennas with Dielectric Plugs — C. P. Wu 2305

(Continued inside back cover)

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THE BELL SYSTEM
TECHNICAL JOURNAL

DEVOTED TO THE SCIENTIFIC AND ENGINEERING
ASPECTS OF ELECTRICAL COMMUNICATION

Volume 48 September 1969 Number 7

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Integrated Optics: An Introduction

By STEWART E. MILLER

(Manuscript received January 29, 1969)

This paper outlines a proposal for a miniature form of laser beam circuitry. Index of refraction changes of the order of 10^{-2} or 10^{-3} in a substrate such as glass allow guided laser beams of width near 10 microns. Photolithographic techniques may permit simultaneous construction of complex circuit patterns. This paper also indicates possible miniature forms for a laser, modulator, and hybrids. If realized, this new art would facilitate isolating the laser circuit assembly from thermal, mechanical, and acoustic ambient changes through small overall size; economy should ultimately result.

I. INTRODUCTION

Laboratory work and experimental repeater work at laser wavelengths (0.4 to 10 + μm) has been carried out by interconnecting the oscillators, modulators, detectors, and so on, using a form of extremely short-range radio. A freely propagating beam has been reflected around corners, occasionally refocused with lenses to avoid energy loss resulting from beam spreading, and often sheltered by tubular enclosures from refractive distortions resulting from thermal gradients in the ambient air. Typical separations between components range from a few centimeters to a foot; aggregations of apparatus in a single-channel experimental laser repeater are measured

2059

Fig. 2. 1969 BSTJ Cover and First Page of S. E. Miller article [1].

A. Disclaimer

This memoir was written with the understanding that it be based on my personal recollections from years at Bell Labs and later. It is not intended as a comprehensive history that acknowledges all the significant worldwide contributions to integrated optics. That would be too big a job.

II. Origins of PICs at Bell Labs

In my experience, Stewart E. Miller made the first serious proposal for a PIC in 1969 [1]. At the time of the first demonstration of the laser in 1960, Stew was Director of a laboratory doing research on millimeter waveguide transmission systems. I was a member of his lab and was greatly influenced by his proposal. We were located at the Crawford Hill Lab of Bell Labs in rural Holmdel, NJ. The laser was similar to a microwave source but with shorter wavelength and offered the possibility for improved telecommunications. His lab therefore changed its emphasis to laser-based telecom. By 1969, EICs had made significant commercial progress with more than 10^3 transistors per chip (see Fig. 1). It was a natural step to consider integrating some of the photonic components in a network circuit element, such as a repeater between optical fiber transmission links that provided regeneration and routing functions, with the goal of achieving improved performance and lower cost.

Fig. 2 shows the cover of the September 1969 issue of the old *Bell System Technical Journal* (BSTJ) and the first page of the Miller article. Historically, many of the important Bell Labs research and development results first appeared in the *BSTJ*. Fig. 3 shows some of the figures from the Miller article that illustrate the planar guided-wave devices he envisioned as comprising an integrated optical circuit, or PIC, as we would say today. The influence of his microwave orientation is evident.

A planar strip **dielectric waveguide** is illustrated in Fig. 3[a]. Dielectric waveguides had been used in his lab to connect millimeter wave components in place of metal waveguides, which were getting difficult to manage at short wavelengths. Over the years a variety of optical dielectric waveguides, in which $n_2 > n_1$, where n_2 is the core refractive index and n_1 the cladding index, have been employed in photonic devices and interconnects. For example:

1) passive waveguides in silica with P- or Ge-doped core;
2) polymer waveguides in PMMA, in which UV radiation produced the cross-linked core [2]
3) silicon waveguide cores surrounded by silica and air cladding on commercial silicon-on-insulator (SOI) substrates; the large index difference allows small modal cross section and short radius bends ("silicon wire" guides); a larger modal cross section, for easier coupling to single-mode fiber, can be obtained using a rib structure, rather than buried structure in Si (see later section);

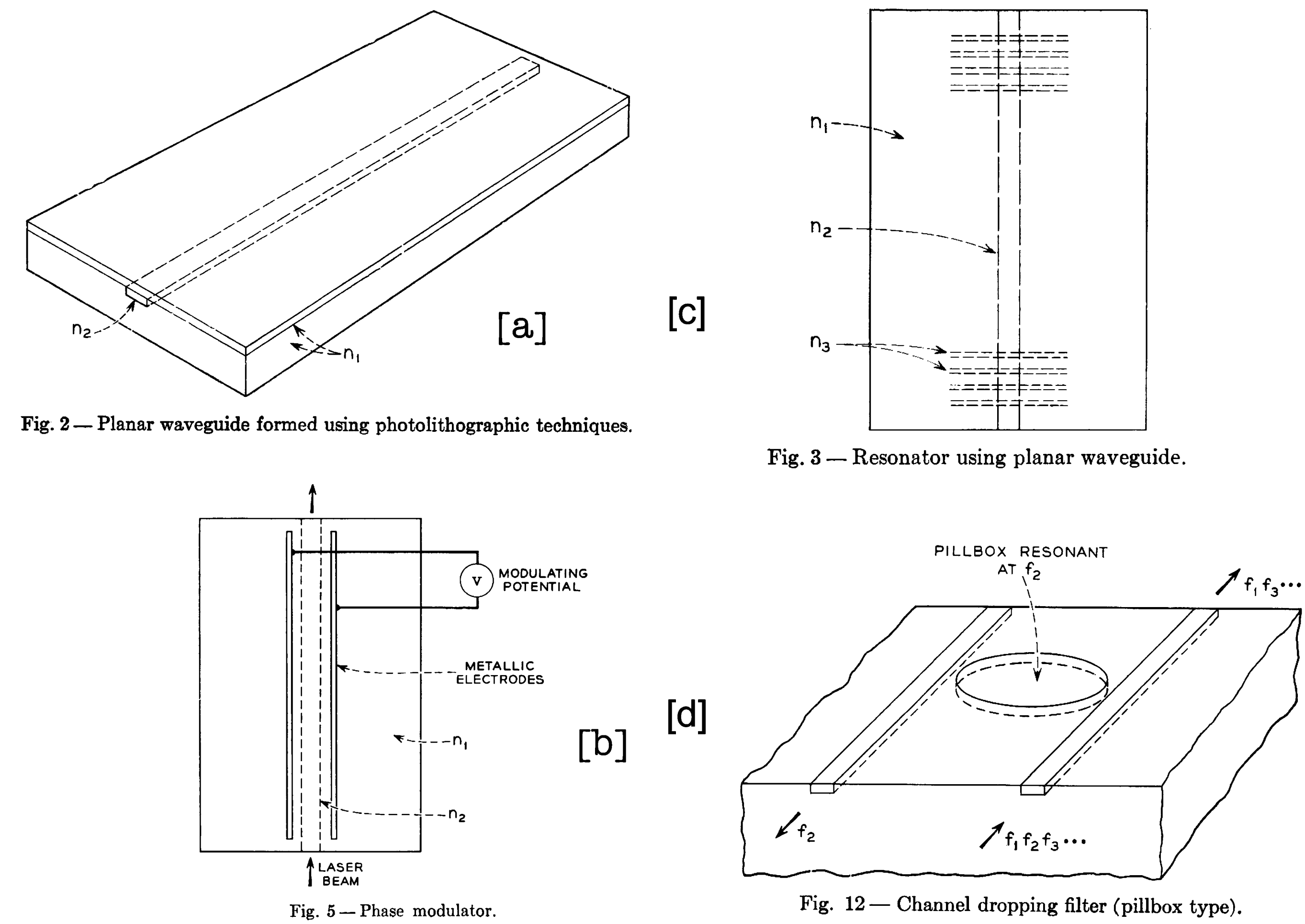

Fig. 3. Figures from 1969 BSTJ [1].

4) buried waveguides in ternary and quaternary semiconductor lasers and detectors, in which composition controls indices;
5) titanium-diffused lithium niobate waveguide modulators, in which Ti diffusion defines the core [3].

Fig. 3[b] is a schematic of a proposed **waveguide phase modulator**. It has the efficiency advantage of confining the optical and modulating fields to the same narrow strip. The Ti-diffused lithium niobate waveguide was invented [3] in 1974 and has been employed in many commercial wideband modulators of various configurations.

Fig. 3[c] illustrates a proposed **planar resonator** with Bragg grating mirrors that can be used as an optical filter or laser cavity. The first laser based on the Bragg resonator was demonstrated in 1971 in PMMA doped with rhodamine 6G as the gain medium [4]. It was subsequently named a distributed Bragg reflector (DBR) laser and has been realized in commercial semiconductor devices. An important variant of the Bragg resonator is the distributed feedback (DFB) resonator, which comprises a *continuous* grating. The first DFB laser was demonstrated in 1971 in doped dichromated gelatin [5] and, subsequently, in commercial semiconductor lasers.

The laser resonant wavelength in the DBR, a form of Fabry–Pérot resonator, is determined by the spacing, L, between gratings and the waveguide index n. The roundtrip phase change at resonance is given by

$$\Phi = \{2\pi n/\lambda)L + \phi\}2 = m2\pi$$

where $\phi = \pi/2$ is the phase change on reflection from a Bragg grating and m is an integer. The frequency interval between resonances is

$$\Delta v = c/2\,nL$$

with c the vacuum velocity of light. In order to obtain a single-longitudinal-mode laser, $\Delta\nu$ must be less than the gain bandwidth of the medium and the reflection band of the gratings.

The DFB [6], on the other hand, corresponds to a continuous grating with $L = 0$. It supports two closely spaced resonances straddling the Bragg wavelength, $\lambda_B = 2n\Lambda$, where Λ is the grating period. A small asymmetry in the longitudinal laser structure, such as the points of cleavage at either end, can favor one mode, effectively yielding single-mode operation. A more reliable method for achieving single-mode operation is to split the grating in two and introduce a quarter wave phase shift by separating halves by $\lambda_B/4n$. In effect, the resonator be-

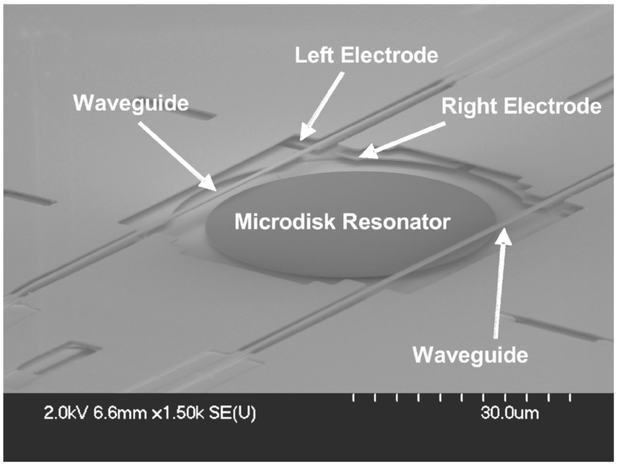

Fig. 4. Silicon microdisc resonator with variable waveguide couplers [8].

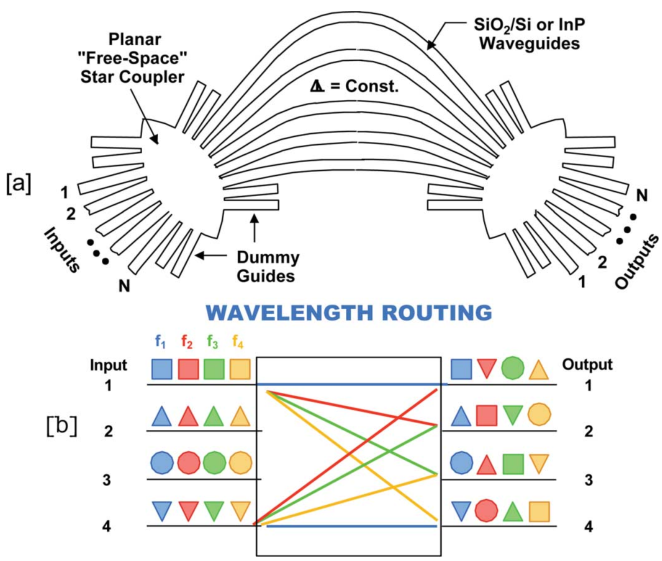

Fig. 5. [a] Arrayed waveguide grating router; [b] wavelength routing diagram.

haves like a DBR with $L = \lambda_B/4n$ and $\Delta v = 2c/\lambda_B = 2v_B$ where v_B is the operating laser frequency. Thus, the next mode $(m = 2)$ is outside the reflectivity band of the Bragg grating.

Fig. 3[d] depicts a channel-dropping filter based on a **ring resonator**. This figure is from an article by Marcatili, [7] another member of Miller's lab, in the same September 1969 issue of BSTJ. As in microwave systems, the resonant cavity selects carrier frequency f_2 from a frequency division multiplexed (FDM) carrier spectrum. Currently, silicon microdisk resonators with very high $Q(\sim 10^5)$ have been reported [8]. A photo of a microdisk resonator with electrostatically controlled coupling-waveguide spacings is shown in Fig. 4. The coupling ratios can be varied through under-, critical-, and over-coupled conditions.

III. Arrayed Waveguide Grating Router

The arrayed waveguide grating router (AWGR) is a planar device that has proven to be ideal for multiplexing and demultiplexing wavelength-division-multiplexed (WDM) spectra, as well as serving as a fast wavelength-controlled switch. A schematic diagram of the device is shown in Fig. 5. It consists of two star couplers connected by an array of waveguides of progressively shorter lengths. (Note: WGR was the abbreviation chosen by Bell Labs researchers; AWG was chosen by NTT. AWG has prevailed, but we offer the four-letter acronym AWGR as another option.) In the following, I give my view of the development of this key planar element.

An ideal lossless **star coupler** has M_I inputs and M_O outputs such that all the power P_j input to port j is equally distributed to all output ports, $P_k = P_j/M_O$ (i.e., without loss). In a general case, the number of input and output ports need not be equal; however, the input power is still ideally divided equally among all outputs without loss. Corrado Dragone, at the Crawford Hill Lab, invented an ideal planar star coupler in 1989 [9], [10]. As shown in Fig. 5, the input and output waveguides of each star converge on a planar "free-space" region. The guides approach their neighbors adiabatically (gradually), where the gap between adjacent waveguides converges toward zero. In practice, the gap width is limited by the photolithography. In theory, there is no coupling between widely spaced guides far from the free-space region but the coupling gradually increases as neighboring guides approach. Dragone showed that power is inherently coupled into adjacent guides with a particular distribution and phase at the input to the free-space region. Ideally, with just one input guide excited, the array of coupled guides, as they enter the input to the free-space region, produces a far field at the opposite edge of the free-space region such that all the output guides in the waveguide grating array are excited uniformly and without spillover loss. This simulated and, later, experimentally demonstrated [11], efficient performance was quite a surprise since earlier "brute force" star couplers were quite lossy. An explanation is offered in [12]. Intuitively, the output mode represented by the uniform distribution in the far field of the free-space region can be regarded as the adiabatic transformation of the input array super-mode comprising the single excited input guide. (Note: The "dummy" waveguides in Fig. 5 ensure that all guides connecting the free-space region experience the same environment simulating an infinite array of waveguides. Then crystallographic Bloch modes can be used in the analysis; and the uniform excitation of the waveguide grating array viewed as a Brillouin zone.)

The lossless star coupler is the key element of the NXN multiplexer, [13] or AWGR, shown in Fig. 5. Suppose that only the central input port of the left-hand star is excited; the inputs to the waveguide grating array will be uniformly excited in phase thanks to the adiabatic coupling. As the wave front propagates through the grating array it's phase front is skewed by $\Delta\theta/a$, where $\Delta\theta$ is the phase-shift difference between adjacent guides at the inputs to right-hand star. Since

$$\Delta\theta = (2\pi n/\lambda)\Delta L$$

with ΔL the difference in length of adjacent grating guides, the phase front angle skews linearly as $1/\lambda$ varies. By reciprocity with the left-hand star, all the power is now focused on one of the output ports of the right-hand star as determined by λ.

As noted by Dragone, the AWGR is a generalization of the 2×2 Mach–Zehnder multiplexer, where the beam splitters

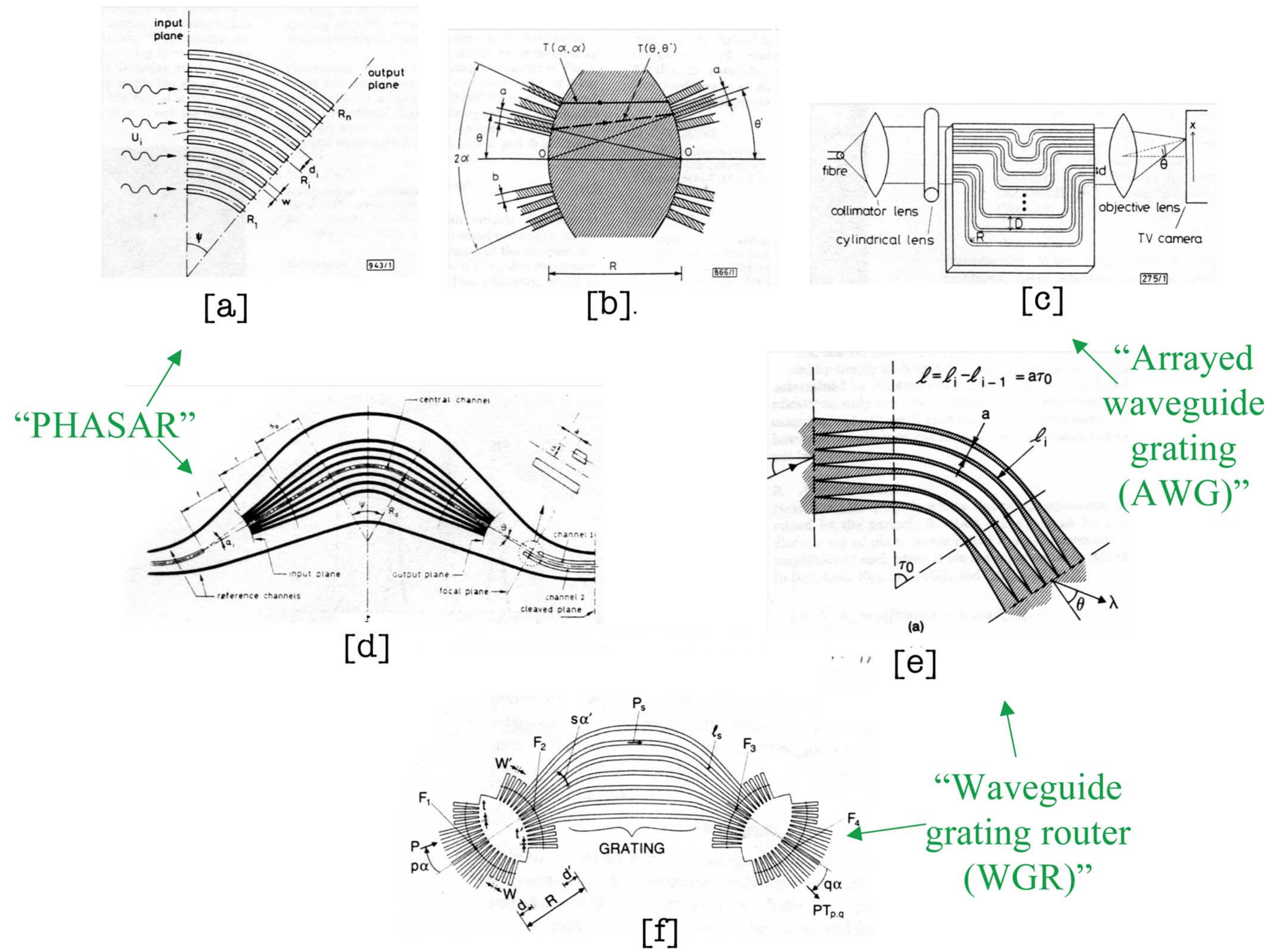

Fig. 6. Origins of the AWGR. Created by C. R. Doerr.

serve as lossless stars and the two connecting arms of unequal length serve as the waveguide array. Others have also proposed the use of a waveguide grating array as a dispersive element (and such waveguide arrays have been used in microwave frequency scanning antennas) but they have not incorporated an efficient star. Fig. 6 compares these contributions: [a], [c] and [e] show the waveguide gratings proposed by Smit, [14] Takahashi, [15], and Dragone, [16], respectively. The grating in the “Phasar” [17] multiplexer in [d] is illuminated by the far field from an input waveguide, which provides non-uniform excitation that extends beyond the array inputs. Similarly, the “AWG” [15] is excited by a lens with nonuniform distribution and excess loss. Only the Dragone star shown in [b] [11] in the “WGR” configuration [f] [7] can provide a square distribution that is uniform over the grating array with no excess spillover loss at the edges, in the ideal case.

The wavelength chart in Fig. 5 illustrates the routing behavior of the AWGR when all input ports are excited by a WDM spectrum with equally spaced frequencies. If only one input port is excited by a WDM spectrum, the device serves as a demultiplexer. If only one output port is used, the device is a multiplexer. If a discretely tuned laser excites only one input port, the device is a wavelength-controlled switch, routing each color to its own output. If all ports are used, novel applications can be realized particularly by taking advantage of the periodicity (free spectral range) of the AWGR response. [19]

IV. Early Examples of Integration

Two early examples of an OEIC are a) the monolithic repeater comprising transistor detector and amplifier, and laser on a GaAs substrate [20]; and b) the PIN-FET combining a PIN photodiode with a JFET field effect transistor amplifier on an InP substrate. [20] They combine III–V photonic with III–V electronic elements on the same chip. Such monolithic ICs have not been pursued commercially because non-integrated hybrid transceivers, with separate optimized photonic III–V components and electronic Si transistor-based components, have higher performance and lower cost, at least at the current telecom rate of 10 Gb/s. However, III–V EICs may yet become competitive with Si CMOS ICs at speeds >100 Gb/s, which may lead to III–V OEICs. On the other hand, Si OEICs may already be near, as we discuss later.

An early effort to integrate two photonic functions combined a laser and a modulator. [22] The challenge here was to join a waveguide with a bandgap that provides laser gain with a modulator whose bandgap provides transparency, on the same chip. The first successful InP laser + modulator combination was

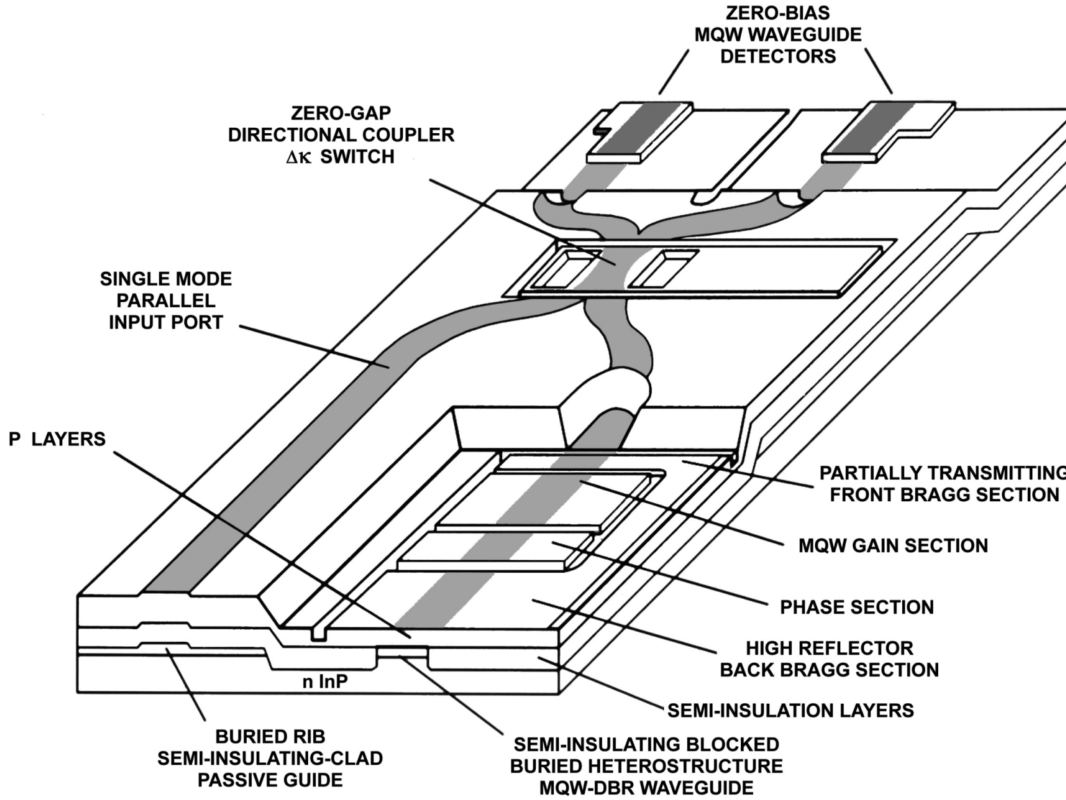

Fig. 7. InP heterodyne receiver [24].

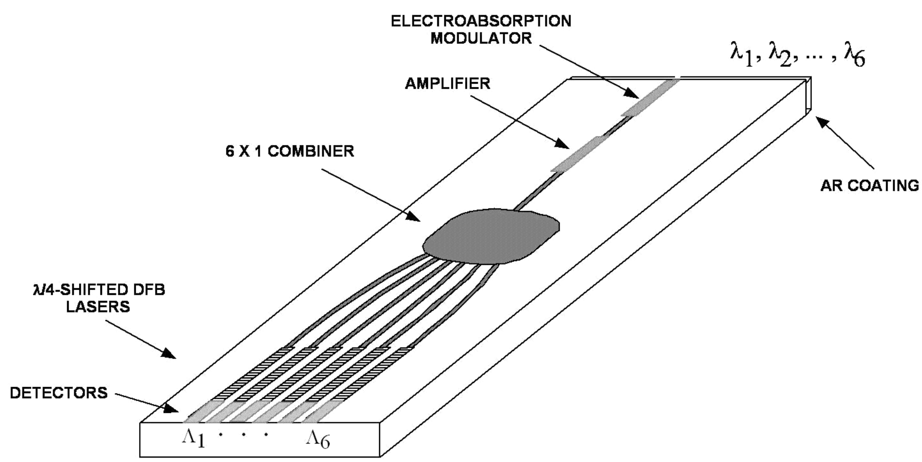

Fig. 8. Selectable six channel transmitter [25].

demonstrated in 1987; this device is now called an **electroabsorption modulator laser (EML)** [23].

The **integrated heterodyne receiver** was an ambitious early PIC [24]. The InGaAsP chip is illustrated in Fig. 7, which shows a continuously tunable 1.5-μm multi-quantum well (MQW)-DBR laser with a single-mode directional coupler/switch and zero-bias MQW waveguide photodetectors. The authors achieved error-free reception of FSK-modulated pseudorandom digital code at 105 Mb/s. While this research device was ahead of its time, it seems likely that, with processing advances and the growing need for heterodyne systems to improve spectral efficiency, we may soon see InP heterodyne receivers integrated with silicon data processors.

A six-wavelength **laser array** with an integrated amplifier and modulator designed for transmission of a single selectable wavelength is shown in Fig. 8 [25]. This research PIC was intended as a transmitter for a WDM system with fixed channels spaced by 200 GHz. The same chip can serve many transmitter channels, by activating the appropriate laser, thereby saving inventory costs.

A **multifrequency, or WGR, laser** was proposed [26] and demonstrated [27] in 1994. The device, illustrated in Fig. 9, integrates an AWGR into the cavity of a laser, where it serves to select a Fabry–Pérot cavity frequency. Internal semiconductor optical amplifiers (SOA) select the laser frequency by providing gain on a particular path. A similar structure can also operate as a tunable filter with gain or as a tunable receiver with photodiodes in place of SOAs.

The AWGR has proven to be a remarkably fertile device in WDM system applications. Fig. 10 illustrates an

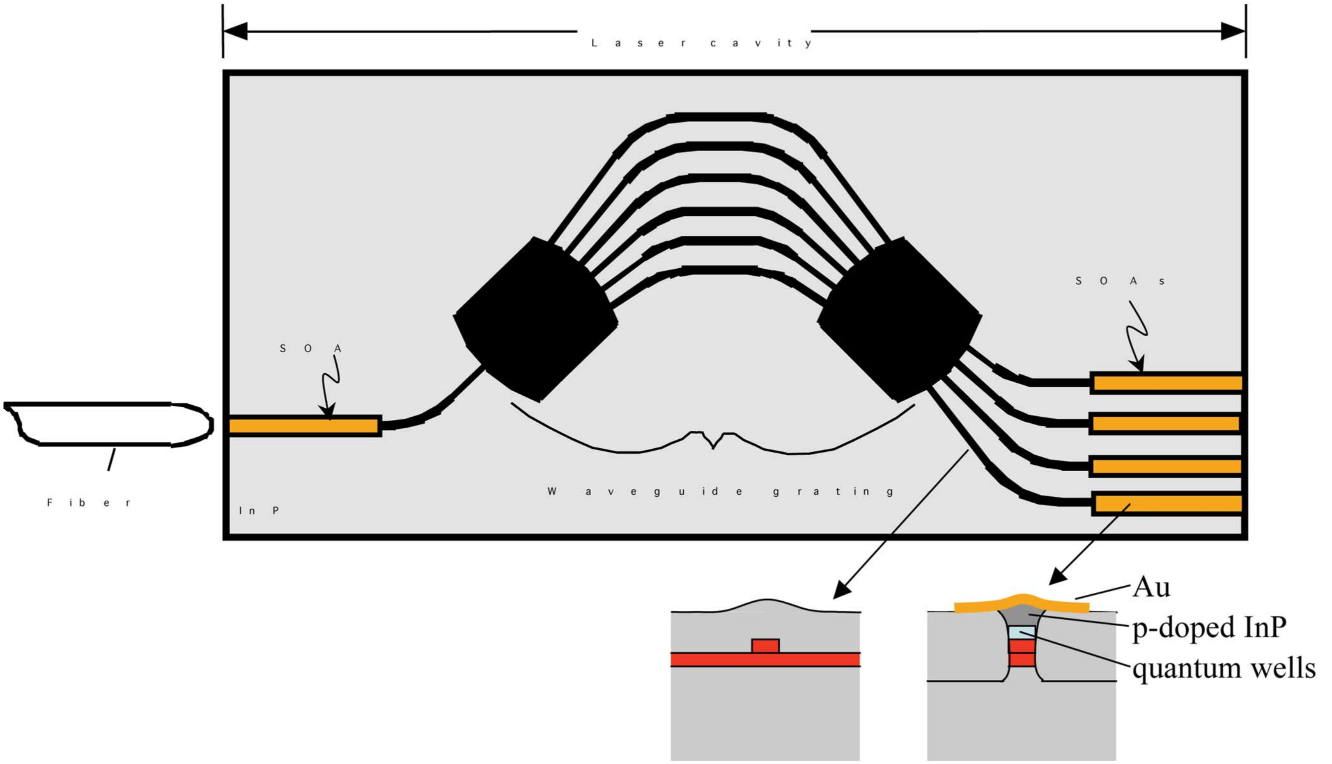

Fig. 9. WGR multifrequency laser [26], [27]. Created by C. R. Doerr.

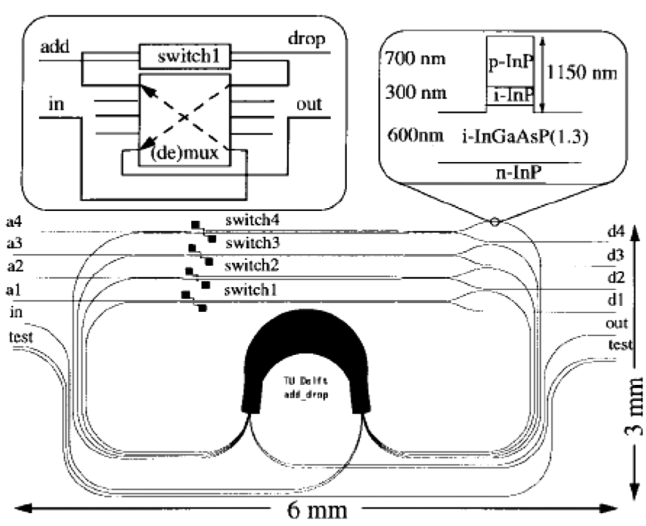

Fig. 10. InP reconfigurable optical add–drop multiplexer [28].

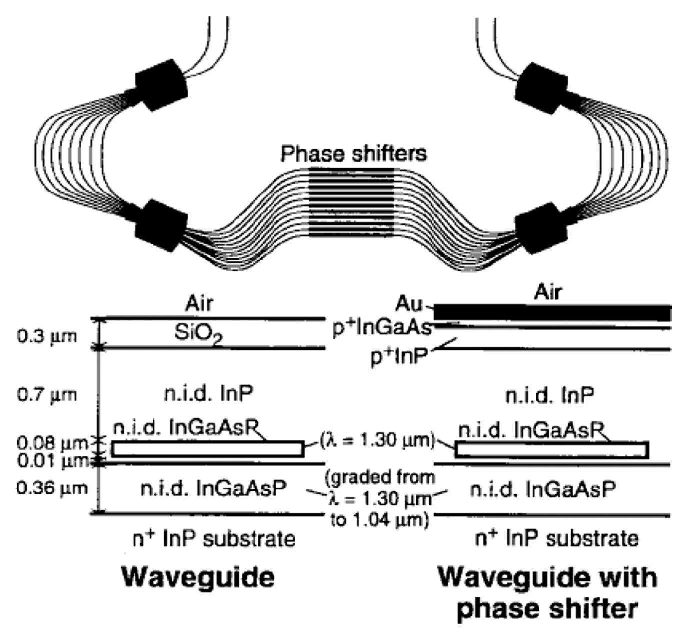

Fig. 11. 2×2 wavelength selective switch [29].

early InP integrated **reconfigurable optical add–drop multiplexer (ROADM)** [28]. It has four-channels and comprises a (PHASAR) AWGR demultiplexer integrated with Mach–Zehnder interferometer electrooptic switches.

Fig. 11 depicts an early **wavelength selective switch (WSS)** in InP [29]. It is a two-input $\times$ two-output, six-channel, WDM cross connect in InP that can route any wavelength signal to a given output. It consists of two interleave-chirped waveguide grating routers connected by an array of waveguides with current-controlled phase shifters. This device is just one of a host of components based on combinations of one or more AWGRs. They afford unparalleled capability and reflect considerable insight and ingenuity. Doerr and Okamoto, two of the principal contributors to the field, have written a thorough summary of AWGR-based components, including theory of operation and experimental performance, in a recent chapter [19].

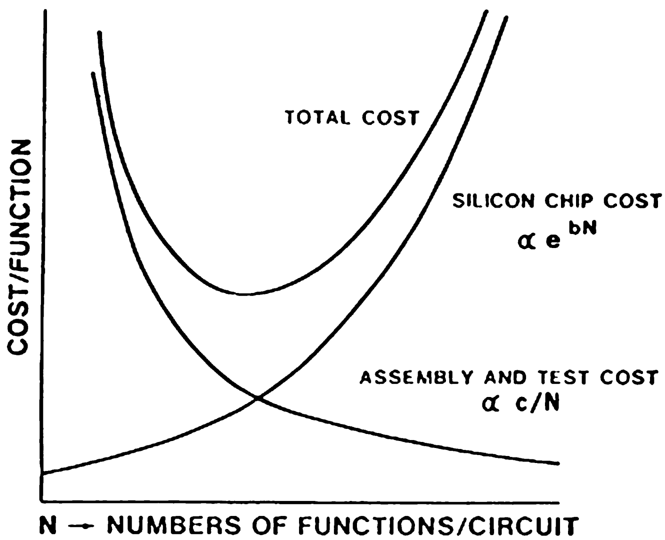

Fig. 12. Optimizing scale of integration: Cost/function versus complexity [30] (b and c are constants).

V. Commercialization of Integrated Optics

More than 35 years after S. E. Miller's proposal, we now have at least two examples of commercial integrated optical circuits. Their emergence at this time can be attributed to lessons learned in the processing of Si ICs over many years and the identification of two applications that can justify the large investments required.

InP-Based PIC

The first application of commercial medium-scale integrated optics is a pair of InP-based PICs that support ten 10-Gb/s channels in transmitter and receiver chips, respectively. These PICs are key elements in a much larger expensive telecom system; thus, a relatively high cost and small volume, compared with Si ICs, is economically acceptable. Infinera is the company that designed and fabricated the PICs and system. We describe some of the features of the PICs below; a detailed account can be found in a recent chapter [30].

The general business proposition for employing ICs is illustrated in Fig. 12 [30], [31]. The cost of a chip (or circuit) includes the fixed cost of design and production of a mask set. In addition, the cost increases exponentially with number of elements (or functions) N due to the growing probability of finding a defect that requires discarding the entire chip (yield). On the other hand, the cost of assembly and testing of a chip can be divided by the number of elements to get a cost per element that decreases as $1/N$. The minimum defined by the sum of yield and processing costs sets the economical level of integration. As the yield curve improves and moves to the right, the minimum cost per function decreases as N increases. For Si ICs, N is about one billion today (Fig. 1) and, for the Infinera PICs, N is about 100, as noted later.

The commercial WDM application is illustrated in Fig. 13. The receiver chip comprises an AWG demultiplexer and ten PIN photodiodes; the transmitter chip comprises a multiplexer and ten channels, each containing a tunable DFB laser, optical performance monitor, electroabsorption modulator, and a voltage controlled attenuator to equalize the channels. Thus, the 100-Gb/s commercial transmitter contains 41 elements. An experimental 40 channel by 40 Gb/s transmitter contained 161 photonic elements.

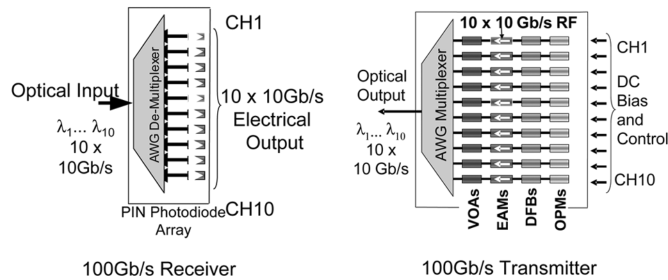

Fig. 13. Infinera receiver and transmitter PICs [30].

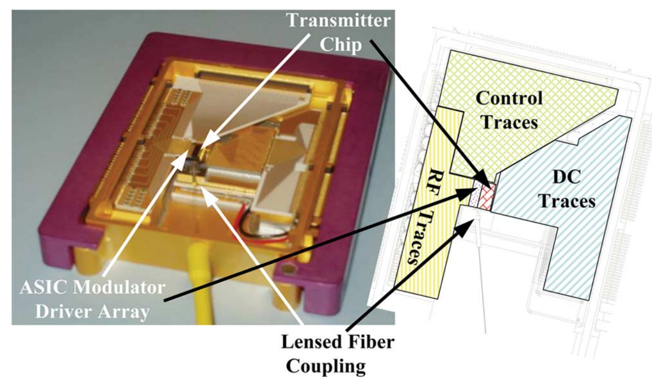

Fig. 14. Transmitter PIC showing wirebonds to Si ICs and fiber coupling [30].

A photo of the 100-Gb/s transmitter is shown in Fig. 14. Since III–V electronics is not competitive, in cost or performance, with Si CMOS at 10 Gb/s, Si ICs are situated close to the InP PIC, permitting short broadband wirebond connections to the modulator drivers. Thus, the transmitter can be regarded as a hybrid OEIC. The coupling to the output transmission fiber can also be seen in the photo.

The chief commercial advantage of the PIC is in its reduction in the number of component coupling and packaging steps. The result is greater reliability, lower cost and power, and smaller size.

Silicon Photonics

The remarkable success and capability of CMOS electronics has long motivated university and industry research on silicon photonics, with the goal of processing the electronic and photonic functions on the same chip in a public CMOS fab. (At present, the device developer must fabricate the three to five PICs, since public fabs do not exist.) Conventional IC wiring would allow broadband photonic–electronic interconnects and high-performance digital signal processing. Gunn and Koch review recent progress in silicon photonics in their recent chapter [32]. Some highlights follow.

The mode size in a waveguide is a function the effective index difference between core and cladding. Fig. 15, [32] shows three designs for Si guides on silicon-on-oxide (SOI) substrates in order of increasing confinement. (Note: for Si, $n = 3.5$; $SiO_2, n = 1.4$; air, $n = 1$.) In Fig. 15[a], the shallow rib step

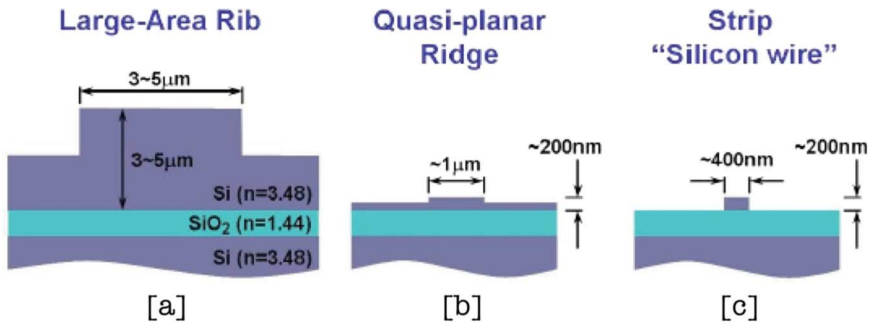

Fig. 15. Three designs for silicon waveguides [31].

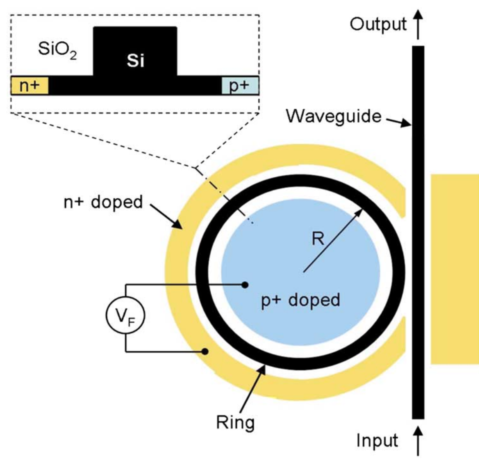

Fig. 16. Plasma-controlled ring resonator modulator [32].

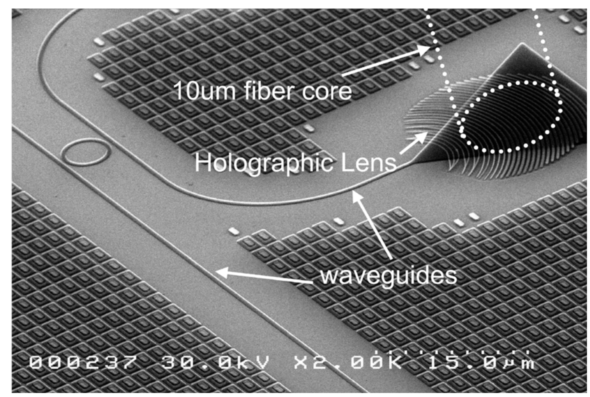

Fig. 17. Silicon photonic circuit with external fiber, grating coupler, waveguides and ring resonator [31].

gives weak lateral confinement and large mode size; the thinner vertical ridge dimension in [b] gives somewhat tighter confinement; and the strip or "silicon wire" guide in [c], with 400 $\times$ 200 nm Si surrounded by air and SiO_2, provides the smallest mode size. The tighter confinement allows for tighter bend radii; the larger mode size allows for more efficient coupling to optical fiber with $\sim$8-mm diameter mode diameter.

Fig. 16 [33] pictures a silicon wire ring resonator (diameter = 12 mm) tuned to $\sim$1.5 μm and coupled to a straight waveguide as deomonstrated at Cornell. The effective index of the ring can be tuned by injecting carriers by means of a PN junction, as shown in Fig. 16. Tuning the ring resonance modulates the throughput of the straight guide. The resonant behavior of the ring offers low power operation at the expense of critical wavelength control and narrow operational bandwidth.

The electron plasma effect with PN-junction injection can also be employed in conventional Mach–Zehnder (M-Z)-configured modulators, which then offer less critical operating conditions at the expense of higher modulating power. A compact, 10 Gbps, PIN, silicon wire M-Z modulator was recently reported by IBM researchers [34]. Unfortunately, the superior performance of the linear electrooptic effect, used in lithium niobate and InP modulators, requires a crystal with symmetry lacking a center of inversion, which is not afforded by Si.

Luxtera recently introduced the second commercial integrated optics application based on a hybrid Si PIC. Earlier, they explored means of providing the necessary components to be fabricated in standard CMOS facilities. Fig. 17 [32] shows a Si on SOI circuit illustrating an add–drop ring and proprietary holographic focusing coupler to a vertical optical fiber. Other elements demonstrated include a ring and a M-Z modulator.

In addition to the absence of a linear electrooptic effect, Si also has an indirect bandgap, which means that it is not able to provide laser gain, and a bandedge of 1.1 mm, which means it is not suitable for a photodiode in the 1.3- or 1.5-mm telecom bands. Ge does have a longer bandedge wavelength, although it has a lattice mismatch with Si. Nevertheless, suitable SiGe alloys can be grown epitaxially on Si and is currently employed in CMOS fabs to provide higher-performance strained transistors. Luxtera and others have demonstrated integrated SiGe photodetectors.

The final obstacle to monolithic Si photonics then is the laser source. It has been argued that an off-chip laser coupled to the Si PIC by the grating coupler in Fig. 17 is a solution. However, if the goal is cheap mass production (the rationale for CMOS photonics is to eliminate component coupling and packaging costs), it is necessary to find a cheap means of fiber alignment and connection.

The University of California, Santa Barbara, and Intel demonstrated another approach to hybrid laser coupling [35]. A schematic of their approach is shown in Fig. 18. A Si waveguide with cleaved mirrors provides the laser cavity. A coupled AlGaInAs medium provides the electrically pumped gain; it can be tightly bonded to the Si providing strong evanescent coupling between media. Critical lateral alignment is not required because the proton-defined gain stripe is produced after

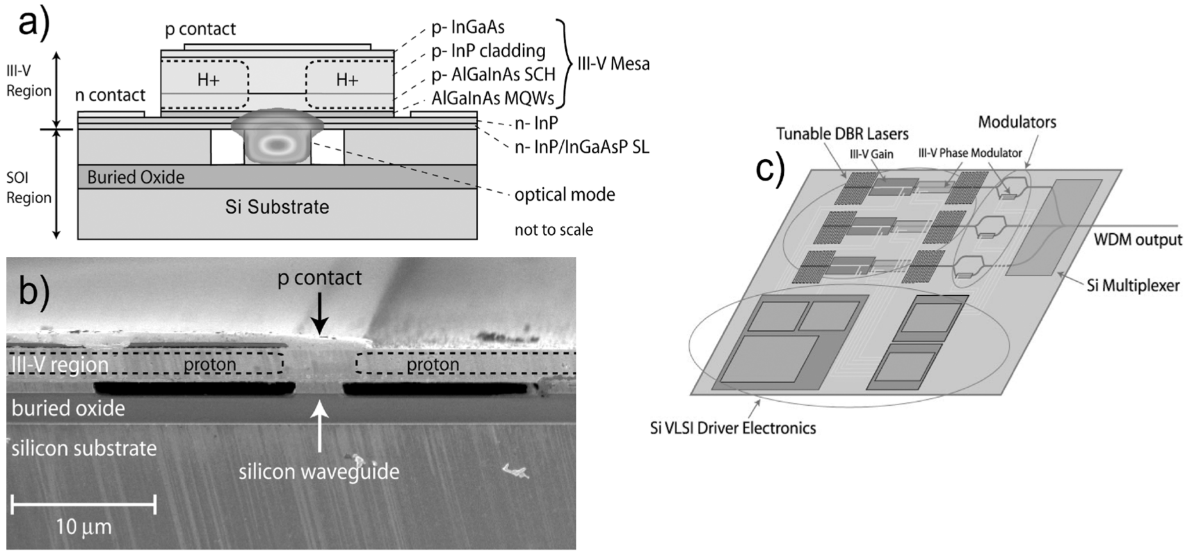

Fig. 18. Electrically pumped InP/Si hybrid laser and proposed IC layout: (a) schematic, (b) SEM, and (c) possible electronic-photonic circuit [33].

bonding. On the downside, the InP processing steps may not be entirely CMOS compatible. Fig. 18(c) illustrates a possible three-channel use of evanescently coupled III–V media for the lasers and modulators with on-chip connections to Si PICs and EICs.

The commercial Luxtera application is a hybrid PIC incorporated in a 40 Gb/s (4×10G b/s) transceiver for data center rack-to-rack links.

VI. Conclusion

Integrated optics has finally demonstrated some real progress in commercialization. Further advances depend on solving technical problems (e.g., CMOS-compatible optical sources and detectors on Si) and identifying cost-effective applications that can benefit from monolithic or hybrid OEIC capabilities (e.g., reducing coupling and packaging costs, integrating photonic and electronic processing, and realizing low cost per unit at high volumes).

R. Tucker's Fig. 1, optimistically based on a 10^2 element PIC in 2005 as a starting point and with a slope equal to EICs, shows a prospective Moore's law for PICs, 1agging EICs by only a factor of 10^7. A few more points for commercial applications are required to define a trend.

Acknowledgment

I am grateful to C. Doerr and T. Li for their insightful comments.

References

[1] S. E. Miller, “Integrated optics: An introduction,” *Bell Syst. Tech. J.*, vol. 48, p. 2059, 1969.
[2] W. J. Tomlinson, I. P. Kaminow, E. A. Chandross, R. L. Fork, and W. T. Silfvast, “Photoinduced refractive index increase in poly (methylmethacrylate) and its applications,” *Appl. Phys. Lett.*, vol. 16, pp. 486–489, 1970.
[3] R. V. Schmidt and I. P. Kaminow, “Metal-diffused optical waveguides in LiNbO3,” *Appl. Phys. Lett.*, vol. 25, pp. 458–460, 1974.
[4] I. P. Kaminow, H. P. Weber, and E. A. Chandross, “Poly (methyl methacrylate) dye laser with internal diffraction grating resonator,” *Appl. Phys. Lett.*, vol. 18, pp. 497–499, 1971.
[5] H. Kogelnik and C. V. Shank, “Coupled-wave theory of distributed feedback lasers,” *J. Appl. Phys.*, vol. 43, pp. 2328–2335, 1972.
[6] H. A. Haus, *Waves and Fields in Optoelectronics*. Englewood Cliffs, NJ: Prentice-Hall, 1984.
[7] E. A. J. Marcatili, “Bends in optical dielectric guides,” *Bell Syst. Tech. J.*, vol. 48, p. 2059, 1969.
[8] M. C. Wu, O. Solgaard, and J. E. Ford, “MEMS for lightwave communication,” in *Optical Fiber Telecommunications*, V. A, I. P. Kaminow, T. Li, and A. E. Willner, Eds. New York: Academic/Elsevier, 2008, ch. 19.
[9] C. Dragone, “Efficient N × N star couplers using Fourier optics,” *Electron. Lett.*, vol. 24, pp. 242–244, 1988.
[10] C. Dragone, “Efficient N × N star couplers using Fourier optics,” *J. Lightw. Technol.*, vol. 7, no. 3, pp. 479–489, Mar. 1989.
[11] C. Dragone, C. H. Henry, I. P. Kaminow, and R. C. Kistler, “Efficient multichannel integrated optics star coupler on silicon,” *IEEE Phototon. Technol. Lett.*, vol. 1, no. 8, pp. 241–243, Aug. 1989.
[12] I. P. Kaminow, “FSK with direct detection in optical multi-access FDM networks,” *IEEE J. Sel. Areas Commun.*, vol. 8, no. 6, pp. 1005–1014, Aug. 1990.
[13] C. Dragone, “An N × N optical multiplexer using a planar arrangement of two star couplers,” *IEEE Photon. Technol. Lett.*, vol. 3, no. 9, pp. 812–814, Sep. 1991.
[14] M. K. Smit, “New focussing and dispersive planar component based on an optical phased array,” *Electron. Lett.*, vol. 24, pp. 385–386, 1988.
[15] H. Takahashi, S. Suzuki, K. Kato, and I. Nishi, “Arrayed-waveguide grating for wavelength division multi/demultiplexer with nanometer resolution,” *Electron. Lett.*, vol. 26, pp. 87–88, 1990.
[16] C. Dragone, “Optimum design of planar array of tapered waveguides,” *J. Opt. Soc. Amer. A*, pp. 2081–2093, 1991.
[17] A. Vellekoop and M. Smit, “Four-channel integrated-optic wavelength demultiplexer with weak polarization dependence,” *J. Lightw. Technol.*, vol. 9, pp. 310–314, 1991.
[18] C. Dragone, C. A. Edwards, and R. C. Kistler, “Integrated optics N × N multiplexer on silicon,” *IEEE Photon. Technol. Lett.*, vol. 3, no. 10, pp. 896–899, Oct. 1991.
[19] C. R. Doerr and K. Okamoto, , V. A, I. P. Kaminow, T. Li, and A. E. Willner, Eds., “Planar lightwave circuits in fiber-optic communications,” in *Optical Fiber Telecommunications*. New York: Academic Press/Elsevier, 2008, ch. 9.
[20] M. Yust, N. Bar-Chaim, S. H. Izadpanah, S. Margalit, I. Ury, D. Wilt, and A. Yariv, “A monolithically integrated optical repeater,” *Appl. Phys. Lett.*, vol. 35, pp. 795–796, 1979.
[21] R. F. Leheny *et al.*, “Integrated In/0.53/Ga/0.47/As p-i-n F.E.T. photoreceiver,” *Electron. Lett.*, vol. 16, pp. 353–354, 1980.

[22] L. A. Coldren, B. I. Miller, K. Iga, and J. A. Rentschler, "Monolithic two-section gainasp/inp active-optical-resonator devices formed by reactive ion etching," *Appl. Phys. Lett.*, vol. 38, pp. 315–317, 1981.

[23] M. Suzuki, "Monolithic integration of InGaAsp/InP distributed feedback laser and electroabsorption modulator by vapor phase epitaxy," *J. Lightw. Technol.*, vol. 5, no. 9, pp. 1277–1285, Sep. 1987.

[24] T. L. Koch *et al.*, "GaInAs/GaInAsP multiple-quantum-well integrated heterodyne receiver," *Electron. Lett.*, vol. 25, pp. 1621–1623, 1989.

[25] M. G. Young *et al.*, "Six wavelength laser array with integrated amplifier and modulator," *Electron. Lett.*, vol. 31, pp. 1835–1836, 1995.

[26] B. Glance, I. P. Kaminow, and R. W. Wilson, "Applications of the integrated waveguide grating router," *J. Lightw. Technol.*, vol. 12, no. 6, pp. 957–962, Jun. 1994.

[27] M. Zirngibl, B. Glance, L. W. Stulz, C. H. Joyner, G. Raybon, and I. P. Kaminow, "Characterization of a multiwavelength waveguide grating router laser," *IEEE Photon. Technol. Lett.*, vol. 6, no. 9, pp. 1082–1084, Sep. 1994.

[28] C. G. M. Vreeburg *et al.*, "First InP-based reconfigurable integrated add-drop multiplexer," *IEEE Photon. Technol. Lett.*, vol. 9, no. 2, pp. 188–190, Feb. 1997.

[29] C. R. Doerr, C. H. Joyner, L. W. Stulz, and R. Monnard, "Wavelength-division multiplexing cross connect in InP," *IEEE Photon. Technol. Lett.*, vol. 10, no. 1, pp. 117–119, jan. 1998.

[30] C. Joyner, D. Lambert, P. Evans, and M. Raburn, , V. A, I. P. Kaminow, T. Li, and A. E. Willner, Eds., "III-V Photonic integrated circuits and their impact on optical network architectures," in *Optical Fiber Telecommunications*. New York: Academic/Elsevier, 2008, ch. 10.

[31] R. N. Noyce, "Large-scale integration: What is yet to come?," *Science*, vol. 195, pp. 102–1106, 1977.

[32] C. Gunn and T. L. Koch, , V. A, I. P. Kaminow, T. Li, and A. E. Willner, Eds., "Silicon photonics," in *Optical Fiber Telecommunications*. : Academic/Elsevier, 2008, ch. 11.

[33] Q. Xu, B. Schmidt, S. Pradhan, and M. Lipson, "Micrometre-scale silicon electro-optic modulator," *Nature*, vol. 435, pp. 325–327, 2005.

[34] W. M. J. Green, M. J. Rooks, L. Sekaric, and Y. A. Vlasosov, "Ultra-compact, low rf power, 10 Gb/s silicon mach-zehnder modulator," *Opt. Express*, vol. 15, pp. 17106–17113, 2007.

[35] A. W. Fang, H. Park, O. Cohen, R. Jones, M. J. Paniccia, and J. E. Bowers, "Electrically pumped hybrid AlGaInAs-silicon evanescent laser," *Opt. Express*, vol. 14, pp. 9203–9210, 2006.

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