Proposed Photonic Integrated Circuit For Photonic Networks

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Abstract

Optical technologies have great potential for the implementation of high-speed systems due to their potential for a decrease in size, weight and power consumption and an increase in speed, capacity, bandwidth and integration degree. In this paper a study for the Integrated Photonics properties versus Integrated Electronics had been presented, different types of photonic components are maintained, the fabrication technology is explained using the Encoder/Correlator on GaAs-Based Photonic Integrated Circuit for Photonic Networks, various limits and challenges are discussed, different suggestion are discussed for the future.

Keywords: Integrated photonics, Photonic integrated circuits (PICs), Silicon Photonics, Indium Phosphide.

مقترح الدوائر الضوئية المتكاملة للشبكات الضوئية

الخلاصة

أن التقنيات البصرية تتمتع بإمكانيات كبيرة لتنفيذ نظم عالية السرعة نظرا لصغر الحجم و أنخفاض في الوزن واستهلاك الطاقة وزيادة في السرعة والقدرة وعرض النطاق الترددي ودرجة التكامل. في هذا البحث سوف يتم تقديم دراسة عن خواص البصريات المتكاملة كنظير منافس للألكترونيات المتكاملة. أن أنواع مختلفة من المكونات الضوئية سوف يتم عرضها و كذلك تكنلوجيا الصناعة قد تم شرحها بستخدام: التشفير / معدل على بلورات زرنيخيد الغاليوم الضوئية القائمة على الدوائر المتكاملة الضوئية للشبكات، أن خواص و فوائد فوسفيد الأنديوم قد تم عرضها كمثال على المواد المستخدمة في صناعة الألكترونيات الضوئية. أن محددات مختلفة و تحديات لصناعة الدوائر الضوئية المتكاملة قد تم مناقشتها.

1. Introduction

The term “integrated photonics” refers to the fabrication and integration of several photonic components on a common planar substrate [1]. These components include [2]: beam splitters, gratings, polarizers, interferometers, sources, micro/nano-size waveguides, directional couplers, multi-mode interference devices, switches, AWGs, ring-resonators, photonic crystal devices, plasmonic devices, quantum devices, detectors and others as in Fig (1). In turn, these can then be used as building blocks to fabricate more complex planar devices which can perform a wide range of functions with applications in optical communication systems, instrumentation and sensors [2]. Materials may include polymers and silicon semiconductors. Silicon photonics is currently a very active and progressive area of research, as silicon optical circuits have emerged as the replacement technology for copper-based circuits in communication and broadband networks [3]. The demand for ever improving communications and

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computing performance continues, and this in turn means that photonic circuits are finding ever increasing application areas [4]. Silicon Photonics opens with a highly informative foreword, and continues to features [4, 5]:

-the integrated photonic circuit.
-silicon photonic waveguides.
-photonic band gap waveguides.
-mechanisms for optical modulation in silicon.
-silicon based light sources.
-optical detection technologies for silicon photonics.
-passive silicon photonic devices.
-photonic and electronic integration approaches.
-applications in communications and sensors.

The term photonic integration has also sometimes been incorrectly applied to sub system modules, for example the 300-pin 10Gb/s transponder Multi-Source Agreement (MSA) modules [5]. This is misleading as such modules are actually comprised of individually packaged single-function components connected by external fiber couplings and electronic traces. Thus the only “integration” actually achieved is the incorporation of all devices into one module, and this is generally not considered true integration.

2. Background of Integrated Photonics

photonic and opto-electronic devices based on integrated photonic circuits have grown in a way that they not only clearly dominate long-distance communications through optical fibers, but have also opened up new fields of application, such as sensor devices, and are also beginning to penetrate in the own field of the information processing technology. In fact, the actual opto-electronic devices may be merely a transition to a future of all-optical computation and communication systems. The history of integrated photonics is analogous to that of other related technologies: discovery, fast evolution of the devices, and a long waiting time for applications [6]. The first optical waveguides, fabricated at the end of the 1960, were bidimensional devices on planar substrates [7]. In the mid-1970s the successful operation of tridimensional waveguides was demonstrated in a wide variety of materials, from glasses to crystals and semiconductors [2]. For the fabrication of functional devices in waveguide geometries, LiNbO3 were rapidly recognized as one of the most promising alternatives. The waveguide fabrication in LiNbO3 via titanium in-diffusion was demonstrated at the AT and T Bell Laboratory [2, 3], and gave rise to the development of channel waveguides with very low losses in a material that possesses valuable electro-optic and acousto-optic effects. In the mid-1980s the viability of waveguide devices based on LiNbO3, such as integrated intensity modulators of up to 40 GHz, and with integration levels of up to 50 switches in a single photonic chip had already been demonstrated in laboratory experiments. Because of the parallel development of other materials, both dielectrics such as polymers, glasses or silica on silicon (SiO2/Si), and semiconductors such as indium phosphide (InP), gallium arsenide (GaAs) or even silicon (Si), a wide variety of novel and advanced integrated photonic devices was ready to emerge on the market. For many years, engineers and researchers have been trying to reproduce this electronic success in the fabrication of photonic integrated circuits (PICs). Photonic integration can be divided into two main technology thrusts, coinciding with two material systems. First, III–V semiconductors—such as indium phosphide (InP) and gallium arsenide (GaAs)—are traditionally used for the manufacturing of photonic devices, especially lasers and photodiodes, because of their good electro-optic properties [7]. However, integrating these materials has traditionally been very difficult, especially achieving the process uniformity and reproducibility required for mass production in such processes as Epitaxy, dry etching, and lithography [6]. Photonic integration in the second material system, silicon, can potentially leverage the enormous experience and knowledge of silicon processing amassed in the electronics industry [5]. Unfortunately, silicon has very poor electro-optic properties resulting from its being an indirect bandgap material. This means that optical gain, a necessary condition for the creation of laser sources, is very hard to generate in silicon [3], so light sources, for example, must be externally coupled to the silicon chip [7].

3. Integrated Photonics

Optics can be defined as the branch of physical science which deals with the generation and propagation of light and its interaction with matter [3]. Light, the main subject of optics, is electromagnetic (EM) radiation in the wavelength range extending from the vacuum ultraviolet (UV) at about 50 nanometers to the far infrared (IR) at 1 mm. During the last quarter of the past century, the science of optics has suffered a spectacular renaissance, due to various key developments [8]. The first revolutionary event in modern optics was, no doubt, the invention of the laser by T.H. Maiman in 1960 at Hughes Research Laboratories in Malibu [1, 8], which allowed the availability of coherent light sources with exceptional properties, such as high spatial and temporal coherence and very high brightness. A second major step forward came with the development of semiconductor optical devices for the generation and detection of light [1, 8], which permitted very efficient and compact optoelectronic devices. The last push was given by the introduction of new fabrication techniques for obtaining very cheap optical fibers, with very low propagation losses [9]; close to the theoretical limits Fig. (2). As a result of these new developments and associated with other technologies, such as electronics, new disciplines have appeared connected with optics: electro-optics, optoelectronics, quantum electronics, waveguide Fig. (3) technology, etc. Thus, classical optics, initially dealing with lenses, mirrors, filters, etc., has been forced to describe a new family of much more complex devices such as lasers, semiconductor detectors, light modulators, etc. The operation of these devices must be described in terms of optics as well as of electronics, giving birth to a mixed discipline called photonics [1].

As in electronics, photonic integration can include both hybrid and monolithic integration [10]. In a hybrid PIC, multiple single-function optical devices are assembled into a single package, sometimes with associated electronic ICs, and inter-connected to each other by electronic and/or optical couplings internal to the package. Many integrated photonic devices available today utilize hybrid integration to consolidate packaging. However, the assembly of hybrid integrated components can be highly complex, as many discrete devices must be interconnected internal to the package with sub-micron tolerances required for aligning optical components. Adding to the packaging challenge is the fact that different materials may require different packaging designs due to differences in optical, mechanical and thermal characteristics. For example, if two materials have different coefficients of expansion, they can become misaligned at different operating temperatures and require different thermo-electric coolers, thus compounding packaging complexity and cost. In practice, this has limited hybrid PICs to integrating at most three to four optical components into a common package. In contrast, monolithic integration consolidates many devices and/or functions into a single photonic material. As in electronic ICs, the fabrication of monolithic PICs involves building devices into a common substrate so that all photonic couplings occur within the substrate and all functions are consolidated into a single, physically unique device. As can be seen in Table 1, monolithic integration provides the greatest level of benefits, including significant packaging consolidation, testing simplification, reduction in fiber couplings, improved reliability and maximum possible reduction in space and power consumption per device.

Obviously, whether a light source is required, materials with a direct bandgap are necessary, as could be GaAs (gallium arsenide), GaAlAs (gallium-aluminum-arsenide), GaAlP (Gallium-Aluminum-Phosphide), GaInP (Gallium-Indium-Phosphide), InP (indium phosphide), GaN (Gallium Nitride) and other III-V and II-VI compounds [11]. Passive materials as silicon, glass or LiNbO3 (Lithium Niobate) are the most commonly used in hybrid integration, since its indirect bangap prevents from obtaining reliable light sources. However, a significant effort is being made in order to obtain light emitters and amplifiers by incorporating Er+ (Erbium) ions into these substrate materials especially for telecommunication purposes (erbium ions emit at 1.533μm) [11]. The major advantage of hybrid approach is that IOC can be obtained using the well-known technology of both fields, while its major disadvantage is the possibility of misalignment or even failure during the assembly process because of vibration or differences in its expansion coefficient.

The GaAlAs/GaAs is one of the precursors of monolithic integration working at a wavelength of 0.8μm. The components obtained with these semiconductors are generally used for short-range interconnects. Due to its high refractive index and the high index contrasts, layers are generally very thin and with a high numerical aperture, causing its insertion losses to be very high. Changing the relative concentration of the ternary system, it is possible to obtain light at wavelengths between 0.65 and 1.7μm. Moreover, they show relatively large electro-optic and acusto-optic effect (but minor than LiNbO3), making them useful for switches and modulators. The increasing use of these compounds has significantly reduced its price. Another point that has to be taken into account is the fact that GaAs and AlAs almost have the same lattice constant (5.646 and 5.369Å, respectively) [12]. Thus, consecutive layers with different concentrations of Al in the GaAlAs compound do not cause lattice strain in the structure [11]. This is particularly important in the fabrication of multilayered, heterojunction lasers. In order to obtain monolithic laser sources at the telecommunications range (1.3/1.5μm), the GaInAsP/InP system was developed. Although their lattice constant do not match as good as with the GaAs/AlAs compounds [11, 12], it is possible to obtain highly efficient laser diodes at wavelengths where losses in fiber optics are extremely low. However, they also have a high refractive index, which requires reduced dimensions for monomode behavior and increases its insertion losses. For a long time, it seemed that III-V and II-VI technologies would have major application than silicon (and also polymers and LiNbO3). However, the fabrication complexity, yield and cost of the III-V and II-V technologies, their insertion and attenuation losses as well as its significant polarization dependence keeps the situation still today balanced.

4. Fabrication Technology

To study the fabrication technology the fabrication of: Encoder/Correlator on GaAs-Based Photonic Integrated Circuit for Photonic Networks will be explained.

In present optical communication systems, the O/E and E/O conversion of all optical data is done at network nodes [13], and electric routers identify data destinations. Therefore, electric routers would be the bottleneck due to the explosive growth of network traffic [14]. To overcome this problem, the photonic label routing technique has been discussed. In this technique optical label encoders/correlators perform the generation and recognition of photonic label codes, which represent the destinations of optical data. The semiconductor-based optical label encoder/correlator had been consisted of a Semiconductor Optical Amplifier (SOA) and an optical circuit, and successfully demonstrated the optical coding and correlating functions of the device [15]. Fig. (4) shows the configuration of the encoder/correlator device and its operation principle. A 1×4 splitter, four optical delay lines with a relative length of 900μm, four GaInNAs-SOAs as optical switches and a 4×1 combiner were monolithically integrated on a GaAs substrate. The encoder generates a time-spreading unipolar optical code pulse from a single short optical pulse by switching these SOAs. Passing the optical code through the correlator, which has the same optical circuit as that of the encoder, a correlation signal is generated. The correlation signal represents whether the switching state of the SOAs on the encoder matches that of the correlator. Only in the matched case, the correlation signal has one peak pulse [13, 15].

The fabrication process of the device is shown in Fig. (5). The device was fabricated by three-step low-pressure Metalorganic Vapor Phase Epitaxy (MOVPE). First, a 1.5-μm Si-GaInP cladding layer and an active region sand-wiched between two 0.14-μm undoped GaAs optical confinement layers were grown on a GaAs substrate. The active region consisted of a Ga0.69 In0.31N0.01 As0.99 double quantum well (7 nm) separated by a GaAs barrier layer (8 nm). Second, after removing the active layers in the passive region, a 0.3-μm undoped GaAs waveguide layer was butt-jointed to the active layer of the SOAs. Both the active and passive waveguide mesas were formed by conventionally used photolithography and wet etching. Finally, a 1.5-μm Zn-GaInP upper cladding layer and a Zn-GaAs contact layer were deposited over both the active and passive region. After the electrodes were formed, the wafer was cleaved and both facets were antireflection (AR) coated with Al3O2/TiO2 films. The chip size was 2.4×3.25 mm2 [13].

Fig. 6 shows the cross-sectional views of the SOA and the passive waveguide, since the built-in potential at the p-n junction of the GaInP cladding layer (about 1.9 eV) is much higher than that at the GaInNAs (Gallium Indium Nitrides) active region (about 0.95 eV), the current can be confined effectively in the active region even without an additional current blocking layer [16]. Because the SOA (Semiconductor Optical Amplifier) structure and the waveguide structure are identical except for the active GaInNAs layers in the SOA structure, the monolithic integration devices can be fabricated using maskless regrowth. This process is suitable for integration of the SOAs and waveguide circuit, such as splitters or combiners [17].

5. Indium Phosphide Photonic Integrated Circuits and its benefits

By consolidating many optical devices into a single device, InP PICs enable system designers to implement improvements in system size, power consumption, reliability and cost. Photonic integration delivers these benefits in various ways. For example, integrating multiple devices and functions into a single PIC greatly reduces the number of optical packages required. Since packages and associated assembly dominate total cost of optical components, accounting for at least 50% of total cost and up to 80% for more complex devices, the consolidation of dozens of components into a single device creates significant efficiencies. Packaging reductions also save on costs associated with the individual burn-in and testing of many individual components.

Both electronic and photonic integration address the classical problem of “tyranny of numbers”. In the electronic case, the wires between transistors represented a significant scaling and reliability problem. In the photonic case, the tyranny of numbers refers to the optical equivalent of wires; fiber couplings. Photonic integration therefore reduces the need for precise and complex sub-micron optical assemblies required to couple light from optical devices into optical fiber, and minimizes the time-consuming manual alignment and/or complex and costly robotic alignment systems required to do this. In addition, since each fiber coupling is a potential failure point, the use of many fiber coupled devices in optical transport systems has a negative impact on system reliability. Each fiber coupling must be robust enough to maintain efficient coupling while withstanding the manipulation, mechanical shock, vibration, temperature shifts and temperature extremes expected over the system operating lifetime. Any change to the fiber attachment will reduce the performance of the component, typically by increasing component loss or reducing output power. Because of this, fiber couplings are the dominant failure mode of today's optical components, with approximately 70% of device failures over life being traceable to fiber coupling failures. The ability of photonic integration to significantly reduce the number of fiber couplings in an optical transport system therefore creates flow-through benefits for system reliability. Another ramification of having many discrete fiber couplings is the impact on cumulative optical loss at each fiber-device interface. Depending upon the mechanics of the fiber coupling, losses can be between 1dB to 3dB (note that a 3 dB loss is a 50% reduction in power). When many devices are cascaded, these losses accumulate and require better upstream performance in order to achieve a given final optical launch power into the network fiber, thereby increasing the cost and complexity of optical component design. Because device reliability increases exponentially with decreasing power levels, and since monolithically integrated DFB lasers in a PIC can be operated at one quarter or less of the power of discretely packaged DFBs for the same system-level performance, this further improves component and system reliability of PIC-based systems.

Finally, with the ability to easily and cost-effectively integrate diagnostic devices in a PIC, functional on-chip testing can be performed at a wafer level. This allows in-situ testing and screening to be performed before incurring downstream costs for device separation, mounting and testing. In comparison, many optical components such as lasers, modulators and detectors fabricated at a wafer level must first be separated and individually mounted on carrier substrates before their performance can be tested. This process adds additional value-added cost to each component even before basicfunctional screening can be implemented. This creates not only manufacturing inefficiencies but also increases end-to-end device manufacturing time and cost.

6. Challenges and Limits

The dominant challenge is how to realize the integration of different materials and very different device structures. Many of the first attempts involved pick and place with In bump bonding or wafer bonding at the device level, but alignment tolerances, expansion coefficient differences, optical coupling between fiber, waveguides and devices and overall yield limited the gains one hoped to realize from integration [19]. However, photonic technology presents some fundamental design challenges, specifically because of its lack of efficient buffering and processing capabilities. Optical buffers based on recirculating fiber delay lines have been demonstrated, as have interferometeric optical logic gates, but their dimensions and bulkiness prohibit them from becoming cost-effective solutions.

The main impediment to the construction of photonic interconnection networks lies in the high cost and large footprints associated with using discrete optical elements such as lasers, modulators, switches, and passive optics.

Traditional two-dimensional (2D) PICs are limited by substrate size and the number of electrical and optical connections that can be made to the chip. This is a problem for the increasingly dense, complicated circuits developed today. By making the leap to multilayer interconnects, more compact devices can be obtained and further creativity in circuit design is afforded. Vertical integration to avoid the crossing of physical beam paths can lead to lower crosstalk as well. Also, because different types of devices (lasers, detectors, switches, etc.) are often best made with different materials, methods of integrating different materials onto a single chip must be addressed. Finally, some devices can be made smaller when vertical integration, rather than lateral integration, is employed. Three-dimensional routing of signals will thus be very advantageous for significantly more compact and powerful photonic ICs.

It is well known that integrated circuits speed is mainly limited by built-in resistances and capacitance in it's I/O’s. The practical difficulties associated with implementing high-performance active opto-electronic functions such as lasing, modulation and light detection in silicon [20] generally limits its usefulness to the integration of passive optical devices only. However the relative maturity and ease of manufacture of this technology has led to the increasing use of silicon-based planar light wave circuits (PLCs) for integrating “all-optical” functions such as reconfigurable optical add/drop multiplexers (ROADMs).

The recent attempts to overcome this limitation lead to hybrid electro-optical modules and devices [21, 22]. The natural advantage of light consists in its high propagation velocity, reduced cross talk and the absence of electrical noise. Such devices can operate at very low operational power and are capable of parallel processing.

7. The Future of Integrated Photonics

Photonic integration is in its infancy relative to the electronics industry, and many of the techniques used in scaling silicon ICs can be leveraged to drive continuous improvement in the manufacture of PICs. This promises ongoing scaling of device capacity, functionality, and reductions in the “cost per bit” for optical transmission capacity [23]. But even in its infancy photonic integration has proven the ability to be a break-through technology; given the benefits it provides, once available why would optical transmission system designers revert back to the use of discrete single-function devices over photonic integrated circuits? The impact of photonic integration on the telecommunications industry can therefore be as significant as that of electronic integration, especially as network capacity grows and fiber deployments penetrate further into the network. In the future, use of PICs, like today’s electronic ASICs, will be limited only by the agnation of designers. Future PIC developments could impale the way for even more advanced packages, integration of electronics and optics, and the development of functional “macros” similar to those available for electronic ICs to enable standardized design and fab out-sourcing of PICs.

8. Conclusions

From this study it became clear to the all; the main topics of Integrated Photonics and the main components that may be used in the photonic integrated circuits fabrication, due to the bottleneck in the electronic router because of the explosive growth of network traffic, the Encoder/Correlator on GaAs-Based Photonic Integrated Circuit for Photonic Networks is proposed and a brief fabrication technique is explained and it had been concluded that the monolithic integration devices can be fabricated using maskless regrowth and this process is suitable for integration of the SOAs and waveguide circuit, such as splitters or combiners. It had been shown that Indium Phosphide reduces the number of optical packages required. Since packages and associated assembly dominate total cost of optical components, accounting for at least 50% of total cost and up to 80% for more complex devices. We had found that the most effective challenge to the construction of photonic interconnection networks lies in the high cost and large footprints associated with using discrete optical elements. A Photonic Integrated Circuit consolidates all the optical functions required in an optical transport system into a single device. Like in electronics, a Photonic Integrated Circuit provides cost, space, power and reliability advantages compared to the use of discrete single-function devices

9. References

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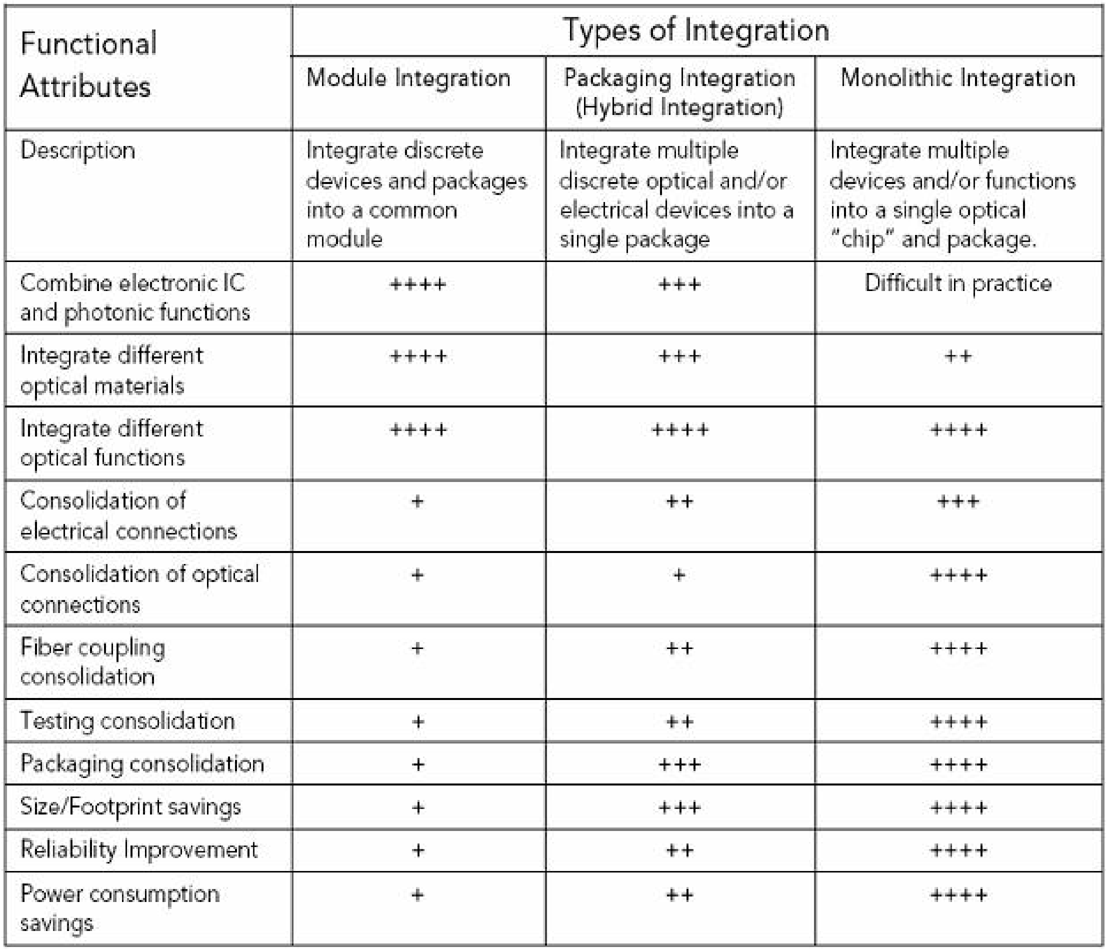
Table (1) Different levels of photonic integration offer differing level of benefits depending on the degree of integration achieved.



Functional Attributes	Types of Integration		
	Module Integration	Packaging Integration (Hybrid Integration)	Monolithic Integration
Description	Integrate discrete devices and packages into a common module	Integrate multiple discrete optical and/or electrical devices into a single package	Integrate multiple devices and/or functions into a single optical "chip" and package.
Combine electronic IC and photonic functions	++++	+++	Difficult in practice
Integrate different optical materials	++++	+++	++
Integrate different optical functions	++++	++++	++++
Consolidation of electrical connections	+	++	+++
Consolidation of optical connections	+	+	++++
Fiber coupling consolidation	+	++	++++
Testing consolidation	+	++	++++
Packaging consolidation	+	+++	++++
Size/Footprint savings	+	+++	++++
Reliability Improvement	+	++	++++
Power consumption savings	+	++	++++

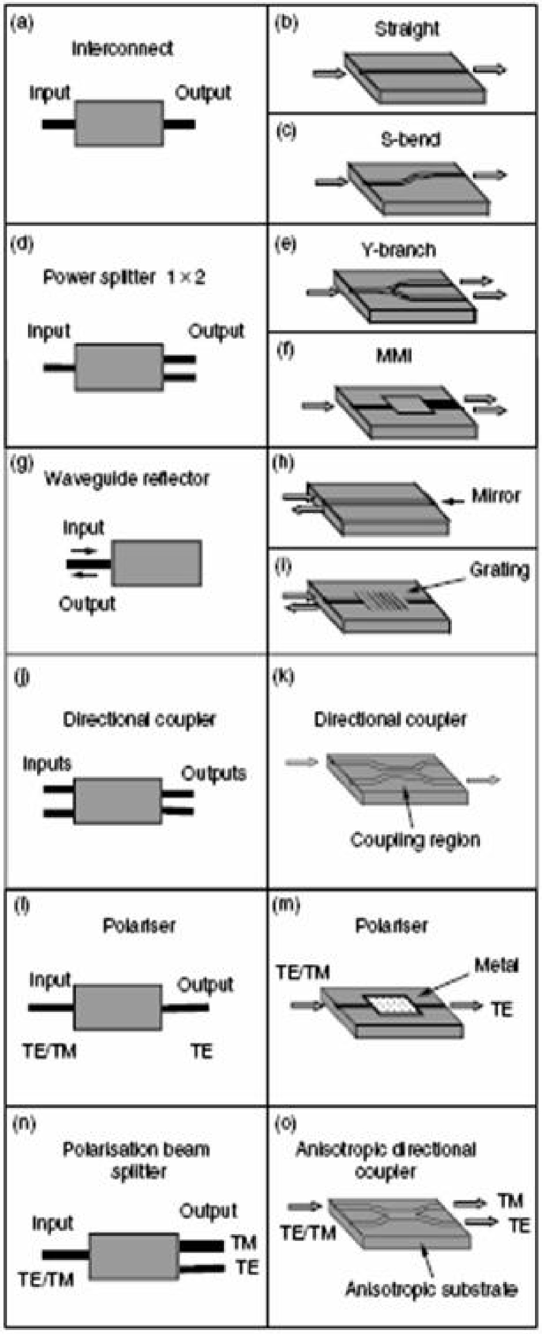


Figure (1) Basic Integrated Photonic Components.

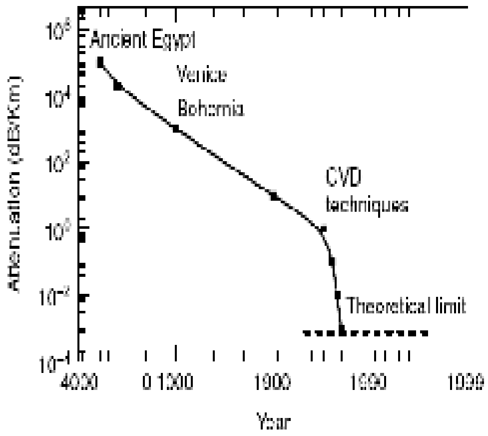


Figure (2) Evolution of the attenuation in silica glasses.

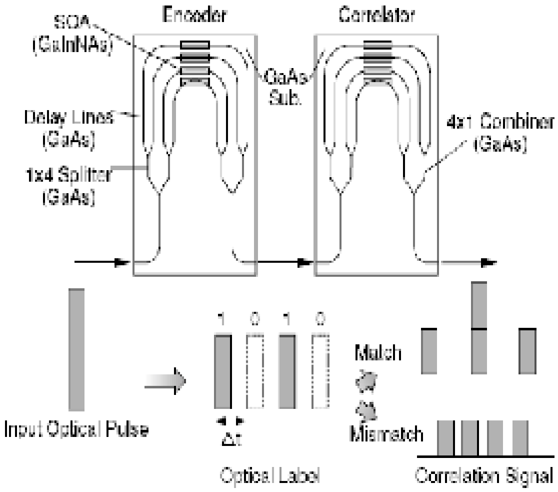


Figure (4) Configuration of encoder/correlator.

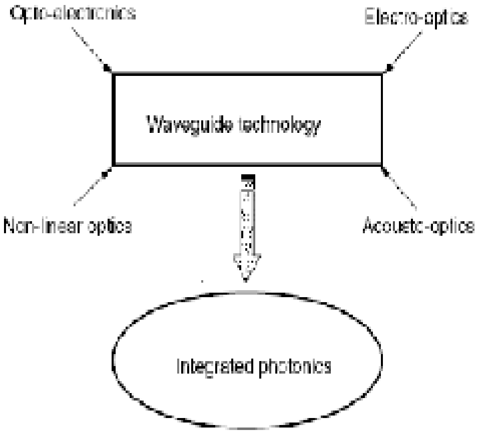
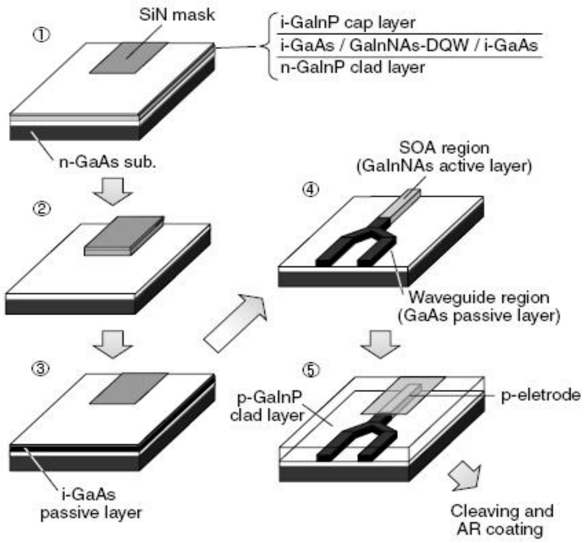
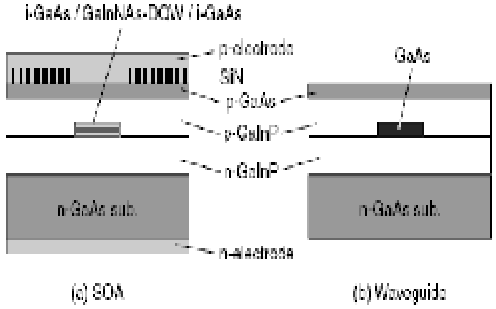


Figure (3) Confluence of various disciplines into integrated photonics.



Figure(5)Semiconductor encoder/ correlator device fabrication processes.



(a) SOA
(b) Waveguide

Figure (6) Cross-section of encoder/correlate