Integrated Opto-electronics

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Abstract

Integrated opto-electronics has been intensively studied for many years, with gradually increasing numbers of commercially successful implementations. The optical communications industry is now poised for explosive growth in the field, driven by the overwhelming successes of DWDM, high data rate transport systems, and the opportunities presented as volume deployment of optical data transportation extends from the long-haul backbone into the metro, access and in-building markets. Integration technology will be required to work with automation technology to solve the space, cost, and introduction time constraints associated with upcoming communications systems. This talk will first introduce some optical network basics, discuss attributes of components relevant to the required optical functions and integration opportunities, and then will discuss practical aspects of hybrid and monolithic integration, focusing on photonic integration (integration of various optical devices, often without substantial electronics).

INTRODUCTION

Expansion of optical communications networks around the globe has lead to high demand for optical components in general. Demand for 'turn-key' solutions results from several factors: the emergence of new systems vendors lacking the size and vertical integration of the more established companies, the more rapid pace of technical innovation reducing the market window, the large numbers of terminals associated with DWDM (Dense Wavelength Division Multiplexing) transmission technology, and the global shortage of opto-electronic design skills. Figure 1 shows a reference optical transmission system. Time domain multiplexing has successfully leveraged electronic integration to aggregate traffic in the electronics, using a single optical transmitter (Tx) or receiver (Rx) per signal. High rate long haul TDM systems rely on raw optical and electrical performance; size, cost, and complexity of the optics are tolerable since only one Tx and Rx is required. WDM systems require a transmitter and receiver for each colour of light, and the extension of the optical transmission systems, from a few wavelengths less than 5 years ago to 160 or more today, has resulted in a large demand for higher density implementation requiring components that are smaller, and, ideally, have lower power. Metropolitan area networks are even more cost and space sensitive than long haul systems, and provide a clear driver for increased integration. Managing the signals into and out of a transmitter/receiver pair operating at high data rates requires many high-speed optical transceivers as well. Reducing the size of these tributary Tx/Rx components is critical to achieving the required system density. Very short reach and access applications, such as Gigabit Ethernet and 10 Gigabit Ethernet, combined with the high aggregate data rates associated with many of the large routers and switches, leads to the requirement for many high speed optical channels in very small spaces at very low cost.

The global market for opto-electronics is many billions of dollars per year, with high prices per unit - often many thousands of dollars for a single assembly. Long haul communications products currently sell for more than $1000 per Gb/s, while access optics such as Gigabit Ethernet transceivers are priced at less than $50 per Gb/s. Increased penetration of high performance optics into the communications market will require that selling prices be reduced to values similar to those of access components.

These are some of the strong, clear reasons for increased functional integration, but there are substantial difficulties in achieving the desired result.

KEY ISSUES

Integration has been slow in the field of opto-electronics for a number of reasons. Some of the reasons are historical, some related to the (relatively) small volumes of opto-electronics, and some the result of lack of basic technological capabilities. Understanding the components required in the system is necessary to understand the integration constraints. Opto-electronic integration is predominantly concerned with optimizing the electrical connections between the optical and electrical devices, while photonic integration primarily addresses the interconnection of optical devices. (In general, devices that interact with light are classed as optical devices, whether or not they also have electrical characteristics, and so the distinctions, though useful, are not always accurate)

Table 1 lists some of the key devices and some of their important integration related attributes. As can be seen, there are substantial differences in materials, dimensions and configuration. While producing arrays of identical devices on a wafer is fairly straightforward and there are a few devices made from interconnection of such structures - Mach Zehnder (MZ) modulators and Arrayed Waveguide Grating (AWG) devices for example - most of the system requirements involve incorporation of multiple, substantially different, functions. While interconnecting multiple transistors produces useful functions, opto-electronics has no equivalent base component, and different functions in general require substantially different devices Although work is being done on monolithic integration of these different components, hybrid integration is currently the main route forward. Even the apparently simple MZ modulator and AWG components are in competition with less integrated technologies. While MZ modulators would be intractable if made from bulk optic components, AWGs are, despite tremendous work in the area, still generally inferior to bulk optic assemblies of filters.

As a useful frame of reference, many of the requirements and challenges in opto-electronic integration are similar to those of RF engineering; in this case the carrier is around 200 THz, our signal bandwidth is up to a few 10s of GHz, the channel spacing is currently around 50 GHz, with the operating band around 60 THz (1200 nm to 1600 nm optical wavelengths). Hybrid integration in optics is driven by the same types of considerations that apply to assemblies of HEMTs, bipolars, dielectric resonators, CMOS etc..

TABLE 1

Key optoelectronic devices and some important properties

Device type	purpose	Key technologies	Critical aspects	typical dimensions (μm) thickness: lateral x lateral	physical topography (μm)	nominal optical mode size (μm)	elements per function	variables
Laser	Generate light	III-V processing DFB gratings	Emission frequency Power Spectral purity	4: 4x400	1.5	~2	1	$\delta\upsilon$~12.5 GHz/K facet phase
Modulator	Impress the data	$LiNbO_3$	Travelling wave velocity matching	8: 100x30,000	0	~6	7	bias instability
		InP EA	Chirp ($d\phi/dL$)	4: 4x100	4	~1	1	narrow $\delta\upsilon$
		InP MZ	Speed, $dL/d\phi$	4: 50x1,000	4	~1	6	C vs. Vpi
Amplifier sub system	Signal boost	Er doped fibre	Gain/length	10^8: 125x125	fibre coil	10	1	$\delta g(\lambda)$~10 dB
		III-V Pump lasers	Power and reliability	4: 5x800	1.5	3-20	2-6	
multiplexer & Demultiplexer	Combine & separate optical signals	optical thin film filter assemblies	Assembly cost channel count	~10^4:10^4x10^4	bulk	400-1000 (beam)	>10	
		Silica on Si, SOI, polymer Planar waveguides	Crosstalk	~30:10^4x10^4	1-10	6-8	100's	$\delta\upsilon$~12.5 GHz/K
Isolator	Prevent back reflections	Garnet crystals	Bulk optic Polarization independent	~10^3:10^3x10^3	bulk	1000 (beam)	~5	Limited $\delta\upsilon$
Detector	Convert to electrical	III-V p-i-n	Sensitivity and speed	3: 50x50	2	20-100	1	
		III-V APD	Gain & temperature					
		III-V MSM	Response		0	20	20	
Variable optical attenuator (VOA)	Optical level control	MEMS	Reliability	100: 500x500	100	300-1000		
		PWG MZ	Power dissipation & polarization sensitivity	30:10^4x10^4	1-10	6-8	1	
MESFET	transistor	Gate Schottky	Surface control	0: 5x200	0	none	1000	
HBT	transistor	III-V processing		1: 10x10	2	none	200	

MAIN TECHNICAL CHALLENGES

-performance

Traditionally, optical devices have been operated near their performance limits, which does not allow substantial tradeoffs in the design to aid integration processes. This is a key factor favoring hybrid integration over monolithic integration.

-geometry and structures

Optimized optical device structures, especially in the key active regions, are often very different, even within a single material system. While this has obvious implications for monolithic integration, the effect on the optical mode can have implications in hybrid integration as well. Coupling surface-normal devices to edge-emitting devices is difficult in a monolithic environment. Edge-emitting devices, the most common style currently in use, actually make use of the cleaved edge of the chip as the optical interface.

Cleaved output faces are an intrinsic part of many devices, and it is necessary to achieve pattern to cleave alignment of better than 5 microns over 50 mm.

-processing

Epitaxial crystal growth is used extensively in III-V opto-electronic components. Some laser processes require 4 separate growth stages, with conventional semiconductor processing steps between them. Epitaxial growth becomes an intrinsic part of fab operations, and makes foundry growth intractable.

The topography of optical structures often necessitates substantial process development. Etches of 3 to 5 microns are common, and it is usually necessary to provide air bridge contact across 10 micron (or larger) trenches.

Smooth etch sidewalls are critical. Optical waveguide loss is often dominated by scattering from the etched surfaces.

-materials

With optical components made from materials spanning a large range of physical properties, Optical materials range from refractive index of 1.3 (styrene and foamed materials) to more than 3. This results in difficulty controlling reflections from different surfaces. Low thermal conductivity in some materials and high conductivity in others make it difficult to manage the device temperatures.

-yield

Device yields in optical components are often not yet at the levels of those for electrical components. In some cases the yield is low due to fundamental physical processes. Efforts to improve the yield of the basic device can include monolithic integration of additional features,

-Tolerance, tuning and trimming

Yield improvements are often achieved at the wafer level with processes that adjust the centroid of a distribution, rather than trim each device, and then final trimming is done during assembly.

Device level tuning of the oxide structures is being used, but the III-V devices are generally tuned using temperature.

-optical, electrical and thermal properties

Polarization effects in the devices are extremely important. Typical specifications require less than 0.1 dB variation in characteristics due to polarization states. Applications requiring -40 to +85 C operation are common, requiring extremely good temperature compensation to maintain DWDM specifications.

-optical interconnect

Interconnecting optical components is not as straightforward as connecting electrical signals. The efficiency of a connection depends on structural details and the degree of alignment. Hybrid optical systems must deal with geometric stability, lens aberrations and contamination. One of the biggest challenges in optical interconnection is isolation: the sources are generally very sensitive to reflections (usually frequency pulling or intensity noise results from feedback) and the only effective isolators are bulk optic devices which necessitate the use of lenses for most applications.

-cycle times

Optical assembly processes are generally slow in comparison to electrical processes, predominantly due to the tolerances that must be achieved. Assemblies often must maintain 3 dimensional tolerances on the order of 100 nm through the entire assembly cycle. This level of accuracy is often achieved using multi-step assembly methods and stabilization steps.

-Automation

Pick and place machines are used for assemblies, and automated systems are used for optical alignment. Key issues in automating optical alignment are the initial precision, since lens aberrations can make the optimization algorithms tough if the system doesn't start off close enough to the final position, the cure rate and shrinkage of the epoxies, and the precision required of the piece part when laser welded.

LOOKING FORWARD

Despite the challenges in implementing integrated opto-electronics, there are many positive steps being taken, from monolithic integration through hybrid assemblies.

<u>MOCVD selective area growth:</u> This technique allows different structures to be grown on different parts of the wafers. The process results in thickness variations related to the mask geometry, which can be used to form tapered regions to accomplish changes in the dimensions of the optical mode.

Underlined "MBE/CBE selective area growth:" Unlike MOCVD selective area growth, the growth rate in these techniques is almost independent of the mask geometry. While this does not allow tapered structures to be grown, it does allow nominally independent regions of the desired structures. This facilitates the transition from optimized individual devices to monolithically integrated components. MBE growth typically results in polycrystalline material forming on the mask, while CBE growth leaves clean masks, which reduces the opportunity for defect formation.

Planar waveguide components: Various functions are now being incorporated onto a single die. A Variable Optical Attenuator (VOA) with monolithically integrated taps and hybrid attached photodetectors for monitoring the signals is one example.

Flip chip bonding: Tremendous strides in accuracy have enabled applications that were out of reach only a few years ago. While ~2 μm 3σ placement error was considered top of the line a few years ago, vendors are now offering machines with 0.5 to 1 μm 3σ deviations.

Planar lightwave circuitboards: These are being proposed to achieve higher levels of hybrid integration, working in conjunction with flip chip die bonding. One notable example: arrays of semiconductor optical amplifiers, with spot size converters, mounted on Silicon with Silica waveguides that are used to achieve fast optical switching.

Parallel optical interconnect modules: These are being commercially deployed in highly sophisticated packages, with up to 12 parallel optical channels (from a monolithic array of sources) with associated drive electronics in a very small, low power module.

More complex optical devices are also being derived from integrated structures. New device designs making use of integration technologies are also more amenable to integration with other devices. All optical signal processors, for example wavelength converters, make use of monolithically integrated structures to achieve the desired result, while eliminating the need to convert back into electronics to process the signal.

CONCLUSION

Despite the challenges, the increasing demand for integrated solutions to the basic goals, i.e. generating, amplifying, manipulating and receiving suitable optical signals, is providing the impetus required to bring opto-electronic integration into the mainstream. Companies are aggressively pursuing improvements to provide still higher margins now, with reduced selling prices in the future. While the applications are few at the moment, ubiquitous integration is not far off.

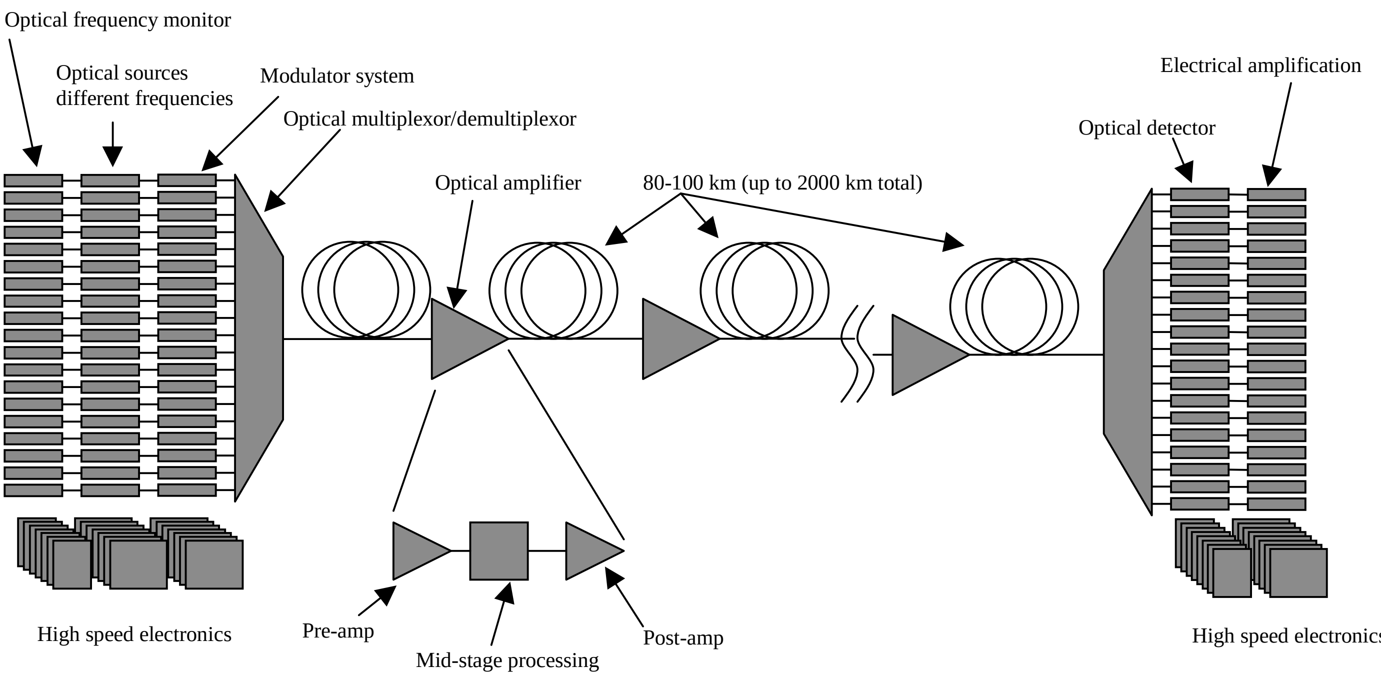

Fig. 1