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Optical WDM Networking Sub-System Functionalities: Hybrid Solutions

Applications Note No. 0005

WDM Optical Networking

The introduction of wavelength division multiplexing (WDM) into the existing telecommunications infrastructure represents the first serious deployment of optical networking in the evolution of the modern day network. The need for increasing throughput is real and pressing, driven by the requirement to provide a range of high-speed data and video services and the explosion in Internet use. With the introduction of a new range of revenue-bearing services, the problems of creating a future-proof system need to be solved as a matter of urgency. Optical networking has a combination of characteristics that make it a compelling candidate for meeting these requirements. Providing a transparent optical physical layer allows easy upgrade whilst supporting the existing electronic infrastructure.

WDM optical networking has evolved rapidly from being simply a more efficient way of using single mode fibres by carrying multiple wavelength signals on each one to the increasing adoption of photonics to implement other functions such as switching and add/drop directly in the optical domain. Today, it is almost universally acknowledged that the network will evolve as follows (Figure 1):

- WDM Point-to-Point Links
- WDM Point-to-Point Links with Add/Drop
- Hub Rings
- Meshed Rings
- Interconnected Ring Networks
- Mesh rings

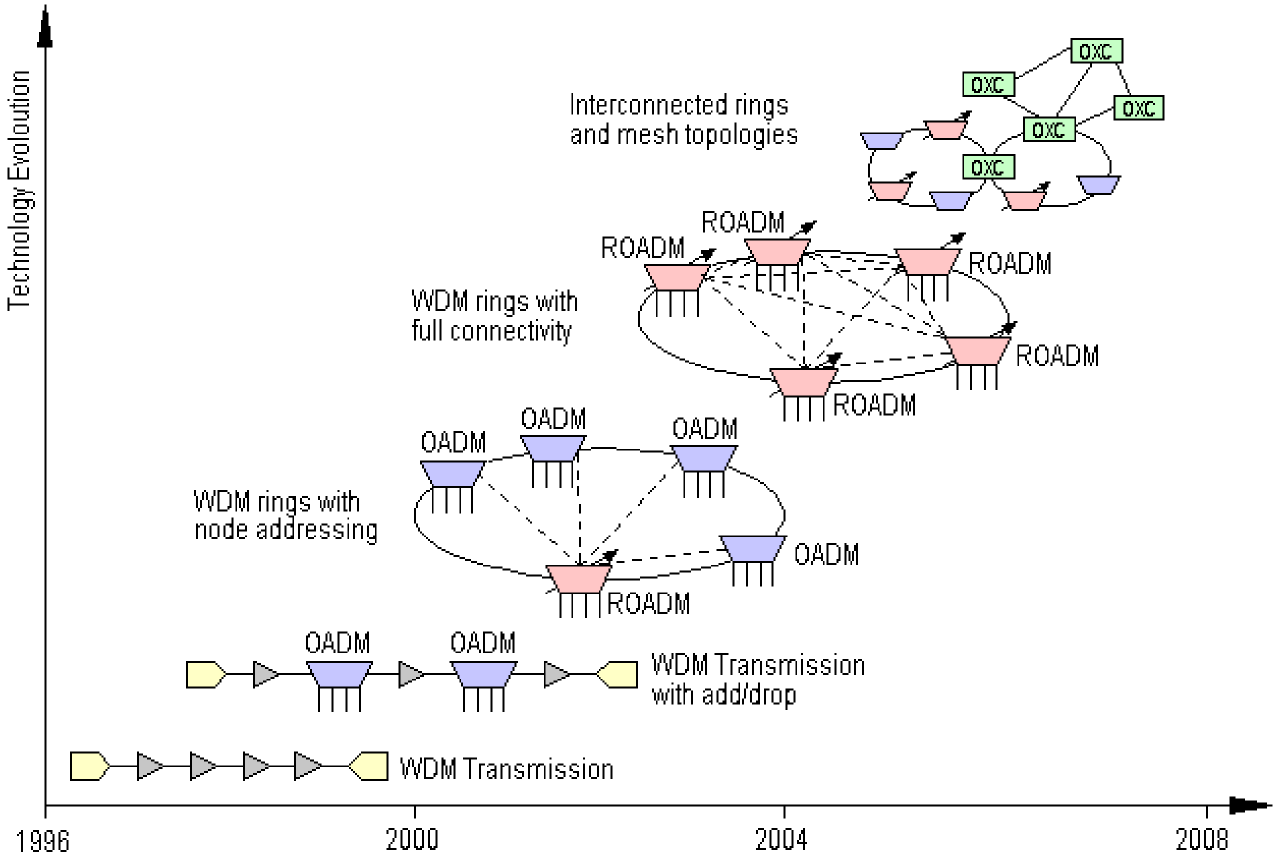

Figure 1: WDM optical networking evolution.

Sub-system functionalities

Given the range of application sectors, the deployment of next generation optical networks will require additional functionalities executed directly in the optical domain. Optical add/drop, optical cross-connects, optical packet switches, and all-optical regenerators are examples of key sub-blocks within this evolution. It is also becoming evident that the mass deployment of advanced photonic techniques relies on developing routes to the integration of passive waveguiding technologies with active semiconductor devices. In so doing, the advantages of each material system are harnessed effectively viz. passive waveguide technology e.g. silica-on-silicon, silicon or polymer waveguides for on-chip signal distribution and semiconductor devices for signal manipulation will provide enhanced system performance at reduced cost. A cost-effective solution to hybrid photonic chips incorporating the proper monitoring and electronic interfaces is central to any viable network strategy.

Advanced components will need to be manufactured in a scaleable way to meet the volume and cost demands of the systems integrators. Kamelian is developing a platform technology that will uniquely address these requirements. The basis of the platform technology will be an ability to design and manufacture customised (mode matched) active components that are then integrated on a silicon micro bench with outsourced passive components to realise hybrid modules (Figure 2). Such an approach is potentially highly scaleable and allows volume production of optical sub-assemblies at relatively low cost.

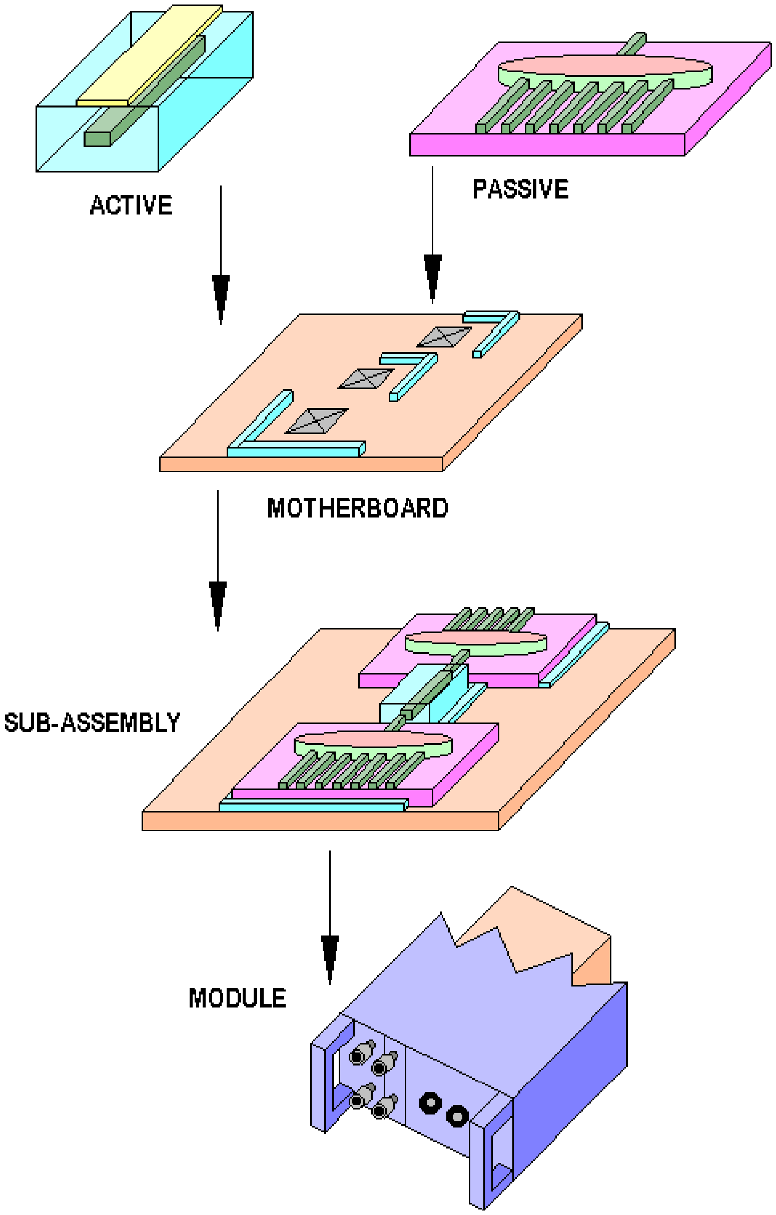

Figure 2: Kamelian's technology platforms.

Kamelian's product evolution thus reflects these systems evolution paths and has as the core component, and the enabling device for providing increased functionality, the semiconductor optical amplifier (SOA). This versatile component can be used in several modes:

1. lasers
2. optical amplifiers
3. optical gates
4. wavelength converters
5. all-optical logic devices

Semiconductor Optical Amplifiers (SOAs)

A semiconductor amplifier (Figure 3) is basically a laser diode operating below threshold. There are two basic types of amplifiers; Fabry-Perot amplifiers (FPAs) and travelling-wave amplifiers (TWAs). In FPAs the two cleaved-crystal facets act as partially reflective mirrors, forming the cavity. The reflectivity can be varied over a wide range using dielectric coatings (the natural reflectivity is 32 %). Once a signal is coupled into the cavity, it experiences amplification during its successive traversals between the mirrors. The structure of a TWA is more or less identical, the difference being that in this case, the facets have a multi-layer antireflection coating in order to prevent internal feedback. Thus the light signal traverses through the cavity only once and emerges intensified at the output.

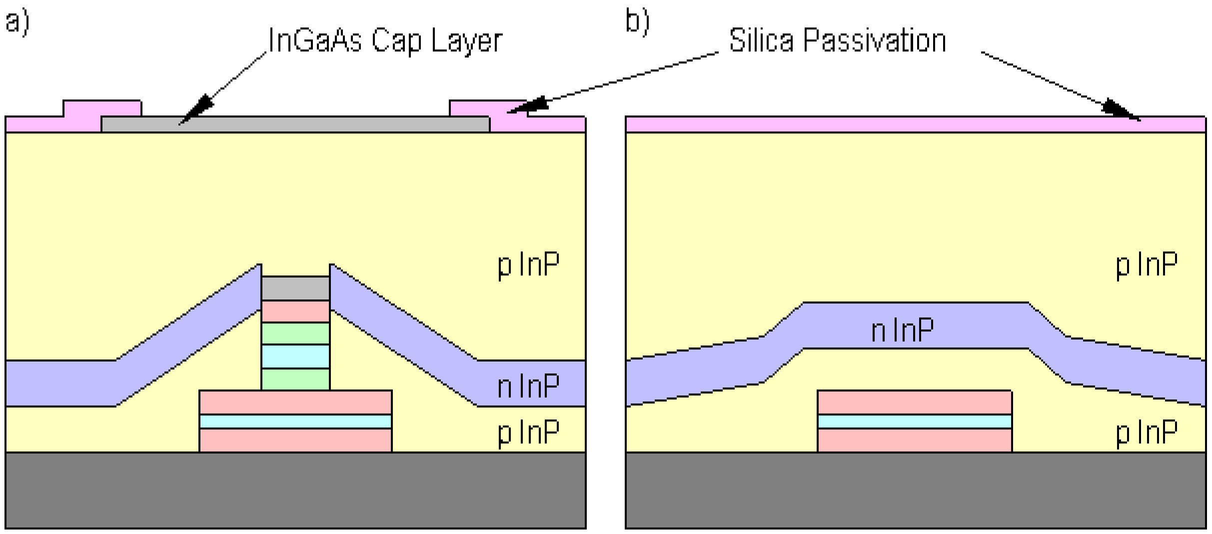

Figure 3: Schematic of SOA after overgrowth, capping and passivation. a) active b) passive area of device.

The TWA SOA is preferred for network applications, the parameters of importance being:

1. gain bandwidth
2. gain saturation
3. noise
4. polarisation independence
5. conversion efficiencies
6. input dynamic range
7. extinction ratio/crosstalk
8. tuning speed
9. wavelength of operation

The SOA has been the subject of extended development stretching back to the early 1970's. Since the gain dynamics in SOAs occur on nanosecond time scales and are thus comparable to the bit period of present multi-gigabit systems, they have found limited applications as linear amplifiers. This has been the exclusive domain for erbium doped optical fibre amplifiers, especially in high wavelength count (>100), high bit rate transport applications. However with proper selection of the operating conditions and for specific application scenarios, the SOA can be a low cost solution to providing amplification. For example 460-km transmission of a single 10Gbit/s channel has been achieved through 15 SOAs at an average spacing of 30km; and recently transmission of 32 wavelength channels at 2.5Gbit/s over 125km has been achieved (3 SOAs, 42km spans).

The Kamelian strategy therefore utilises the SOA as a low cost optical amplifier, either as a stand-alone component or indeed as an amplifier within a hybrid module, in niche applications especially in the metro at this time and as the penetration of optical fibre gathers momentum in access scenarios, has a future role to play in controlling costs of providing increased bandwidth to the customer.

WDM Optical Add/Drop Multiplexers (WADMs)

A WDM optical add/drop (WADM) extracts one or more wavelengths from a fibre (drop function) and re-inserts these wavelengths (add function), a very important function in WDM rings as well as point-to-point links. They can either be fixed or re-configurable, either under local or network management control. Reconfigurable devices perform add/drop on single, a group of or all wavelengths whilst the remainder pass straight through the device.
WADM implementations have been demonstrated based on the bulk filter, fibre Fabry-Perot, the arrayed waveguide grating (AWG) and acousto-optic tuneable filter technologies (AOTF). The former has the advantage of relative simplicity and is the only approach widely available commercially; however it can predominately implement add/drop on one wavelength or a sub-set of wavelengths, making it suitable for hubbing rings. AOTF add/drop nodes are being offered but have not been deployed extensively. The AWG is fast becoming the key route to the implementation of a number of add/drop functions. Configurations that combine switching (mechanical, thermo-optic, electro-optic) with the base substrate can add and drop multiple wavelengths.

The Kamelian R-WADM design strategy draws on two basic components; arrayed waveguide gratings (AWGs) as the core wavelength de/multiplexer and optical switches realised through SOA gates, as a means to add and drop multiple wavelengths, suitable for fully interconnected mesh rings. The R-WADM is a hybrid, through the integration of passive waveguide/filtering technology with active semiconductor switches on a single motherboard (Figure 4). Each switch block is a realised through SOA gates. The waveguide interconnection path for the add/drop channels pattern is manufactured with passive waveguide splitters/combiners, fully compatible with the AWG, increasing further the extent of the integration.

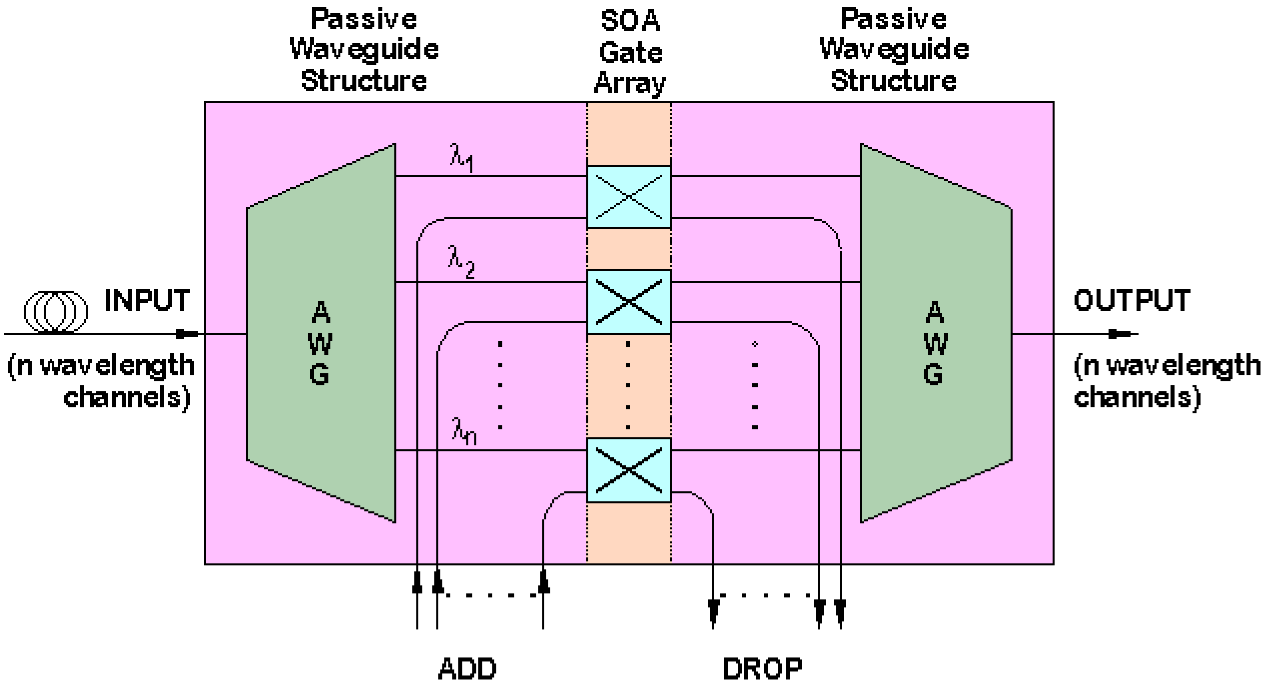

Figure 4: Kamelian's re-configurable optical add/drop using SOA gate technology.

The Kamelian R-WADM has several potential advantages when compared to other implementations:

1. lower overall insertion losses
2. lower crosstalk between adjacent channels (> -50dB)

3. inherent gain due to SOA (range 0dB - > 20dB) which provides a lower noise figure
4. dynamic signal level control via feedback to set individual SOA gains
5. generic design is scalable up to 128 wavelengths set by AWG size
6. node cascadability and inter-node distance increased on metro rings due to these benefits

In addition to the improved crosstalk performance advantage provided by the SOA gate, a strength of the Kamelian design is the improved node noise figure, of the add channel in particular. Comparisons between systems incorporating high performance EDFAs (input and output of the node) to compensate for the losses in large (>150km in diameter) metro rings and the Kamelian R-WADM with SOAs (EDFA at the input only) shows the advantage of utilising the SOA gain/gate in the node. Despite the higher noise figure of the SOA when compared to the EDFA, in this application the effective noise figure (including node losses) of the add channel is >4dB better for the Kamelian approach.

All-Optical Wavelength Converters/Regenerators

All-optical wavelength and all-optical regenerators will find extensive applications within the transport layer of the network at the optical cross-connects, providing increased flexibility with respect to path provisioning and restoration/protection, effectively a direct replacement for transponders. As this layer evolves, the role and the complexity of the optical nodes will increase and the hybrid integration of the necessary components becomes central. WCs will be integral in advanced OXC and optical packet node designs; longer term, the same building block will be used to the design and manufacture of 2R and ultimately to 3R all-optical regenerators.
In general, wavelength converters (WCs) allow more efficient use of the wavelength resource, affording a substantial increase in re-configurability. They have the ability to convert from one to another distinct wavelength, selected out of a range of wavelengths directly, in the optical domain; virtual paths and channels can now be implemented in an efficient manner with ATM-like connectivity. This adds a new degree of flexibility and, additionally, gives the opportunity to build new optical switching architectures and regenerative blocks.

Presently first generation optical cross-connect designs implement opto-electronic wavelength conversion and/or regeneration (transponders) through signal detection and regeneration at a different wavelength, a technique that compromises transparency and increases costs as the bit rate rises. New approaches to wavelength conversion have been developed that circumvent these restrictions, operating directly in the optical domain utilising cross gain modulation (XGM), cross phase modulation (XPM) and four wave mixing (FWM) in SOAs.

In XGM implementations, if a strong data signal is input to an SOA on l1 together with a weaker probe on l2, the strong signal modulates the gain of the amplifier and this modulation is imposed on the probe (Figure 5). The strong signal is then filtered out, whilst the probe signal is amplified.

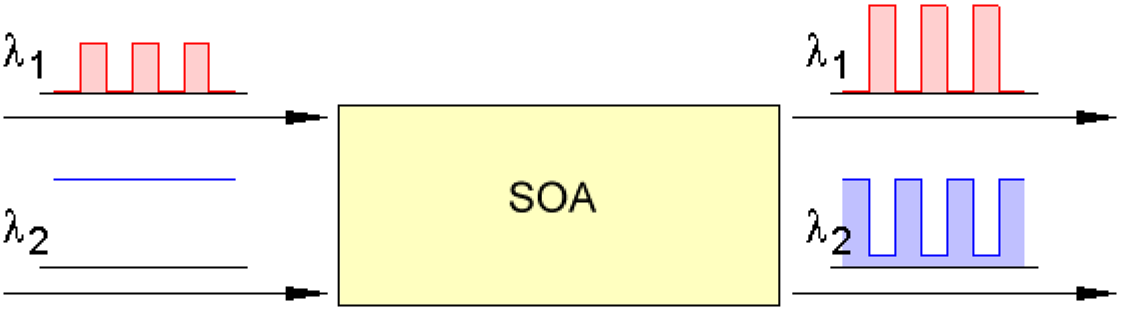

Figure 5: XGM wavelength conversion.

Cross phase modulation for wavelength conversion are realised interferometer configurations, most notably the Mach-Zehnder (MZI) and Michelson Interferometer (MI). The principle of XPM is based on the refractive index change induced by the intensity of an optical signal. By injecting a signal of sufficient intensity at one wavelength and a probe signal at the predetermined (converted) wavelength, the intensity induced refractive index modulation impresses the data on the probe signal. Within the interferometer structures, XPM converts optical intensity fluctuations in a particular channel to phase fluctuations in another channel, which in turn, are converted to intensity by the interferometer (Figure 6).

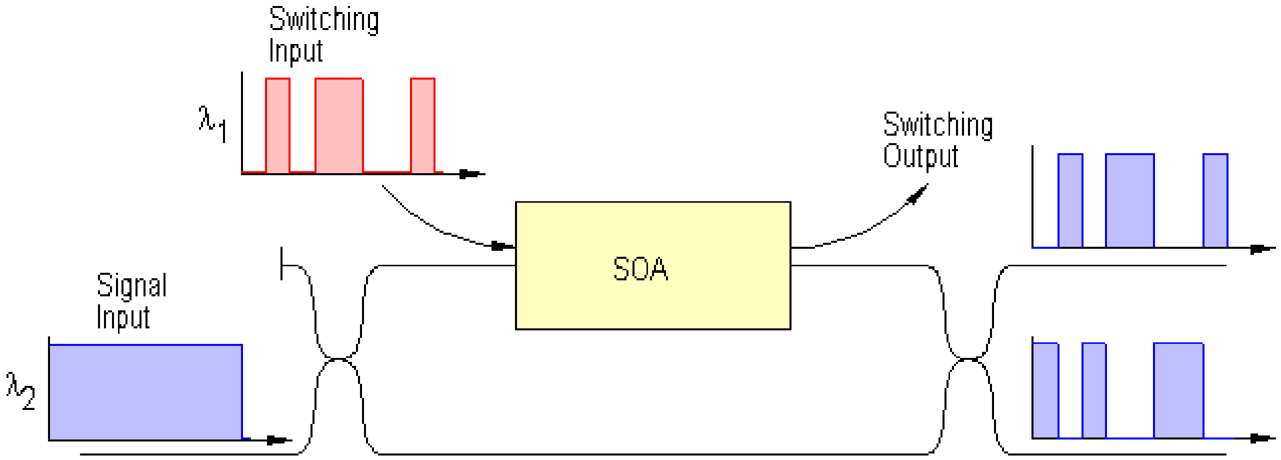

Figure 6: XPM wavelength conversion in a Mach-Zehnder Interferometer.

With FWM the data and the pump signals incident at the input of the SOA beat at a frequency determined by their optical frequency separation. The signals produce a sinusoidal gain modulation along the cavity generating inter-modulation products due to the non-linear characteristic of the SOA. Sidebands are generated in the optical spectrum either side of the input signal (Figure 7). Even though more than just one frequency is generated most commonly, the phase conjunct signal is chosen as the output. This signal has however, a low intensity that can result in power budget problems and low SNR. This is usually overcome by cascading two SOAs, one for the wavelength conversion and a second one for amplification.

Figure 7: Schematic of the Four Wave Mixing (FWM) process.

From a network performance perspective, devices based on XPM have the best set of characteristics since they are regenerative, the chirp can be tailored and can operate in inverting and non-inverting modes. Kamelian's product line will therefore be the XPM wavelength converter as a building block for higher-level functionality.

However the XPM geometry is inherently more complicated with respect to fabrication processes. The instability inherent in fibre based SOA interferometers caused by the relative path length fluctuation between the two arms of the interferometer affects the bias state. In integrated devices, however, the path length can be made sufficiently small (a few mm versus tens of metres in the fibre case) so that the drift in relative path lengths in obviated. Truly monolithic integration of the SOAs and waveguides in InP has the advantage of increased stability, small physical size and the possibility of integration of other components such as SOAs for pre-amplification or DFB lasers for provision of the destination wavelength.

Monolithic integration brings stability and reproducibility; however the Kamelian approach will adopt a hybrid strategy, compatible with its core competency. The waveguide pattern will be realised through passives, the active regions optimised in InP. Although similar performance characteristics result, consideration of cost and yield indicate that the hybrid approach has significant advantages. In addition, it also allows the integration of more advanced passive e.g. AWG and active devices e.g. gain clamped SOAs, thereby providing a range of functionalities (Figure 8).

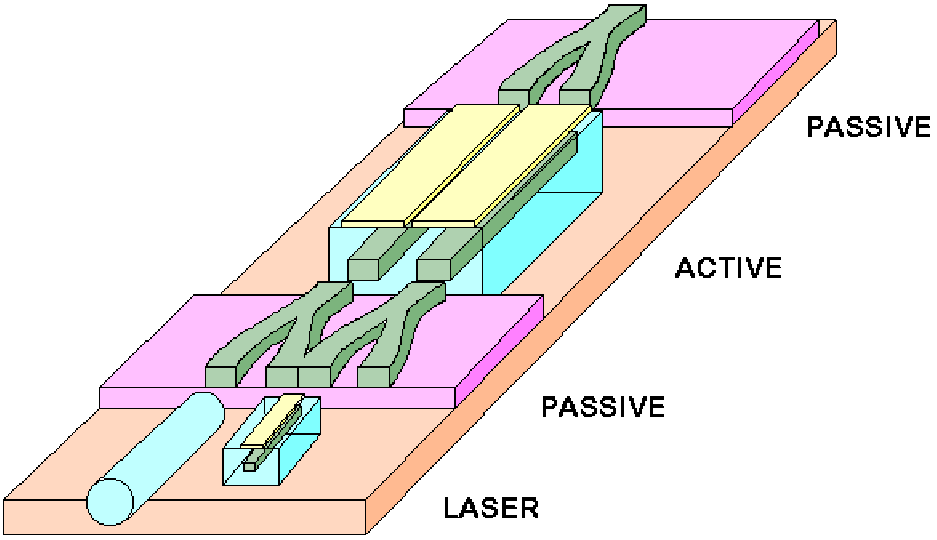

Figure 8: Kamelian's cross-phase hybrid all-optical wavelength converter.

High modulation rates of over 100Gb/s have been demonstrated for the XPM architecture. Moreover the ability to change the converted wavelength at a speed limited only by the tuning speed of the source laser provides an evolutionary capability for the conversion device to all optical packet switched architectures that will eventually replace optical wavelength channel routed ('circuit-switched') architectures. As the network evolves into optical packet transmission and switching, the wavelength dimension is also powerful in executing packet contention resolution.

The use of all-optical wavelength conversion devices with the option of conversion to the same optical wavelength, provides the core capability for optical regeneration and therefore all optical networks that are potentially transparent to the data. The wavelength conversion process performs reshaping (due to the non-linearity of the cross-phase modulation) and re-amplification (due to the inherent gain possible in the process) - i.e. 2R optical regeneration. Retiming for 3R optical regeneration, in addition, requires recovery of the clock signal either using optoelectronic conversion and an electronic clock recovery circuit or using an all-optical clock recovery approach.

Applications

WDM point-to-point links are being deployed extensively; practical networks, however, require increased flexibility with respect to interconnection. Thus the optical wavelength add/drop (WADM) capability along the transmission length has introduced limited flexibility. At the same time point-to-point links have evolved into more resilient ring architectures; hubbing rings, where all paths converge on one node (the hub) are becoming common. In the longer term, mesh rings, much the same as a hub ring, will become the norm, but providing connectivity between any node to any other node by a path thereby providing greater functionality at the optical level. Hubbing rings have the disadvantage of being inflexible since they cannot support any arbitrary mesh connection; nevertheless the passive ring with wavelength reuse is sufficiently flexible to justify its use in metro area applications. The interconnection of rings to form a highly interconnected network is then the extension.

Mesh topologies (not mesh rings) represent the most realistic architecture where the physical geometry consists of nodes, more-or-less randomly interconnected by fibres, using optical cross-connects, evolving from the interconnection of ring networks. Central are the nodes (optical cross-connects or OXCs) that route on the basis of space and wavelength division switching. They permit the routing of the signals that have reached their destination whilst allowing other channels to transit transparently to the next nodes; the latter can be multiplexed to the transit stream and routed to output fibres. Such an optical layer interfaces easily with the electronic SDH layer, avoiding de-multiplexing and processing of transit data.

WDM ring architectures

Vast quantities of optical fibre are now being deployed in the metro in ring geometries; there is a need to realise a re-configurable WDM add/drop (R-WADM) to fully utilise this infrastructure.

Optical ring networks may be categorised and characterised in several ways:

1. number of fibres,
2. number of wavelengths,
3. hub or mesh interconnection,
4. presence or lack of wavelength conversion
5. electrical or optical switching between working and protection paths
6. scalability

A key feature of ring networks in general is their ability to provide protection against faults. Protection and restoration involve the automatic recovery of a network from faults by using its spare capacity. Data rates on optical networks are becoming higher and higher, and networks are becoming more and more sparse, so the effect of a failure is becoming more catastrophic. Also, particularly in banking and commerce, society is becoming increasingly dependent on the telecommunications network as it grows in sophistication and functionality, and any failure would have serious consequences if there were no recovery mechanism. The distinction between protection and restoration is that protection involves the rapid switching over between working and protection paths, under local control. Restoration is more sophisticated and is generally applied to mesh networks, usually instigated by network management. In a ring network, there are three possible protection strategies:

1. no protection,
2. 1:1 protection – there is one working and one protection path between each pair of nodes that are linked by a path; normally the working path is used but in the event of a failure, operation switches over onto the protection path, and
3. 1+1 protection – similar to 1:1 protection but both working and protection paths are always active.

Hubbing rings

In a ring supporting hub traffic, all paths terminate at the hub node. This is inflexible since it cannot support any arbitrary mesh connection, but is useful for some applications such as local access; for example, an exchange (central office) could be located at the hub. All of those implementing protection use 1:1 protection.

In the protected 2-fibre version, centrally controlled optical switches throughout the ring are normally in the cross-state; those around a fault reconfigure to the bar-state, isolating the fault. The hub node receives bi-directionally, depending on an optical protection switch; if a fault occurs, any paths which would pass the hub and loop back to it, do not do so since they are intercepted the first time they pass the hub node. The purpose of this is to reduce crosstalk and noise, hence reducing the bit error rate.

Normally, each remote node has a wavelength assigned to it for communicating with the hub node, and there is an additional wavelength for monitoring. 1:1 protection is implemented over both fibres with switching between working and protection paths taking place electronically or optically. The wavelength channels used between nodes are permanently provisioned; hence a fixed WADM is utilised facilitating the removal and insertion of data streams on dedicated wavelength channels.

Mesh rings

In this ring implementation, “mesh” refers to the logical interconnection between nodes; the physical interconnection is still a ring, not to be confused with a WDM mesh network where the physical interconnection is a mesh. There is no hub node (all nodes have equal status), and a path may exist from any node to any other node. There is some kind of protection path between each pair of connected nodes proceeding around the ring in the opposite direction from the working path; the implementation method varies. Protected meshed rings are usually:

1. two-fibre mesh rings where the working and protection paths for a particular node pair never share the same link, in contrast to loop-back protection. The outer fibre is used for working paths that travel in a clockwise direction; the inner fibre is used for the protection paths travelling in an anticlockwise direction. In the event signal failure on the working path, the destination node switches over electronically or optically to the protection path.
2. four-fibre loop-back mesh ring which operates much like the hubbed loop-back ring but without the hub node. In the event of a link failure, the switches on either side of it are switched under local control into the bar-state, isolating that part of the ring and creating an alternative path to that link around the ring. Similarly, it is possible to isolate a malfunctioning node. The number of wavelengths required for all-to-all interconnection in a four-fibre is roughly ¼ of the circumference of the ring.

Any node can set up connections to any other node on the ring through wavelength. This path provisioning flexibility in the optical domain – the ability to set up and tear down optical (wavelength) paths to follow traffic demands in the network for efficient capacity utilisation – requires additional functionality at the nodes. Re-configurable WADM are necessary to select any wavelength from the multiplex. They also allow for efficient restoration to be implemented, providing the ability to re-route traffic around failed lines or nodes.

Interconnected WDM rings

Beyond single WDM ring networks, the next stage in the evolution of the optical network will be the interconnection of rings in order to form a more extensive, fully connected network. The "gateways" which interconnect a pair of connected rings may be formed in many ways, for example:

1. back-to-back WADMs, including protection switches.
2. Wavelength Path (WP) Optical Cross-connect (OXC) with/without optoelectronic/all-optical regeneration.
3. Virtual Wavelength Path (VWP) OXC based on delivery and coupling switch with/without optoelectronic/all-optical wavelength conversion.

The gateway node will not only affect the optical performance of the network, but also the trade-offs between number of paths that can be accommodated, number of wavelengths, and the size of the network. These are factors that are not yet fully understood, and much work remains to determine these trade-offs, before interconnected rings are deployed in the field.

When interconnecting rings, one option involves having just one gateway between each pair of interconnected rings, implementing the type of routing and resilience measures that would be found in a mesh. For resilience, this would involve allocating a certain amount of spare capacity in the network that could be allocated dynamically to re-routing interrupted paths. It would be necessary to ensure that the network is two-connected i.e. that at least two paths exist from each node to each other node.

A second option involves having two gateways between each pair of interconnected nodes and extending the 1:1 protection scenario to the multiple ring case. "Drop and continue" is a crucial WADM function that is necessary to implement this. Here, capacity must be allocated in such a way that the path from source and destination both impinge upon both gateways.

As the network evolves further into fully meshed architectures with dynamic optical path provisioning, all-optical wavelength converters and all-optical regenerators are key in providing a cost effective solution for multi-node, ultra high speed (> 40Gbit/s) extensive optical layer.

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kamelian

4 Stanley Boulevard,
Hamilton Int. Technology Park
High Blantyre, Glasgow, UK
G72 0BN

Tel: +44 (0)1698 722074
Fax: +44 (0)1698 821101

www.kamelian.com

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