Evolutionary switching devices for all-optical networks

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Abstract: - The Holy Graal in telecommunications and networking today is the 'all-optical network', where every communication would remain an optical transmission from start to finish. The speed and capacity of such a network - with hundreds, if not thousands, of channels per fiber strand would be practically limitless. In this context the availability of new all-optical components has enabled WDM technology to emerge as the right answer to the telecom operators' strategy of deploying very high speed connections in metropolitan and long-haul networks. In such a context all-optical cross-connects, used to selectively switch wavelengths at the network core level, are likely to emerge as the preferred option for switching multi-gigabit or even terabit data streams, and thus are expected to be the cornerstone of the photonic layer on which the future information superhighways are built. This paper deals with the design of next generation optical cross-connect devices proposing an architectural model for the implementation of their data forwarding plane and presenting the fundamental optical components required as the basic building blocks for making evolutionary all-optical switching devices.

Key-Words: - All-optical transport network, WDM, Optical Cross-connect, MEMS

1 Introduction

One of the major issues in the networking industry today is tremendous demand for more and more bandwidth. Before the diffusion of optical networks, the reduced availability of fibers became a big problem for the network providers. However, with the widespread deployment of optical networks and the introduction of Dense Wavelength Division Multiplexing (DWDM) technology, which, by multiplexing many different wavelength signals onto a single fiber can exponentially increase the bandwidth of a fiber optic strand, a new and probably, a very crucial milestone in network evolution has been reached. Many systems in use today have reached 40 different wavelengths (hence the term 'dense'), per fiber, which effectively multiplies the capacity of the network by 40 fold and it has been reported that the newest equipment splits light waves into as many as 160 channels, and prototypes in labs have apparently reached as high as 15,000 channels [1]. New optical devices like DWDM Multiplexers, Add-Drop Multiplexers (ADM), and Optical Cross-Connects (OXC), are making possible an intelligent all-optical network where packets are routed through the network without leaving the optical domain. In fact, the key concept to guarantee desirable speeds and correct functional behaviour in these networks is to maintain the signal in pure optical form, thereby avoiding the prohibitive overhead of conversion to and from electrical form. Such a network would be “optical transparent” in the sense that, in principle, it would be able to transport client signals with any format and with a wide range of bit rates (at least from about 10 Mbit/s to more than 10 Gbit/s). In particular, OXCs, used to selectively switch wavelengths between their input and output ports, are likely to emerge as the preferred option for switching multi-gigabit or even terabit data streams, since the slow electronic per-packet processing is avoided. OXC systems are expected to be the cornerstone of the photonic layer providing carriers more dynamic and flexible options in building network topologies with enhanced performance and scalability. The development of large and scalable all-optical OXCs with good performance is still a big challenge [2] despite
the tremendous progress in this area especially in the past year. Stringent performance requirements are placed upon the components that comprise the OXC and although these may to an extent be overcome, they are still manifested as limitations of the overall performance and scalability of the resulting networks. This paper deals with the design of next generation optical cross-connect devices proposing an architectural model for the implementation of their data forwarding plane and presenting the fundamental optical components required as the basic building blocks for making evolutionary all-optical switching devices.

2 The cornerstone in all optical switching: optical cross connects

The Optical Cross-connect (OXC) is a DWDM system component that provides switching functionality between its input and output ports with each port handling a bundle of multiplexed single-wavelength signals. The cross-connect should support network reconfiguration and allow the network providers to manage their wavelengths efficiently at the optical network level. An OXC is most efficient when it operates as a bit rate independent optical switch. This allows the cross-connect to manage different bit-rates such as OC-3, OC-12, OC-48 or OC-192 and also other formats like SONET/SDH and ATM. The OXC interface includes Lambda Switch Capable (LSC) interfaces that switches the lightpath segment based on incoming wavelength and Fiber-Switch Capable (FSC) interface that switches the lightpath based on the spatial position of the incoming data stream in the physical space. An OXC has several incoming and outgoing LSC interfaces or ports, connected to adjacent OXCs, and several incoming and outgoing LSC interfaces or ports attached to an edge device that can be a router. An OXC includes mainly two functional parts: an OXC Switch Controller and OXC optical matrix. The OXC Switch Controller communicates through Optical Supervisory Channels (OSC) i.e. out-of-band signaling transport mechanism or through dedicated and physically diverse control network i.e. out-of-network signaling transport mechanism. The Optical switch controller and OSCs define the signaling plane of the optical network. When receiving a signaling message, the controller translates to an internal control command, and sends this command to the OXC optical matrix. The optical switching matrix of an OXC has to reconfigure synchronously with the packet flow, within a slow and predictable reconfiguration time (typically ns). The control options of an OXC optical switching matrix are essentially connect (and disconnect) between an incoming LSC interface and an outgoing LSC interface. Properly, an OXC optical matrix receives commands from the Optical Switch controller, and replies whether the command was successful or not. The Optical Switch controller then converts the result into a message that it sends via the OSC channel throughout the signaling plane of the optical network. It is also capable to process status requests, lightpath modification requests as well as notification messages. The same commands apply when the OXC is connected to an LSC capable edge device. Based on these commands, a chain of connections through OXCs can form a point-to-point optical channel i.e. a lightpath. The ingress OXC is the node where the lightpath starts (sender), the egress OXC(s) are the destination end nodes (receivers) and the OXCs in the middle of the tree are referred to as intermediate OXCs.

2.1 The evolution of OXCs

The OXCs used today, called opaque OXCs, use electrical switching fabrics and static wavelength conversion. The optical signal carried in each wavelength is passed to an O-E-O transponder, which usually converts it to the region of 1310nm. This optical signal is then converted to electrical and demultiplexed into standard signals (usually SDH STM-1 or SONET STS-1). These signals are cross connected using an electronic switching matrix and then are multiplexed in order to form a higher transmission rate. Then this signal is transformed to optical, usually in the region of 1310nm and finally converted to the appropriate output wavelength with the use of an O-E-O transponder that does static wavelength conversion. One of the disadvantages of this architecture is that it uses electric switching fabric, which does not scale well. In addition it is very expensive because it involves a large number of O-E-O conversions, which are a
certain number per wavelength (six for SONET), and one transponder per wavelength. Furthermore, this architecture is typically based on SONET/SDH and the fact that the optical signal is de-multiplexed to STS-1 or STM-1 rates implies that this architecture leads to bottlenecks, as the number of wavelengths and the transport capacity of each wavelength increase. For instance, assume an OXC that terminates 25 fibers, where each fiber can multiplex 160 wavelengths. This implies that the OXC must be able to switch 4,000 wavelength connections. It is obvious that for such scenarios, which are expected to be commonplace soon, this architecture is not appropriate. An evolution to this architecture is the one that uses optical switching fabric that are expected to scale in a more cost-effective way than the electrical switching fabrics and they can scale to several thousands ports. However, this architecture does not provide transparency because it involves the use of more O-E-O transponders per wavelength. This means that a great number of transponders are required due to the increasing number of wavelengths that can be multiplexed within a fiber. In addition, this architecture uses static wavelength conversion, which implies that in order to resolve wavelength contention the optical signal must pass through a number of O-E-O transponders. According to this, the wavelength that arrives into an OXC is converted to a particular wavelength with the use of a tunable all-optical converter without being transformed to electricity. It is then passed to the optical switching fabric, which routes the optical signal to the appropriate output fiber. This architecture has obviously some important advantages in comparison to the previously mentioned. First of all, this architecture is totally transparent, that is the optical signal does not need to be transformed to electricity at all; this implies that this architecture can support any protocol and any data rate. Hence, possible upgrades in wavelengths transfer capacity can be accommodated at no extra cost. Furthermore, it decreases the cost because it involves the use of fewer devices than the other architectures. In addition, transparent wavelength conversion eliminates continuity constraints on conversions. In this way, the real switching capacity of the OXC is increased, leading to cost reduction. Products that are based on this architecture are expected to be available very soon.

2.2 All-optical OXC

Enabled by a new generation of optical components such as tunable lasers and filters, the third generation OXC is the all-optical Cross-Connect. This architecture makes use of optical switching fabrics and transparent wavelength converters, which eliminate the need for O-E-O transponders. According to this, the wavelength that arrives into an OXC is converted to a particular wavelength with the use of a tunable all-optical converter without being transformed to electricity. It is then passed to the optical switching fabric, which routes the optical signal to the appropriate output fiber. This architecture has obviously some important advantages in comparison to the previously mentioned. First of all, this architecture is totally transparent, that is the optical signal does not need to be transformed to electricity at all; this implies that this architecture can support any protocol and any data rate. Hence, possible upgrades in wavelengths transport capacity can be accommodated at no extra cost. Furthermore, it decreases the cost because it involves the use of fewer devices than the other architectures. In addition, transparent wavelength conversion eliminates continuity constraints on conversions. In this way, the real switching capacity of the OXC is increased, leading to cost reduction. Products that are based on this architecture are expected to be available very soon.

3 Building all-optical switching devices: technological issues

Optical networking today is hampered by the unavailability of high-performance low-cost optical components. Developing low-cost methods for fabricating large optical switches and tunable lasers is key to the realization of the all-optical networks. There are several available technologies that provide for direct optical switching including liquid crystals, bubbles, holograms, and microelectromechanical systems (MEMS). Between these approaches, MEMS is widely believed to be the most promising for large-scale optical cross-connects.

3.1 MEMS: the basic switching facility

MEMS are semiconductor-made micro-mechanisms, which are generally used as movable micro-mirrors that can deflect optical signals from input to output fibers [3]. VLSI fabrication techniques allow designers to integrate micromechanical, analog, and digital microelectronic devices on the same chip, producing multifunctional integrated systems, thus MEMS is realized with a mechanical integrated circuit where the actuation force
required moving the parts may be electrostatic, electro-magnetic or thermal. These silicon micromachines are built just the same way as a silicon integrated circuit. Starting with a silicon wafer, one deposits and patterns materials such as polysilicon, silicon nitride, silicon dioxide and gold in a sequence of steps, producing a complicated multi-dimensional structure [4]. By using the reflection of light and MEMS technology different kind of mirror arrays can be implemented. An optical switching matrix can be realized whereby the mirror may let an optical beam pass through or reflects it in a different direction. Each mirror may move to accomplish this by one of many methods, depending on the fabrication technology. It may be connected, for example, so that by rotating the mirror between two positions a beam is directed to one of two directions. It may be pulled down or up depending on voltage. Based on this technology, each mirror, connected with a micromachined electrical actuator, may be independently tilted so that an incident light beam is reflected in a desired direction. Thus, an array of \( N \) mirrors can direct \( N \) optical input signals impinging on them to \( N \) positions in space, where output waveguides are positioned. Clearly, this technique may be extended to construct \( N \times N \) mirror matrixes, where \( N \) can be potentially 1000. As far as medium and large-size switching fabrics are concerned, micro-mirrors can be arranged into two-dimensional or three-dimensional arrays. In these switches, mirrors are steered in order to deflect light beams properly. MEMS systems have moving parts, and the speed at which the mirror moves is limited. By applying more current, the mirror can move faster, but there's a limit to how much current can be sent into the array of mirrors. If this isn't bad enough, it seems that the speed and angular displacement terms in the calculation of the required current have integer powers of around 4 or 5, and so the bottom line is that we have to put a lot of current into the array for a small improvement in speed. By changing the mirror design so that the angle through which light is sent is smaller, it's possible to achieve faster switching speeds. This technique is known as “fast MEMS”. MEMS-based switching matrixes have been described as “exquisite engineering” by several authors [5-7] who highlight the multitude of technical challenges that must be addressed. For this reason MEMS is a very rapidly evolving technology and since it now seems to have a monopoly on the high port-count optical switch market, a huge amount of investment is going into the implementations and into solving the basic problems.

3.2 MEMS-based OXC

There has been a long debate about the appropriate MEMS technology to use for OXCs with the assumption that bulk micro-machining [7] is the only way to achieve sufficiently flat mirrors for low-loss fabrics. However, it is recognized that suitable micromachines alone are not sufficient to provide low loss and high performance optical switching fabrics [5-7]. The optical system design and optical component performance play a significant role in achieving satisfactory behavior and consistent low loss. Really, is very important to choose a design, which minimizes path length variations and any resulting loss variations. The two major architectural approaches for MEMS-based OXCs are the so-called 2-D and 3-D approaches. The 2-D approach involves arranging a set of MEMS mirrors in a plane. Each mirror is placed at a fixed angle with respect to the incoming light and is moved in and out of the path of the light like a shutter. By cascading sets of these mirrors one is able to steer the input from \( M \) input fibers to \( N \) output fibers. For the case in which \( M=N \), the total number of mirrors required is equal to \( N \)-squared. The so-called non-blocking Clos architecture can reduce the number of mirrors but adds a large amount of complexity to the system. This approach works quite well for small port counts (\( N<32 \)) but as the port number grows, the system requires many more mirrors and the total path length increases, which increases the insertion loss. At these higher port counts, 3D MEMS technology is the preferred choice. 3D MEMS arrays operate by steering beams of light in an analog fashion in 3-dimensional space. For \( N \) fibers in and \( N \) fibers out the total number of mirrors needed is \( 2N \) and the length that the light travels does not increase as quickly with port count as it does for 2D configurations. Each mirror can rotate about 2 axes and can direct incident light to any mirror in the companion array. The mirror in this array then redirects the light so that it enters the correct output fiber at normal incidence. The fundamental functionality required of each
mirror thus is the ability to rotate to many different positions in both the x and y-axes and hold that position for extended periods of time (up to years) with high accuracy. The fact that the mirror is functioning in an analog fashion greatly increases the complexity of the system. The mirrors for these arrays typically consist of silicon plates coated with a film that has a high reflectivity at the wavelengths used in the network. Each mirror is suspended in space by springs that are compliant enough to allow the mirror to rotate in response to forces applied to it. Because the mirror must be able to rotate about two axes, it is often suspended within a gimbal, which is itself suspended from a fixed structure as shown in the following figure 1.

Figure 1. Detailed MEMS mirror structure

This structure allows the mirror to rotate about one axis within the gimbal, which in turn can rotate about the perpendicular axis. In this way the mirror can achieve compound angles of rotation. The means by which the actuation of the mirror is achieved can be of many forms but often falls into one of two categories: electrostatic and electromagnetic:

—Electrostatic actuation consists of applying a bias between two conductors, which induces an attractive force between them. Whether achieved through a parallel plate or comb-drive architecture, this actuation scheme is very commonly used and has a number of advantages including low power consumption and relative ease of design. The parallel plate architecture is more straightforward and easy to fabricate but suffers from high-voltage requirements and strong non-linearity of force versus displacement. The comb-drive architecture is more linear and requires smaller voltages, but it is significantly more difficult to fabricate.

—Electromagnetic Actuation uses the interaction between an electromagnet and a permanent magnet to rotate the mirror. These devices have the advantages of relatively large torques when used with larger mirrors, and a smaller number of leads per mirror. They do, however, consume more power, which can lead to challenges of heat dissipation. They can also be more complicated to package, as they typically will involve the assembly of external magnets or coils.

There are many requirements imposed on the 3D MEMS that form the core of an OXC. Some of the most important of these are:

—Maximum angle: the most basic requirement for each mirror in an array is that it can rotate enough to direct light to any mirror in the opposing array.

—Mirror size/fill factor: the size of the mirrors in an array must be large enough to capture a large percentage of the incoming light and is thus heavily dependent on the optical design of the system. For a given mirror size, it is often desired to have a high "fill factor" which is the area of each mirror divided by the area of each pixel.

—ROC (Radius of Curvature): in order for the mirrors to be sufficiently reflective, they are coated with a film, which is typically gold. This film will induce some curvature on the mirror, which can be quantified by its radius of curvature. The curvature can induce an unwanted spreading of the reflected light. Therefore, it is necessary to keep this curvature low, i.e. keep the ROC high.

—Switching speed: to fit into the protocol of many optical fabrics, the switching speed often must be less than 10 ms to ensure uninterrupted service. To achieve such switching speed, MEMS designers reduce the mass of the rotating structures while increasing the maximum torque applied to them.

—Pointing stability: as the mirror drifts from its ideal angle, the light it deflects is steered away from the center of the fiber to which it is directed causing a decrease in signal strength. The extent to which angular error manifests itself in an increase in insertion loss is critically dependent on the optical design of the system. This requirement can be quite
challenging under shock, vibration, and temperature cycling and is one of the main drivers for closed loop control.

— **Scalability**: one of the advantages of 3D MEMS is its ability to scale to higher port counts without any radical change in its implementation. However, a number of challenges do arise at higher port counts ranging from increased angular deflection and pointing stability requirements to the difficulty of routing an increasing number of leads.

— **Reliability**: this area is very broad and is influenced by almost every aspect of system design. Reliability tests are governed by the conventional Telcordia specifications. These are used to qualify a system to ensure that it meets standard telecommunication reliability requirements. MEMS designers have the challenging task of meeting these explicit requirements and any additional ones proposed by a specific customer. This often involves a careful choice of materials whose properties change little over time, the use of small actuation signals (whether voltage or current), and hermetic packaging of the device to minimize environmental effects.

The reconfiguration time of an OXC is related with the electrical characteristics of the electro-mechanical-optical switching matrix used, that however should be always less than 25 ms, which is the acceptable threshold for the operations of network configuration. Furthermore, in order to obtain a low-loss system it is necessary to choose, as a rule of thumb, MEMS microlenses with very low aberrations (~1/10), low wave front errors across entire arrays and high focal length uniformity (~1%). The skew angle and angular range must be kept small, typically < 30° to avoid large polarization dependent loss that can arise from large angles of incidence on metal mirrors [8].

### 3.3 Optical amplifiers

In optical fibers, the effects of polarization mode dispersion and attenuation cause the signal strength to decrease rapidly after long distances thus making it impossible to detect the signal at the receiving end. Typically the signal needs to be boosted in power after every 100 km. In the pre-optical amplifier days this was done by converting the signal to the electronic domain, then amplifying it and reconverted it back to an optical signal. This optoelectronic conversion introduces noise in the system and is also costly to implement. Nowadays, **Erbium doped Fiber Amplifiers (EDFA)** are used to boost the signal power inline without the need for any optoelectronic conversion. The EDFA amplifies wavelengths in the region 1530-1560 nm range that is commonly referred to as the C-band. However, attenuation in the fiber is minimum in the range 1500-1600nm. So use of EDFA means that very little of this low attenuation region is being utilized. The solution is to use the **Silica Erbium based Dual band Fiber amplifier** that amplifies wavelengths in a much broader range of 1528-1610nm. The DBFA amplifies the wavelengths in the two bands, 1530-1565nm range (C-Band) and the 1565-1620 nm (L-Band). In addition, the DBFA also provides improved features like flat gain over the broad range, slow saturation and low noise.

### 3.4 Wavelength converters

The operation of the wavelength converter is to convert the input wavelength into possibly different output wavelength within the operational bandwidth of a WDM system. Wavelength converters are one of the important components of an OXC as they enable the reuse of wavelengths in the system by overriding the wavelength continuity constraint. This is necessary for wavelength routing and also to increase the system bandwidth. The typical all-optical conversion module consists of an Opto-Interferometric Wavelength Converter copackaged with a high power DFB tunable Laser. This laser works as a flexible multi-wavelength light emitter. Typically, the most commonly used tuning methods in tunable lasers are mechanical tuning, acousto-optical tuning, electro-optical tuning and injection current tuning. Samples of wavelength converters operating at 2.5 Gbit/s and 10 Gbit/s are already commercially available.

### 4 Putting all together: all optical OXC data plane architecture

A reasonable architectural model for the data/forwarding plane of an all-optical OXC is shown in Figure 2 below:
Here, the WDM Demultiplexers separate incoming wavelengths (N grouped lambdas) from input ports into individual lambdas. The wavelength converters will perform, if necessary, wavelength conversion (that is swapping the optical label when GMPLS is used as the control plane technology) based on the instruction from the control plane. A MEMS-based multi-layer optical switching fabric driven by a micro-machined electrical MEMS actuator redirects, according to the control plane instructions, each wavelength into appropriate output ports passing through optical amplifiers, typically Erbium doped Fiber Amplifiers (EDFA) or Silica Erbium based Dual band Fiber (BDFA) amplifiers, which boost the signal power inline without the need for any optoelectronic conversion to cope with the effects of polarization mode dispersion and attenuation on long distances. The WDM Multiplexer then groups the wavelengths from the above multiple layers of cross connects. By definition, this OXC architecture is strictly non-blocking and transparent to bitrate and data format, due to its all-optical implementation. The OXC is link modular since the addition of new input/output fibers just requires the addition of new elements without changing the OXC overall structure. On the other hand the OXC is not wavelength modular, since the adding of a new channel changes all the used MUXes, DEMUXes, MEMS fabric and wavelength converters.

5 Conclusion

Innovations in the field of optical components will leverage the introduction of all-optical networking in all areas of information transport and will offer to system designers the opportunity to create new solutions which will allow smooth evolution of all telecommunication networks. In the same way that transistors and integrated circuits changed the twentieth century into the “electronic century”, lasers and all optical modules will make the next century “the photonic century”. All winning strategies must rely on new optical technology – a domain in which innovations work at the speed of light.

References: