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Requirements and Technologies for Large Optical Cross-connects

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Introduction

The increasing implementation of optical telecommunications networks, using dense wavelength-division-multiplexing (DWDM), is generating a need for optical cross-connects with large numbers of ports (~1000 or more input and output ports). In this paper we review the basic requirements for the optical switch fabrics for such cross-connects, and the possible technologies for implementing them. One of the challenges in evaluating optical switch technologies is that there are many of them, with quite different characteristics. To deal with this problem, we introduce a system for categorizing optical switch technologies.

Basic requirements for optical cross-connects

Optical cross-connects enable efficient bandwidth management and fault restoration in mesh networks, which are generally acknowledged to be more efficient than traditional ring networks.

Required switch fabric sizes

Current models for cross-connect nodes suggest that such nodes will have of the order of 10 input and output fibers, each of which will be carrying of the order of 10^2 wavelength channels. Giving each of these numbers a range of ±5 dB, and converting to the nearest powers of 2, we conclude that cross-connect nodes will typically have between 4 and 32 input (and output) fibers, each of which will be carrying between 32 and 256 wavelength channels. Given these basic node parameters, the required optical switch fabric size depends on the cross-connect functionality.

For a wavelength-selective cross-connect (which does not involve any wavelength conversions), there is a separate switch fabric for each wavelength. In this case the required switch fabric sizes are in the range of 4×4 to 32×32, and a node will require between 32 and 256 such fabrics.

For a wavelength interchanging cross-connect (which provides greater flexibility, but requires wavelength-interchanging transponders) the required switch fabric size is of order 10^3 or between 256×256 and 4096×4096.

Other requirements

It is generally considered highly desirable to have the total loss of an optical cross-connect fall within the spec for short-reach links, or about 6-7 dB. Strictly non-blocking configurations are generally required, with switching times of < 10 ms. Typical crosstalk specs are ~ −35 dB, with some dependence on the specific system architecture. For protection against switch fabric failures, and to enable future upgrades of fabric size, it is generally considered necessary to provide 1 for 1 redundant switch fabrics. It is also necessary for the equipment to operate over the wide environmental ranges generally required for telecommunications equipment.

Categorization of switch technologies

Large-size optical switch fabrics are all made by interconnecting numerous simpler elemental switch units. We can then categorize switch technologies in terms of the basic switching functionality of the elemental switch units, and the medium used to interconnect the switch elements. It turns out that there are basically just three elemental switching functionalities, and just three types of interconnection media.

Interconnection media

The three basic types of media for interconnecting switch elements are optical fibers, optical waveguides, and free space. Optical fibers have essentially zero propagation loss and crosstalk, but coupling losses between fibers and switch elements, and fiber management, can be problems. Optical waveguides reduce the fiber management problems, but generally have higher propagation losses than fibers, and loss and crosstalk considerations typically limit the functionality that can be integrated on a single chip. Free space interconnections have essentially zero propagation loss and crosstalk, but since the optical beams are not confined within fibers or waveguides, diffraction effects impose a fundamental limit on the physical size of a cross-connect fabric. In most cases this results in a fabric physical size that scales as the square of the port count.

Elemental switch functionalities

There are basically three types of elemental switch functionalities: 2×2, 1×N, and 1×1.

With 2×2 elements there are a number of architecture options, illustrated in the top line of Fig. 1. The crossbar (Fig. 1a) is simple to control, but it requires a large number of elements, and different paths go through different numbers of elements. There are architectures requiring fewer elements (Fig. 1b), and in which all paths go through the same number of elements, but these are very sensitive to crosstalk, and cannot be used with many switch technologies. To achieve acceptable crosstalk levels, it is often necessary to go to dilated designs, as shown in Fig. 1c.

The architectures for implementing cross-connects with 1×N or 1×1 switches are more straightforward. With 1×N's (Fig. 1d), there are only two switch elements per path, but the interconnections can be challenging. With 1×1's (Fig. 1e), there is an intrinsic loss of 20 log(N) dB from the splitters and combiners, so one needs to add gain in the switch.

Review of available switch technologies

We now consider the characteristics of the available switch technologies, grouping them by elemental switch functionality and interconnection medium, as listed in Fig. 2.

2×2 elements with fiber connections

Mechanical 2×2 switches, with solenoid/relay actuators are the most widely used optical switches today. They have excellent optical performance, but because of size, cost, accumulated loss, and fiber management issues, they are probably not viable much beyond 4×4.

1×N elements with fiber connections

Mechanical 1×N switches with stepping motor actuators are also widely available, and have excellent optical performance, except for switching speed, which is 10's to 100's of ms. The slow speed tends to limit them to instrumentation applications.

1×1 elements with fiber connections

Such switches have been demonstrated, using semiconductor optical amplifiers (SOAs) as the switch elements, which also provide gain. While SOAs can switch very fast, they add noise, and the available gains limit their applicability to about 8×8.

Such switches can also be built using a series combination of wavelength selective tunable channel blockers (such as FBGs) plus optical amplifiers. This provides a wavelength-selective cross-connnect functionality, but the intrinsic losses probably limit this approach to modest fiber counts.

2×2 elements with waveguide connections

All such technologies are based on changing a refractive index. Electro-optic, and thermo-optic effects give relatively small index changes, so switches using them need long pathlengths to accumulate sufficient phase shift. Polymer-dispersed liquid-crystal elements can produce somewhat larger index changes, but also present significant challenges, such as PDL. The required length of the elements, and the space required for the interconnecting waveguides, probably limit these technologies not much more than about 4×4.

A waveguide switch technology, that achieves large index changes, by forming bubbles in a fluid, has been developed and is being offered by Agilent. They use a crossbar architecture, and while they have achieved impressively low pass-through losses, those losses still probably limit the technology to not more than about 32×32.

1×1 elements with waveguide connections

These are in principle possible, but have not been developed to any significant extent.

2×2 elements with free-space connections

Mechanical switches of this type, using solenoid/relay actuators to move macroscopic mirrors or prisms have been offered, and have lower losses than using fiber connections, but they are probably not viable beyond about 8×8, because of the problems of achieving and maintaining alignments.

The most promising technology of this type is based on a crossbar array of "popup" MEMs mirrors, and is being offered by OMM and others. Since the mirrors can be moved completely out of the optical path, there is no *intrinsic* size-dependent or path-dependent loss. However, diffraction effects led to a physical size that scales as the square of the number of ports, which makes achieving and maintaining alignments increasingly difficult as the size increases. These issues probably limit this technology to not more than about 32×32.

New switches of this type have been announced, using liquid-crystal switch elements or electro-holographic switch elements. There is not sufficient information available on these technologies for us to evaluate them.

1×N elements with free-space connections

Switches of this type, based on 2-axis, multiposition, tilting MEMs mirrors are being offered by Lucent, and others have announced products. The mirrors can tilt in two orthogonal directions, and by arranging them in two-dimensional (rather than one-dimensional) arrays, diffraction effects lead to a physical size that scales linearly as the number of ports. This is a major advantage, and because of it, this is the only approach that shows much promise for scaling to large port counts. However, controlling the positions of the mirrors presents significant challenges. Alternative beam-steering technologies have been demonstrated, including liquid-crystal-based holographic grating deflectors and miniature mechanical servo motors, but neither has been announced as a product.

Conclusions

Mechanical switches, with fiber interconnections, using solenoids for 2×2 and stepping motors for 1×N, are the workhorses for small-scale switching. They have excellent optical performance, and proven reliability.

Waveguide switches, with small index change, are possible competitors, but have seldom proven in, because of poorer optical performance (both loss and crosstalk). The major exception is for applications requiring high speed, where lithium niobate meets a niche market.

Switches based on semiconductor optical amplifiers, and mechanical switches with free-space interconnection, have yet to prove in for any significant application.

Bubble switches and popup MEMs mirrors are the two technologies with potential to scale to about 32×32, and which may find applications in wavelength-selective cross-connects.

For larger-size cross-connects, the two-axis tilting MEMs mirrors seem to be the only viable candidate. They might even scale to smaller sizes and challenge the bubble and popup MEMs technologies.

(For tunable FBGs with fiber interconnections, and for free-space switches with liquid-crystal or electro-holographic elements, there is insufficient information available at this time for me to reach any conclusions.)

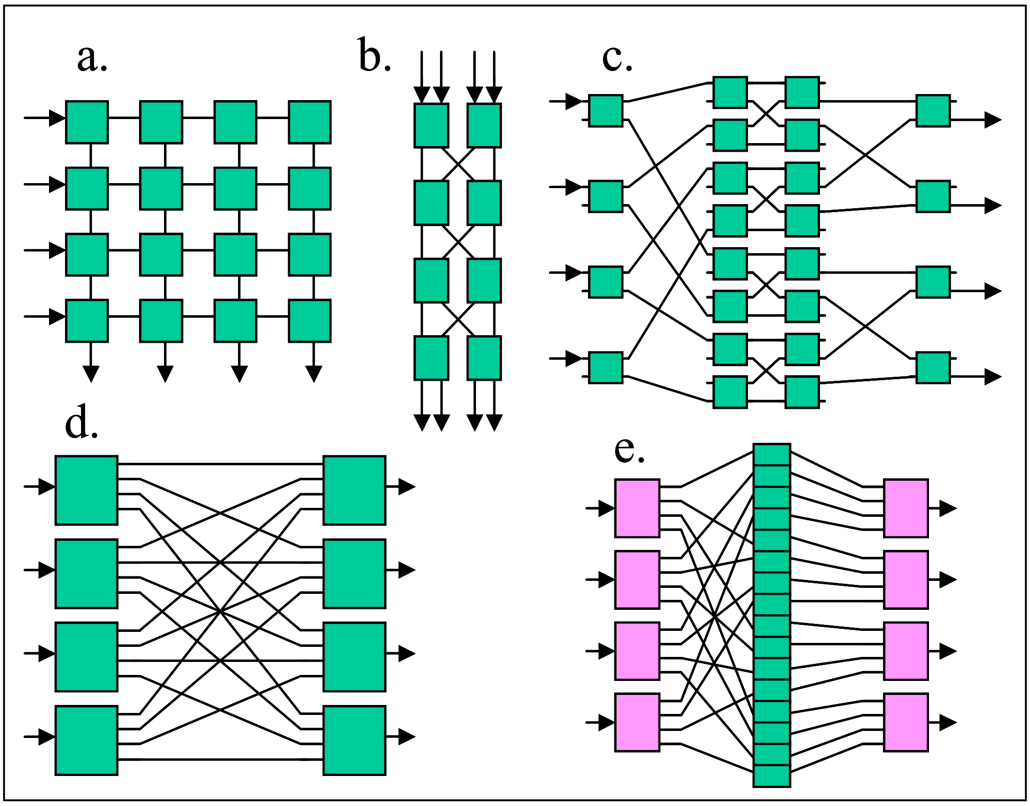

Fig. 1 Switch architectures. (In part e, the input and output boxes are passive splitters.)

Interconnection Medium

Switch Element Functionality	Fibers	Waveguides	Free Space
2x2	Mechanical, Solenoid	<u>Small index change</u> LiNbO3/Glass/Polymer Electro/Thermo-optic PDLCs <u>Large index change</u> Bubbles in fluid	Mechanical, Solenoid Liquid-crystal Electro-holographic Popup MEMs mirrors
1xN	Mechanical, Stepping motor	??	2-axis tilting MEMs mirrors
1x1	SOAs Tunable FBGs	Integrated SOAs	??

Fig. 2. Categorization of switch technologies.