Photonic Switching Technology: Component Characteristics versus Network Requirements

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Abstract—**Components for switching in the optical domain offer substantially different characteristics to electronic switches. However, except in special cases these characteristics do not immediately map well onto the network requirements as currently perceived so that there remains great challenge in establishing a viable technology.**

INTRODUCTION

IN THIS PAPER, we will use the term "photonic switching" to embrace components that either switch signals while they are in optical form or that intimately embrace the use of optoelectronic technology in the switching function. The term switching is interpreted in the telecommunications sense whereby it is synonymous with routing. This does not exclude its use in the logical switching sense (to perform logical AND, OR, etc.) but does embrace a wide range of implementations that are not suitable for implementing computing type logical interactions.

From the network point of view, we take it as axiomatic that switching will be performed electronically rather than optically unless it is either impossible to do so or is cheaper using optics. Since electronic switching is well established both for routing and multiplexing on circuits and systems at today's operating rates, it seems unlikely that optics will displace it from such applications. Thus we are forced to look for new applications where electronic technology is likely to be more seriously challenged. Broadly speaking, we propose four general areas where this might occur:

a) reconfiguring long-lines high data rate cable networks (protection and block switching),
b) ultrahigh-speed (>1 Gbit/s) multiplexing and demultiplexing,
c) routing of wide-band signals in a wide-band BB.ISDN or CATV local network,
d) routing wide-band digital data in circuit or packet format at major network nodes in the long-lines networks.

From a component point of view, the performance requirements for each of these are very distinct. Class a) applications require switches capable of transmitting very wide-band digital signals. The size of matrix required is likely to be small (16×16?), the time between reconfiguring the matrix long (typically measured in hours), and the time available to carry out the reconfiguration operation probably measured in micro- or milliseconds if not much longer. It is also important to note that the whole data stream is to be rerouted as a single block and that no access to the underlying frame structure of the data stream is required in this application, provided that reconfiguration occurs when the system is out of traffic. Even if it is not, data loss will occur because of different cable route lengths (and hence delays) to the destination.

In Class b), the emphasis is upon interleaving or deinterleaving very high-speed data streams. Data rates of many gigabits per second per port can be expected with interleaving complexities of 4 to 1 or 1 to 4 being typical. The challenge here is to use the optics to ease the problems of designing very high-speed electrical drive circuits. The individual switches in such a system must be driven in a fixed sequence but only the first (or last where the highest data rate is assembled) needs to switch with great precision relative to the data bit intervals. Access to the underlying timing data of the digital signal is of course fundamentally necessary in contrast to a) above.

Class c) applications typically involve very large numbers of customers with one or two fibers connected per home to provide a broad spread of new wide-band distributive and interactive services as well as telephony and digital data connections. It is axiomatic that the fiber(s) will carry many different services simultaneously and thus the means of multiplexing these together is critically linked to the means of routing them. The nature of the switching functions required can vary widely between telephony, viewphone, and entertainment TV or audio with "call duration" times spanning minutes to hours and data rates spanning kilobits per second to many megabits per second. In addition, depending upon the availability of bandwidth, the need to deliver services that are largely distributive by nature (i.e., network TV) via a switched channel may be questioned so that some form of hybrid network, part switched, part distributive, may be more appropriate.

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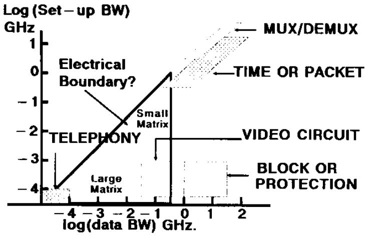

Fig. 1. Summary of switching applications presented in terms of the matrix setup time and matrix complexity.

The Class d) application almost inevitably implies operating directly on a time multiplexed data stream at very high data rate in real time. The exact details of the data formatting will vary considerably between packet type data, TDM data streams, and asynchronous time division data as favored for some future wide-band networks. In each case, the ability to reconfigure the switch very fast is essential and this must be done during time intervals that are sharply defined relative to the data flow. Exactly how much time is allowed for such a reconfiguration then depends upon the specification of the multiplex data format. Access to the timing of the multiplex signal is necessary and a typical switching operation involves moving data from one time mutliplexed channel to another, implying an ability not only to time separate blocks of data but also to time shift them. Switching between many input streams and many output streams of such data presents even more complex problems.

We will now examine a variety of different photonic switching technologies against these applications, each bringing unique possibilities to the subject but also problems or limitations. The strengths of optical transmission such a huge transmission bandwidth and freedom from optical "crosstalk" generally carry over to the switching domain. However, in many cases we find that the electrical control problems of setting optical switches may be more difficult than for their electrical brothers, so that the benefit to be gained from their use is not immediately obvious. In discussing them, we will group them according to their switching characteristics rather than their optical implementations. These applications are summarized in Fig. 1 in which we attempt to relate in simple terms setup time and matrix complexity for the various categories.

PASSIVE PATHWAY SWITCHES WITH ELECTRICAL CONTROL

Here, the light traverses the switch unchanged, apart from attenuation and hopefully only minor reflection and crosstalk from adjoining elements. Prime examples of such elements are those made using optical fibers as the guidance elements and those formed in a planar "integrated-optic" waveguide format in materials such as $LiNbO_3$.

Fiber switches may involve the mechanical movement of one fiber relative to another to change the coupling between them [1] or they may involve the use of a material such as a liquid crystal film sandwiched between two exposed cores electrically modified to adjust the coupling coefficient. In the former case, switching times are likely to be limited by the mechanical time constant of the movement mechanism which is likely to be measured in milliseconds. The time to switch liquid crystal films can vary over a wide range according to the material used and spans, in the extreme, microseconds to seconds. The coupling between fibers may occur in an endfire format or laterally through evanescent field coupling [2]. In the latter case, removal of the cladding is necessary to expose the core, although this might be achieved through the use of fiber having a *D* cross section as pulled leaving the core exposed.

In general, these fiber switches share the characteristic that they have extremely low insertion loss in the "closed" state and large isolation in the open state. If they are configured in the form of an "exchange-bypass" switch with four terminals offering either a straight-through or crossover connection, then the insertion loss in the cross and bar states is likely to be different, normally higher in the cross state. Furthermore, since both signals are simultaneously present in the same structure, crosstalk is now possible, the exact value being extremely device dependent. The devices are relatively large, typically of millimeter-length interaction regions and with fiber tails that are likely to be in centimeter dimensions. Packaging large numbers for a complex array is thus likely to involve handling large quantities of fiber. The fact that the fiber devices can offer very low insertion losses suggests it may be possible to construct large matrices using them, perhaps serving many thousands of terminations. However, the mechanical problems involved in handling such large numbers of discrete fibers in an orderly manner remain unsolved.

From the control point of view, these devices typically have two electrical connections per switch. For the fiber "reed relay" format switch, switching is bistable and the properties thus do not depend in an analog fashion on the electrical control signals. For fiber switches using precision V-groove arrays for location, the same is true. However, the switches in which the movement is controlled by a piezoelectric analogue "pusher" or by electrical modification of a liquid crystal or other material, precision control of the individual elements may be necessary. Most of the fiber devices are not polarization sensitive.

Switches formed in $LiNbO_3$, typically by the diffusion of Ti to form a planar waveguide directional coupler structure, are again electrically controlled but now through the electrooptic effect [3]. Many detailed designs exist and these have been reviewed extensively elsewhere. Their characteristics are significantly different from the fiber devices. Being produced lithographically in a planar substrate, it is now possible to form many devices simultaneously in a single substrate. Because the directional coupler is typically millimeters long yet micrometers wide, matrices of such devices tend to be very long and thin. To make better use of the substrate area and achieve a more tractable device structure, an 8 × 8 full cross point array (64 devices) has been made on a substrate measuring 68 mm in length using individual elements of 4 mm in length in a folded array, folded by reflection across the matrix diagonal [4]. Larger arrays seem likely to be fabricated by wiring together chips of this level of complexity using optical fibers, and switches of 32 × 32 Clos type have been reported using 8 × 8 building blocks [5].

Discrete switches can operate very rapidly, substantially subnanosecond [6]. However, since the capacitance of the electrode structure associated with each device is typically a few picofarads and switching voltages are of the order of 10 V, significant electrical energy is involved in switching each device ($0.5\ CV^2$ at 100 MHz rate corresponds to 5 mW). Add to this the fact that the discrete devices for a large matrix are spread over a large area of substrate and it is apparent that the electrical problem of delivering and switching signals with precise timing and no electrical crosstalk is severe. This problem is further compounded by the fact that most devices exhibit analog (nonlatching) switching characteristics and thus require close control of switching voltage. Many designs also require two separately controlled voltages per device to ease fabrication tolerance problems and variations in manufacture often mean each has to be individually adjusted. For these reasons, the construction of large arrays that must switch synchronously with a high data rate signal stream is extremely difficult if not impossible. Moreover, we note that the transit time through 2 × 70 mm of lithium niobate would approach 1 ns so that synchronizing data streams at multigigabit-per-second rates traveling via different pathways would be very difficult.

The optical characteristics of these waveguide switches share in common with the fiber devices a very large data bandwidth so that this is unlikely to be a major design consideration. However, the spectral bandwidth is finite and the switching characteristics (extinction, crosstalk, etc.) are likely to be wavelength dependent so that some control of carrier wavelength may be necessary. For systems involving multiple carrier wavelength, this may be a problem. The insertion loss is higher than for equivalent fiber devices, typically 0.4–1 dB/switch. Crosstalk tends to be more of a problem, as does incomplete extinction in the discrete device and it is these effects that currently limit the useful array size. The fiber and planar integrated optic switches could operate bidirectionally if required.

A feature not present in most fiber devices is dependence of the switching properties upon light polarization direction. The planar waveguide devices are polarization dependent unless specifically designed not to be, when other penalties accrue such as larger drive voltage and tighter fabrication tolerances [7].

Another factor that should be noted in the switching context is that both the lithium niobate and fiber-based switches tend to be used in a toggled mode, ON or OFF, exchange, or bypass. Some applications require the ability to fanout a signal to many points on a switched basis. Without some form of signal amplification, this necessarily implies attenuation of the available power by at least a factor $1/N$ where N is the fanout level. Matrices having this characteristic have been designed and built in lithium niobate using passive waveguide power splitters [8]. So also have special designs aimed at achieving extremely low levels of crosstalk [9]. A further topic of detailed study is that of crossovers between waveguides in planar circuits where NO power transfer is the design objective [10]. These are required in the construction of "wiring patterns" such as banyans or perfect shuffles which appear in the more efficient matrix designs that use fewer cross points for a given size switch.

The long term stability of $LiNbO_3$ devices is still a subject of study and some concern. The optical properties can change because of refractive-index damage effects, while the electrical properties can change because of the buildup of electrical carriers within the crystal material, leading to local space charge effects (see, for example, [11]).

Large crossbar circuit switches have also been proposed using optically written phase holograms operating in a free-space beam steering mode [12]. The concept here is to optically write a phase grating in a suitable photorefractive material and to place it normal to an incident beam. The grating then deflects the beam at some angle A to its original direction with large A corresponding to many lines per millimeter in the grating, and at some angle B in the azimuth direction set by the orientation of the grating in rotation about the beam axis as shown in Fig. 2. Thus the beam can be scanned over a circular area centred about the original beam direction. By associating a separate holographic grating with each input beam in a parallel array, perhaps derived from a square array of fibers, it is possible in principle to direct beams at a similar sized array of detectors. To couple the light directly into output fibers would then require a second grating array with matching gratings to beam steer each beam into its target fiber, and this seems likely to present further difficult implementation problems since writing the single grating array seems a challenging task in itself if it is to be done with speed and accuracy. Moreover, in a real circuit switch, it will be necessary to selectively erase single gratings in the array prior to rewriting them for connection to another output channel. The technique's major attraction appears to be that it offers some potential for scaling to very large arrays since the insertion loss appears largely independent of matrix size. However, since deflection angle is related to wavelength (and grating pitch), larger matrices will require even tighter tolerancing of these parameters. When used as an optical switch for remote sources, this could be extremely difficult to arrange.

Of the above devices, lithium niobate devices seem well suited to Class a) applications provided that the long-term stability problems can be proven solved. However, fiber devices might well be preferred on the grounds that they may offer superior reliability and long term stability and provide adequate fast switching.

The Class b) application clearly requires devices of the lithium niobate type (or another electrooptic material).

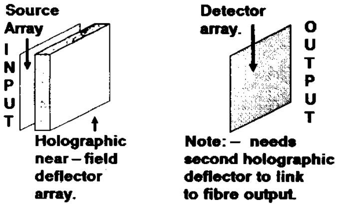

Fig. 2. Schematic layout of a holographic space switch.

Here emphasis is placed upon speed of switching coupled with modest insertion loss in a small matrix. However, it may reasonably be commented that if the electronic drive circuit can drive the modulator at the required speed, it could probably have driven an electronic modulator for the laser source directly. Some advantage is obtained in interleaving multiple random bit streams in that the interleavers are switched with a fixed frequency 10101.. signal, etc., and only the modulators, operating at a submultiple of the line rate need to operate with random data streams (see [13]). It is not obvious to this author that either the fiber or the integrated-optic devices have any substantial role in Class c) applications. The need to handle a wide variety of signals, each of which is at rates that could be switched electrically and with the transmission between the switch and the customer in a time or frequency multiplexed format suggests that other techniques may be more appropriate (see later sections) including some that are not optical. Likewise, the holographic switch, while sometimes presented as a switch for use in wide-band local networks, seems again ill suited to handling any form of multiplexed traffic so that in the application, it would be restricted to one video channel per port operation. Finally, the Class d) switches look difficult to implement using any of the above techniques since normal time multiplexed transmissions contain many time slots per frame, implying that need for a very large switch fanout and many different integer delays available on demand. If the many channels are at low data rate, then switching is more readily done electronically while if many channels of high data rate are interleaved, the line rate rapidly moves out of the electronic control range, so that only simple 1 to 4 or 4 to 1 multiplexing is conceivable. All these switches involve resetting of the switching matrix during time periods that are precisely linked to the multiplex format and which must be short relative to the byte or packet time. However, we note that some proposals for wide-band services suggest that extra time spaces be left between "packets" of data specifically for this purpose so that only these reset periods be synchronized with the switch, the underlying data being unsynchronized [14]. This would then allow the broad transmission bandwidth of the lithium niobate switch to be exploited but still allow matrix resetting times of many data clock cycles length. Note that time slot interchange switching involves not merely the breaking out of discrete packets of data destined for any given source but their reassembly in a different time sequence. Optical memory is thus a key constituent and one element that can provide fixed time delay with low attenuation is the optical fiber, offering storage delays of approximately 5 ns/m. The techniques for assembling and accessing an array of such delay lines have already been given some consideration [15].

ACTIVE PATH OPTICAL SWITCHES WITH ELECTRICAL CONTROL

These devices amplify or in other ways modify the optical data flowing through the device so that they are not optically passive like a block of glass. A prime example is the semiconductor laser amplifier (SLA) based upon a laser chip but operated with antireflection coatings to suppress laser oscillation. The device can exhibit substantial power gain, say 20 dB, under electrical control. Hence inserting the device in an optical pathway is equivalent to inserting a variable gain amplifier. Add to this the fact there is usually substantial insertion loss associated with coupling such devices to fibers or planar waveguides and we see that the potential exists for a new type of switch [16]. In Fig. 3, we show such a switch using a passive 3-dB two-way splitter with two SLA's, one in each arm. By adjusting the gain of either laser, the attenuation between them and the output port can be set to 0 dB. Turning the laser off will introduce a loss of at least 3 dB. In practice this will be much greater, probably 10–15 dB. Thus the possibility exists of building networks in which signals are fanned out and/or routed under electrical control. Combining four SLA's with four 3-dB splitters as shown in Fig. 4 then leads to an optical crossbar switch. The 3-dB bandwidth for the semiconductor laser amplifier is typically in the range 1–10 GHz, although some special laser devices respond to higher frequencies. Interconnecting discrete devices to form a switching matrix could be done with fibers although a novel and possibly better technique involves SiO_2 waveguides formed on Si substrates by chemical vapor deposition and lithographic techniques. Milling slots across an array of such guides then allows a linear array of laser devices to be inserted and electrically connected in hybrid circuit fashion to conductors on the silicon motherboard and optically connected to the optical waveguides, giving a composite electrical/optical hybrid circuit. However, a problem with this as with the $LiNbO_3$ planar waveguide circuits is the need to cater for crossing noninteracting waveguides. This can be done with optical waveguides in a single layer format by careful control of waveguide dimensions and crossing angle.

As with the lithium niobate devices, severe problems seem likely if both fast switching large matrices are to be constructed simply on the grounds of electrical crosstalk, inductance, capacitance, and delay problems. Moreover, even in the case of a slow circuit switch, the electrical power dissipated by a large number of SLA's is certain to lead to difficult problems of heat sinking. Typical SLA drive currents are likely to be 10–50 mA which, with a voltage drop of a few volts, implies 30–150 mW per amplifier and 60–300 mW per cross point. Hence a full 16 × 16 crossbar could be consuming as much as 80 W of electrical power. Thus to make a large crossbar using this

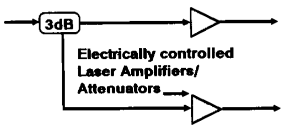

Fig. 3. Simple three-port switch based upon semiconductor laser amplifiers.

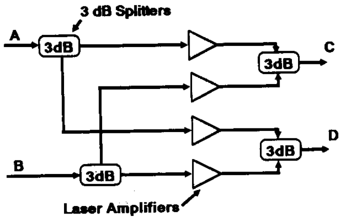

Fig. 4. Four-port switch configuration using semiconductor laser amplifiers, illustrating a minimum of 6-dB insertion loss that can be balanced by the SLA gain.

approach will require very careful attention to minimizing optical loss and maximizing SLA efficiency. (Note that at 1-mW optical per port and 6-dB attenuation per cross point, when all 256 are active, the minimum optical power loss is 0.19 W assuming 100 percent efficiency for all other elements).

Optically Controlled Electronic Logic

Careful examination of the requirements for the Class d) fast time switch quickly leads one to question whether optics has anything to offer. Given that the data stream is time multiplexed with large dead times whenever the switch needs to be reconfigured, then the "slow circuit" switch offered by relatively large $LiNbO_3$ matrices is a potential candidate. However, if switches are required that can be operated synchronously with a wide-band (multigigabit per second data stream, this will become increasingly difficult using any of the optical devices above. An all electronic solution is also likely to be difficult, since the synchronous operation of a large digital circuit runs into severe timing problems arising from clock time skew and variable delay on different data pathways, not to mention the difficulty of feeding large quantities of wide-band real time data into and out of a large chip. Moreover, if the electronics can drive the optical switch, then it can in all probability handle the data directly. However, at such speeds, problems of timing and electrical crosstalk become extremely serious in extended circuits.

A radical approach to this problem has been proposed which seeks to exploit the wide-band interconnect properties of light, coupled with the possibility of constructing complex parallel "zero time skew" wiring patterns using imaging optical systems. This has generally been proposed in conjunction with "optical logic elements" (to be described in the next section) but could equally well be used with electronic logic given only an efficient electronic ⟨--⟩ optical interface capability. This particular problem, coupled with the type of switching matrix architecture that might become attractive using it, has been considered in some detail and ways in which a self routing matrix using such a hybrid optoelectronic technology with optical "wiring" might be constructed has been proposed [17]. Closely related to this general approach are ideas of electronic islands with optical zero-time skew interconnections such as perfect shuffles allowing small electronic processors to operate at the frontiers of electronic speed and also to be connected into a large pipeline type processor closely resembling a large switching matrix [18]. Such a layout is shown schematically in Fig. 5 which highlights the proposed division between optical and electronic componentry to exploit the major strengths of each. A variety of suitable optoelectronic interfaces already exist in discrete component form. For the optical to electrical interface, one of the many types of detector is candidate. A natural approach is to think in terms of simple p-i-n detectors monolithically integrated with simple receivers. These might be formed in silicon or III-V semiconductors. For the other interface, more problems arise. It is tempting to envisage using a III-V LED or laser but these are relatively power hungry devices. Moreover, the laser is also a rather critical device whose performance is easily degraded by the presence of growth or other effects.

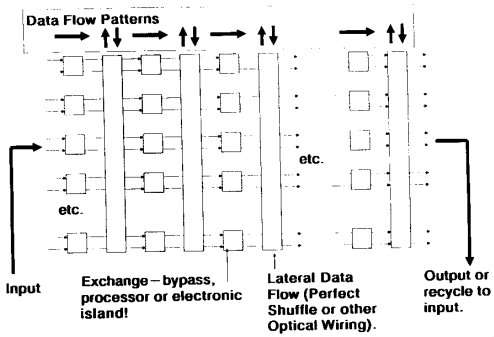

Fig. 5. Pipeline processor based upon electronic islands with optical wiring.

Another approach is to use a modulator rather than a light source, interrogating its status with light generated elsewhere. This approach has the attraction that the laser source can be located remotely and its heat dissipated well away from the logic chip. By operating as an optical power source only, it can be optimised for power efficiency. For the modulator, a variety of possibilities exist. Prime candidates are either electroabsorption or electrorefraction devices. These can be based on the Franz-Keldysh or quantum confined stark [19] effects in bulk and multiple quantum well materials, respectively. The latter look particularly promising, being very fast, low capacitance small area modulators. Monolithic integration of these devices with other electrical devices is however, in its infancy [20]. Candidate materials systems are either an all III-V semiconductor system or a hybrid combination of III-V grown on a Silicon substrate with the electronic logic.

Optically Controlled Optical Logic

Given that optical wiring has attractions, it is natural to enquire whether one cannot dispense with electronic logic altogether and substitute optical logic. Optical bistable devices which exhibit two state switching responses reminiscent of electronic devices have been studied intensively for many years and a huge literature describing their properties exists [21]. However, just as light is good for transmission since it does not interact with itself or with the guidance medium, leading to low crosstalk, attenuation, and dispersion, so the same attributes become serious limitations when interaction is positively sought as in logic circuits.

Optical nonlinear effects are well known and generally involve some form of nonlinear dielectric constant, leading to effects such as harmonic generation, parametric mixing and oscillation, frequency shifting, etc. Of particular interest for logic processing is the intensity dependent refractive index effect. Here the refractive index or optical dielectric constant of the material changes with light intensity. The effect embraces materials where the critical time constant associated with the change can be comparable to or very long compared to an optical cycle or is similar. Thus extremely fast effects can be embraced, typically in materials such as optical fibers at high intensities, or slower effects with time constants typical of thermal heating and conduction or carrier recombination in III-V or II-VI semiconductor materials [22]. To a first approximation, the product of the characteristic response time and the size of nonlinearity is constant, leading to fast high power devices or slow low power devices can be designed. Exploiting the effect involves the use of some optical positive feedback in association with the nonlinear response material to obtain switching. A typical example is the nonlinear Fabry–Perot in which a resonator filled with the nonlinear material exhibits bistable switching of transmission and reflection coefficient as a function of input light intensity. Recent results for such elements are optical switching powers of 1 mW with switching speeds of 30 μs using a 10-μm diameter spot on ZnSe material [23]. However, with a power speed product of 30 nJ it is many orders of magnitude worse than the best electronic devices (at around 100 fJ). Other devices, such as derivatives of the III-V MQW SEED, promise vastly improved performances.

Even given such advances, the problems of operating optical threshold logic devices over large areas and in very large numbers looks utterly forbidding because of the power uniformity and stray light level requirements. It is proposed that large arrays of such elements be formed in an extended planar Fabry–Perot device to provide the basis of a logical processor with all optical wiring. Even at that stage, fundamental problems remain to be overcome before truly ultrafast systems can be constructed, so that the probability of optical logic displacing electronic logic, except for in few very isolated situations, looks minimal. Nevertheless, much serious study is being devoted to matters such as the architectural design of an all optical digital processor [24], [25]. Perhaps the one clear exception is where truly ultrafast multiplexing or sampling is required, at speeds into the femtosecond region, where fiber soliton logic probably offers the only plausible approach.

WAVELENGTH ROUTING TECHNOLOGIES

In the sections above, we have identified two fundamentally different approaches to optical switching. In the cases of the passive and active path optical switches, it was assumed fundamentally that the routing information was carried by some separate channel and was available to provide electrical control signals to establish the route at the switch point. In the optically controlled electrical or optical switches, some form of synchronous logic was envisaged. That could establish routing either through the use of control data from some external source or by means of data carried within the signal, as in packet transmission where the packet header includes the destination address. Another approach that is more analogous to that used in radio communication is to code the destination through the optical carrier wavelength or frequency. Here we find three broadly different approaches as well as a number of different network formats to exploit them.

When using wavelength coding, one key parameter is the wavelength separation between channels. Until recently, this was large, measured typically in tens of nanometers, so that the number of channels that could be packed within the transmission window of an optical fiber (typically 100 nm in extent) was very limited, of order 10. This meant that the technique was seen primarily as a means of multiplexing in place of TDM for a point-to-point transmission system. Advances in laser wavelength control and stability have recently made possible very narrow-spectral-linewidth tunable semiconductor lasers. Linewidths as narrow as a few kilohertz have been reported using sophisticated external cavity sources [26] while single chip distributed-feedback lasers provide linewidths of 1–10 MHz [27]. Moreover, these devices can be turned over large spectral ranges, typically of the order 10–100 nm corresponding to 10^{12} to 10^{13} Hz in optical frequency.

It is immediately evident that such sources open up the possibility that the spectral transmission window in the fiber centered at 1300 or 1500 nm become a "guided-wave free space." To access such a space, however, narrow spectral linewidth receivers must also exist. These can be made either using fixed [28] or tunable [29] narrow-linewidth optical filters or by the use of an optical heterodyne or homodyne receiver (see, for example, [30]) with its own tunable laser local oscillator. Both approaches are being studied intensively and either offers interesting network possibilities. Note that from the numbers above, the fiber could in principle support 1000 to 10 000 channels each occupying 1 GHz of spectrum!

Assuming first that both tunable transmitters and receivers will soon be available, then we can envisage a fiber network of star format where the central node acts as a passive power splitter, splitting the power from each source equally among all receivers. Channel allocation can be done by assigning a given carrier wavelength to the transmitter and receiver(s) that wish to communicate. Routing is fully nonblocking given one wavelength per channel and wavelengths can be reassigned when released if required in addition. An alternative approach would be to assign each transmitter a unique wavelength and to instruct the receivers to tune to the appropriate wavelength to receive a chosen signal. Both approaches allow point to multipoint transmission but also offer limited security. A third approach is to assign each receiver a unique wavelength. This could be done by placing the fixed filter either at the receiver or at the central node connection. In such a network, the transmitter now selects the receiver to be addressed, affording much higher security in transmission but removing the point to multipoint option. Hybrid combinations are also possible, combining point to point with point to multipoint communications by the judicious assignment of discrete wavelengths and wavelength bands [31]. Furthermore, since very large numbers of wide-band channels are potentially available, it is suggested that "tree type" CATV networks may be possible using fibers in which broadcast and interactive wide-band communication can be combined, leading to great economy in use of fiber and fiber cable with benefit to the capital installation cost per terminal.

One major problem in implementing such a network lies in the cost of the sources, filters, and receivers necessary. At present, these are only available in research quantities and in a few laboratories. Given high volume high yield production, there seems no obvious reason why such techniques should not become cost effective. It is then interesting to note that the same technology used to provide wide-band switched and distributive network services could also be used to provide a powerful (circuit) switching capability in a large network node. The control of such a network is again assumed to be "external" and almost certainly electrical. Since the individual sources can retune very rapidly in principle, the possibility exists of establishing a very fast resetting switch, perhaps for packet handling, although the control problem looks particularly severe in this case with the digital logic based self-routing systems strongly favored.

Optimum Component and Technology Choices

From the above discussion, it will have become apparent that photonic switches can offer a variety of different attributes in the terms of switching or routing. These are summarized in broad terms against the technologies discussed below:

a) Mechanical fiber switches: Low insertion loss and crosstalk, potentially large matrices, slow circuit switch operation. Bidirectional, data, and broad-band or narrowband WDM transparent according to design.

b) Liquid crystal based devices: Broadly similar to a) but likely to show faster setting times although not fast enough to synchronize with wide-band data. Probably higher insertion loss than a) thus limiting utlimate matrix size. Bidirectional.

c) Electrooptic devices: Small arrays can be extremely fast, hence suitable for high speed data interleaving, MUX, DEMUX. Larger arrays suffer insertion loss and crosstalk problems. Probably limited to 16 × 16 or 64 × 64 without optical gain elements. Large arrays also severely limited in speed by electrical drive problems, hence only suitable for circuit switching or TSI switch with large time guard bands. Bidirectional data but not WDM transparent.

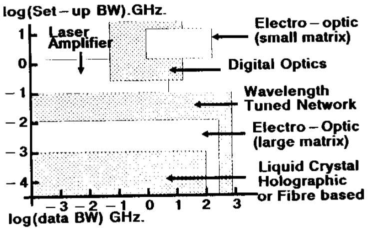

Fig. 6. Summary of photonic switch performances in terms of setup time versus routing bandwidth for comparison with Fig. 1.

d) Holographic array cross-bar switches with optically written grating deflectors may allow the operation of very large optical switches: However, the problems in establishing suitable photorefractive materials for the hologram and in engineering the writing and beam forming optics look very formidable. The switch seems fundamentally to be of the slow circuit type. If the output is to be taken directly in optical form, then a second holographic grating is required, further increasing the engineering and control problems.

e) Active gain switched elements: Presence of gain offers greater extensibility. Size limited by crosstalk and noise buildup but not yet established. Heavy power consumption, unidirectional, bandwidth limited.

f) Optically controlled electronics: Route to very fast synchronous switches for packet or TSI. Extensible to multigigabit per second clock rates. Technology in infancy. Self routing algorithms likely to be used. Common technology base with OEIC.

g) Optically controlled optical switches: These appear to offer the only way to handle data in the subpicosecond regime should that be required. At slower speeds, say longer than 10 ps, they then come into direct competition with electronic logic and at present seem to offer few advantages.

In summary, we can say that while virtually all optical switching techniques offer very large transmission bandwidths, in many cases they appear to be severely limited in application either by the fact that the bandwidths actually required can already be handled electronically or because they arise from multiplexed data channels where the switch is required to operate on the underlying multiplex frame structure. In this latter case, many optical switches are excluded because of their relatively slow switching or resetting times. These conclusions are summarized in Fig. 6 against similar axes to those of Fig. 1 to highlight the overlap (or lack thereof) between the requirements and optical capability. Thus, some applications have been identified as offering real scope for optical solutions and others can be expected to emerge as the technology advances and become better quantified.

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