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Research issues in the next–generation photonic network physical layer

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Research issues in the next-generation photonic network physical layer

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The explosive demand for bandwidth for data networking applications continues to drive photonics technology to ever-increasing capacity and flexibility at the optical physical layer. This is achieved with new optical components for routers, cross-connects, and add–drop multiplexers. We can expect continued capacity (per fibre) increases from the current Tb s^{-1} level to some 100 Tb s^{-1} before fundamental limits inhibit progress.

Keywords: optical devices; optical networking; photonics; wavelength multiplexing; fibre communications; data networks

1. Introduction

The explosive demand for bandwidth for data networking applications continues to drive photonics technology toward ever-increasing capacity in the backbone network and increasing flexibility at the optical physical layer. Several commercial terabit (per fibre) transmission systems have been announced and it can be expected that within the next several years we will become limited by the 50 THz transmission window of the silica fibre. Efficient bandwidth use will be achieved using single channel time division multiplexing (TDM) rates of 40 Gb s^{-1} and higher together with hundreds of wavelength division multiplexing (WDM) channels per fibre.

Because of the dominance of data traffic we can expect the network of the future to consist of multiterabit packet switches to aggregate traffic at the edge of the network and all optical cross-connects with wavelength granularity and tens of Tb s^{-1} throughput in the core. Because the rate of increase of transmission capacity is exceeding the rate at which information can be processed electronically at network nodes, we can expect increasing functionality in the optical physical layer including reconfigurable optical add–drop multiplexers which pass through-traffic without electro-optic conversion, high port count mux–demux devices, wavelength agile lasers for wavelength interchange and wavelength assignment, broadband fibre amplifiers over the entire fibre transmission window, optical regeneration and clock recovery, high capacity fibre and elements for network management such as wavelength monitors. All of these devices are aimed at increasing network flexibility by providing dynamic bandwidth allocation, optical restoration and wavelength routing, while greatly increasing network capacity and reducing the cost per bit for data transmission.

While the initial demand for dense wavelength division multiplexing (DWDM) systems came from long-haul networks, related changes are taking place in metropolitan area networks, enterprise networks, local area networks (LANs), CATV networks and

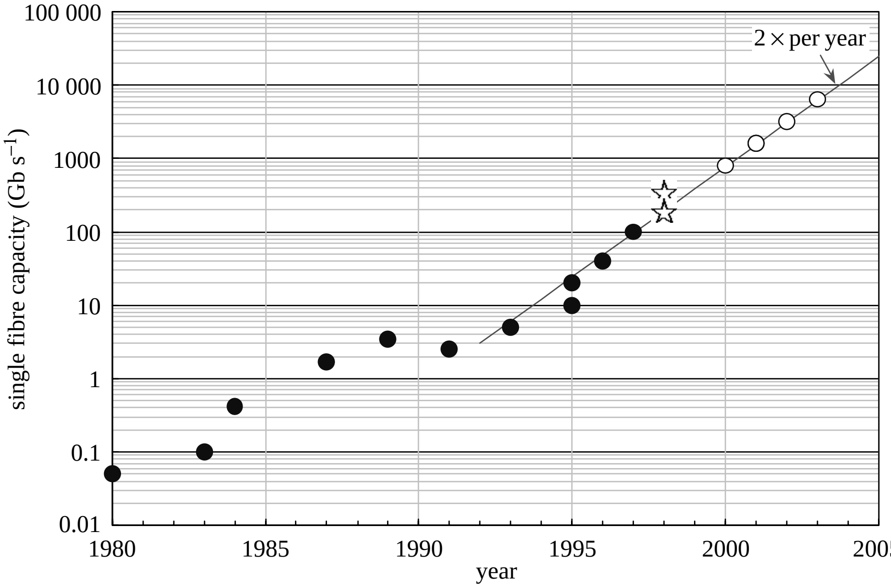

Figure 1. Growth of single-fibre-transmission capacity. Solid circles, legacy products; stars, WAVESTAR 400G (see footnote below); open circles; anticipated future products.

even fibre-to-the-home. For instance, new multimode fibre designs capable of transmitting 10 Gbit Ethernet over distances of 1.6 km, and which are backward compatible with existing LANs (Michalzik *et al.* 1999), are now commercially available. WDM systems using low-cost sources and filters bring the flexibility of optical routing to MAN and LAN systems. Passive optical networks based on ultra-low-cost photonic components are now commercially available which bring broadband ($155\,\mathrm{Mb\,s^{-1}}$) Internet and video access to the home and office.† With this rate of progress we will see commercial $50\,\mathrm{Tb\,s^{-1}}$ systems, approaching the limits of fibre-optic technology, before AD 2010!

2. Backbone network

Figure 1 shows the introduction of long-haul, commercial, fibre-optic systems since 1980. Since the introduction of commercial optical amplifiers in the early 1990s it can be seen that single-fibre capacity doubles each year. With the systems that have been announced by vendors we can expect this rate to continue to at least 2003, with terabit systems becoming available by 2001. At the same time the installed fibre plant is increasing at *ca.* 20% per year, which amounts to about 80 million additional fibre kilometres in the year 2000.

The demand for bandwidth in the 1990s came primarily from the long-haul point-to-point systems. A typical commercial system is shown in figure 2. In this example‡ up to 80 wavelengths are multiplexed onto a single-mode fibre, with each wavelength channel modulated at $2.5\,\mathrm{Gb\,s^{-1}}$ (or alternatively 40 wavelengths at $10\,\mathrm{Gb\,s^{-1}}$) and

† Broadband optical access systems based on passive optical networks. International Telecommunications Union-Telecommunications ITU G983.1, June 1999 (http://www.itu.int/itudoc/itu-t/rec/).

‡ Lucent Technologies WAVESTAR 400G product.

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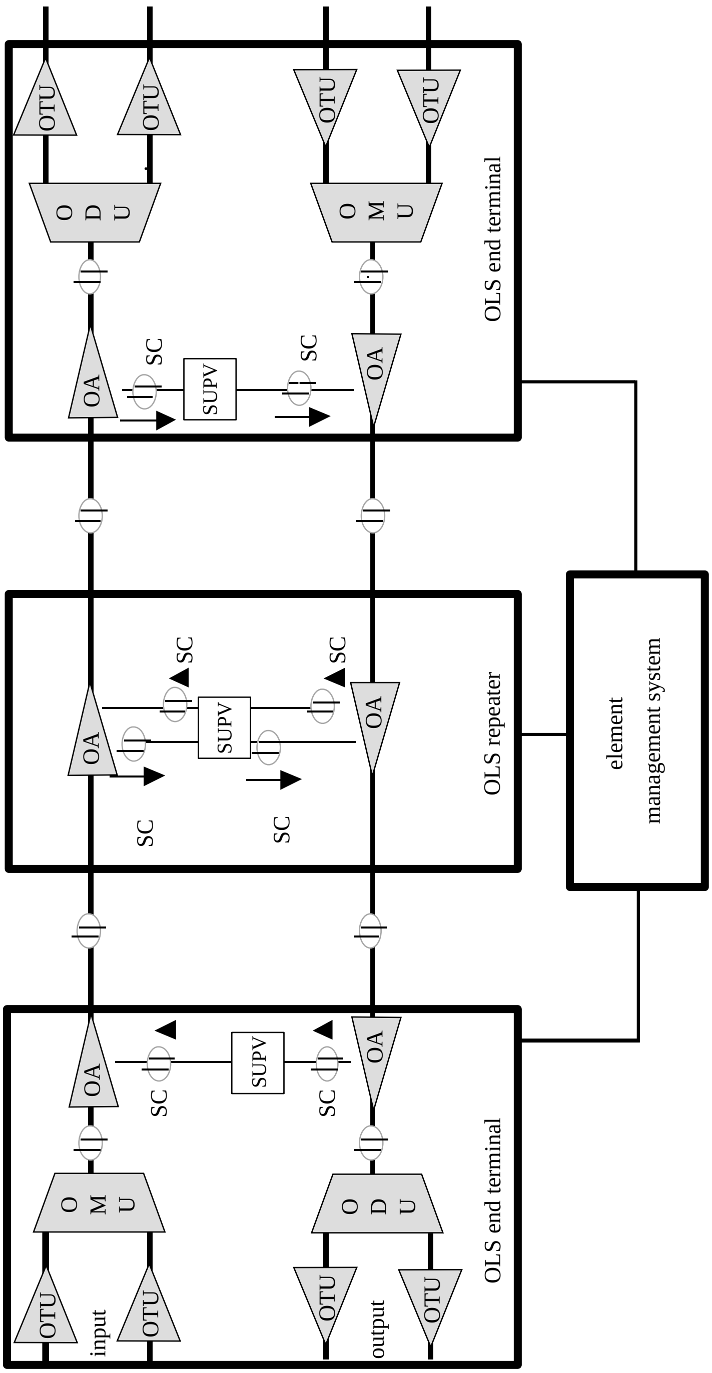

Figure 2. Typical commercial DWDM optical line transmission system (OLS). OTU denotes the optical translator unit, which converts signals to DWDM-compliant wavelengths. OMU and ODU denote optical mux unit and optical demux unit, respectively, which combine and separate wavelengths on the transmission fibre. OA, optical amplifier; SUPV, supervision circuits; SC, supervisory channel.

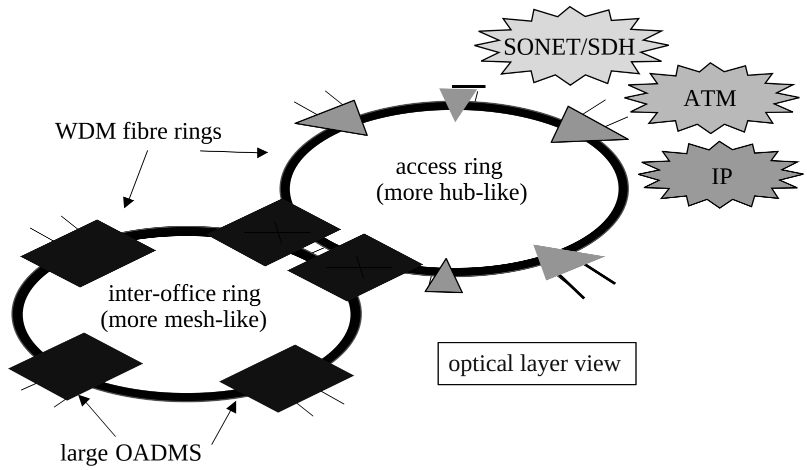

Figure 3. Internetworking of metropolitan interoffice and access WDM fibre rings using optical cross-connects at the ring intersection and optical add–drop multiplexers (OADMs) at the nodes.

transmitted through up to eight optical amplifiers each separated by *ca.* 80 km, for a total reach of 640 km. The first systems used the conventional, C band, wavelength range of the erbium amplifier from *ca.* 1525 nm to 1565 nm. The capacity can be extended further to 160 wavelengths by using the long wavelength band of the erbium amplifier from 1565 nm to *ca.* 1610 nm (Nielsen *et al.* 1999). Further capacity increases have been achieved with the experimental demonstration of 82 channels at 40 Gb s^{-1} in the research laboratory (Nielsen *et al.* 1999) and will form the basis of the next-generation systems. The wavelength channels were separated by 0.8 nm (100 GHz), giving a spectral efficiency of 0.4.

At 40 Gb s^{-1} the high-speed electronics required for such systems is just emerging from the development laboratory. However, a single channel 160 Gb s^{-1} TDM transmission system was recently demonstrated over three 100 km spans of Truewave fibre using optical time division multiplexing (OTDM) to combine eight 20 Gb s^{-1} modulated data streams onto a single fibre (Mikkelsen *et al.* 1999). This system used practical (10 Gb s^{-1} and 20 Gb s^{-1}) semiconductor devices for the source, modulator, demultiplexing, and clock recovery, and demonstrates a clear pathway to higher-capacity systems incorporating WDM.

3. Optical networks

With data traffic doubling about every six months in the US, the capacity increases offered by WDM are now being required in shorter-haul applications such as metropolitan area networks (MANs), and eventually, LANs and fibre to the home. Flexible internetworking can be achieved with new optical elements shown in figure 3. Here, two optical rings are interconnected by an optical cross-connect which permits traffic to remain within a ring or crossover to the neighbouring ring without conversion to the electronic domain. Each of the nodes has optical add–drop flexibility which permits one or more wavelengths to be dropped at each node, while the remaining wavelength pass through the node without electro-optic conversion. Because all of the functionality is in the transport layer, such systems can support a wide variety

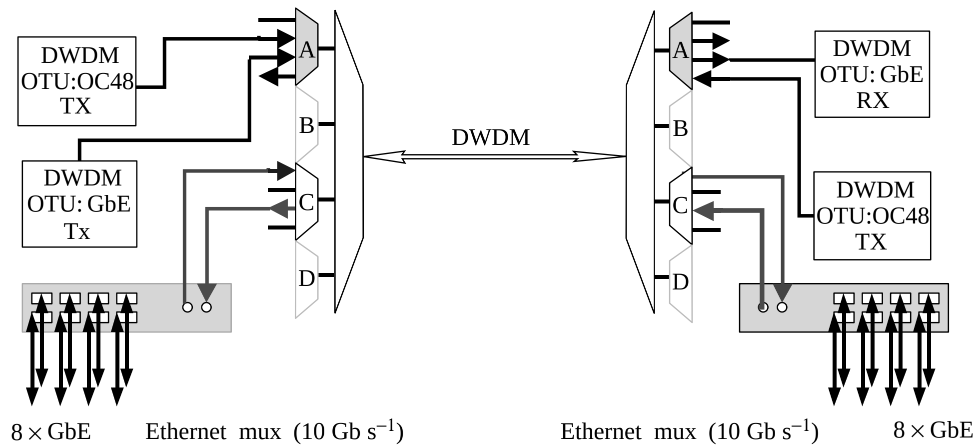

Figure 4. Internetworking of gigabit Ethernet (GbE) traffic with DWDM optical line system. Eight independent GbE channels are multiplexed onto a 10 Gb s^{-1} channel for metro and long-haul DWDM transport.

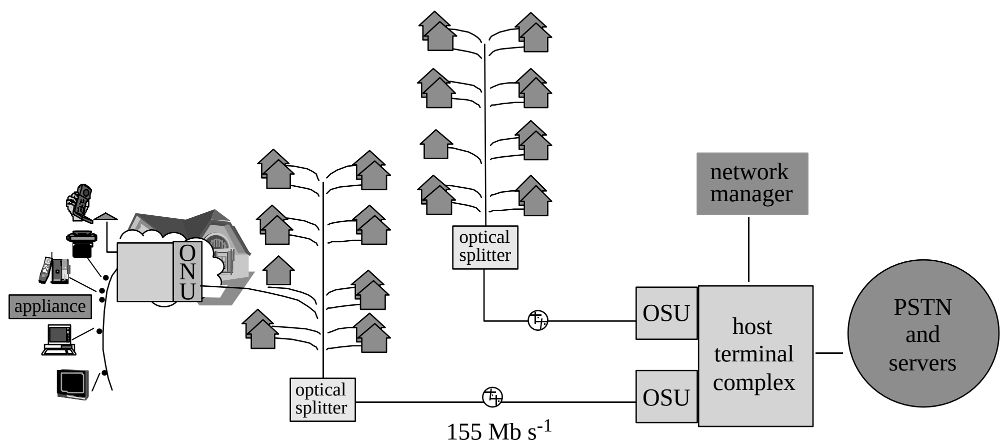

Figure 5. Passive optical network (PON) for residential or business access. The system is designed for full services access (ATM, DS1 and Ethernet) with 155 Mb s^{-1} bidirectional capacity and frequency division multiplexed video overlay.

of services and protocols, with reliable (i.e. restoration in the transport layer) high-capacity bandwidth management and transmission.

A demonstration of networking of a gigabit Ethernet (GbE) network with a DWDM optical line system is shown in figure 4. In this system eight GbE channels were multiplexed onto a single wavelength of the Wavestar optical line system, providing full 10 GbE connectivity for an enterprise network (A. L. Lentine and co-workers, unpublished data (see http://www.bell-labs.com/projects/gigachannel)). This link was completely transparent and compliant with GbE signals while other wavelengths on the same fibre were used for other services.

Perhaps one of the greatest challenges for photonics is to provide low-cost broadband connectivity to the home or office. Here very low cost optics is necessary to make such systems affordable. The ATM-PON shown in figure 5 provides bidirectional

155 Mb s^{-1} transport to the home or office.† Very low cost uncooled transceivers in the optical network unit (ONU) in the home bring the price of such systems competitive with alternate solutions while offering increased bandwidth and upgradability.

Throughout the evolution of photonic systems, progress has been paced by innovation in components: the optical fibre, the transmitter and receiver, the optical amplifier and the multiplicity of new devices for DWDM networking.

4. Optical fibre

Transmission impairments limit the capacity-distance performance of photonic systems. Optical loss, chromatic dispersion and dispersion slope, polarization mode dispersion and optical nonlinearity are impairments of the fibre itself that need to be compensated for in system design. The optical loss of most commercial fibre approaches theoretical limits set by Rayleigh scattering in the 1.3 μm and 1.55 μm transmission regions. Recently, a new fibre has become commercially available in which the entire 50 THz transmission window from 1.2 μm to 1.7 μm falls below 0.5 dB km^{-1}. Residual absorption due to OH ions in the silica has been eliminated by careful purification of the glass during processing (Srivastava *et al.* 1999*a*).

Chromatic dispersion, which causes spreading of optical pulses, has become a key parameter in system design. With WDM systems it is important that chromatic dispersion be compensated over the entire spectral region covered by WDM systems. Ultimately this will mean the entire 50 THz fibre spectrum. It is important to have some dispersion in the fibre to minimize four-wave mixing of different WDM channels in the fibre (Forghieri *et al.* 1997), but each channel requires precise dispersion compensation at the transmitter or receiver in high bit-rate systems. This can be accomplished in a number of ways. Dispersion compensating fibre having an appropriate negative dispersion design has been used successfully for current commercial systems. Recent inventions using fibre grating structures (Ouellette *et al.* 1994) and multimode fibres (Poole *et al.* 1994) have been demonstrated which promise to compensate for chromatic dispersion of a broad range of fibre designs as well as compensate for dispersion slope. Dynamic tunability of dispersion compensation has also been demonstrated (Eggleton *et al.* 1999).

Polarization mode dispersion (PMD) is more difficult to compensate. PMD arises from birefringence of the optical fibre (due to slight core ovality) which varies with position, temperature and stress. While the latest fibre can be manufactured with low PMD adequate for very high speed systems, older fibre already installed may have higher PMD which needs dynamic compensation in high bit-rate systems (10 Gb s^{-1} and above). A number of dynamic PMD compensation devices have been demonstrated in the research laboratory (Bulow *et al.* 1999). Since PMD compensation is required for each wavelength channel, these devices have to be low cost.

Optical nonlinearities within the silica fibre limit the maximum power that can be launched in each channel. Nonlinearities include stimulated Brillouin and Raman scattering, self-phase modulation, cross-phase modulation and four-photon mixing. Nonlinear effects increase with increasing launched power (αP^2) and decreasing channel spacing $(\Delta\lambda)^{-4}$. Since the required pulse power increases with bit rate (decreasing pulse length), nonlinear effects become increasingly important at high data rates.

† Broadband optical access systems based on passive optical networks. International Telecommunications Union-Telecommunications ITU G983.1, June 1999 (http://www.itu.int/itudoc/itu-t/rec/).

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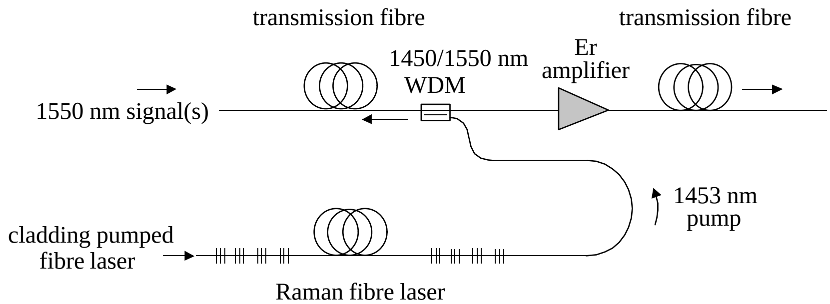

Figure 6. WDM system upgrade by Raman amplification. High-power pump light at 1453 nm from a Raman fibre laser is inserted into the transmission line counter-propagating to the signal.

Raman amplification of signals within the transmission fibre itself offers a simple method for either reducing the required signal launch power or for extending the range of WDM systems. As shown in figure 6, Raman amplification is achieved by launching an intense continuous pump source of 1453 nm laser from a fibre laser or high-power semiconductor laser into the transmission fibre counter propagating to the signal wavelength of 1550 nm. Using the Raman nonlinearity of the fibre, the signals are amplified during transmission, giving a 5–7 dB improvement in system performance for *ca.* 500 mW of launched pump power (Srivastava *et al.* 1999*b*). Raman amplifiers can be designed to operate at any wavelength of the fibre transmission window and will probably be the amplifier of choice beyond the wavelength range of the erbium amplifier.

5. Optical networking elements

Because of the enormous transmission capacity of the optical fibre, all optical network elements for routing, add–drop and cross-connect functions offer considerable cost reduction, and increased scalability over opto-electronic devices. The first of these devices used in most current WDM systems is the integrated wavelength grating router shown in figure 7 (Li & Henry 1997). This device has the property that the output port of a given signal is determined by the wavelength of the signal and the location of the input port. Multiple wavelengths entering the device at a single input port will be demultiplexed by the device with each wavelength exiting from a different output port. Vice versa, multiple wavelengths can be combined onto a single fibre. Full routing is achieved in an $N \times N$ device by controlling the wavelength at each input port with a wavelength-selectable laser, and this in turn routes the wavelength channel to the desired output port. An IP router with multiterabit throughputs can be built with fast tunable lasers and existing grating router technology (Suemura *et al.* 1999). Wavelength-selectable lasers with suitable characteristics are now emerging on the market.

An extension of the device which includes thermo-optic switches integrated together with the router can be used for reconfigurable optical add–drop (Doerr *et al.* 1999). By appropriately setting the switch, optical wavelengths can be directed to a through port for express traffic or to the drop port for local traffic. The switches can be reconfigured on a millisecond time-scale. Designs have been demonstrated that give no filtering on the through channels, thereby permitting cascadability of

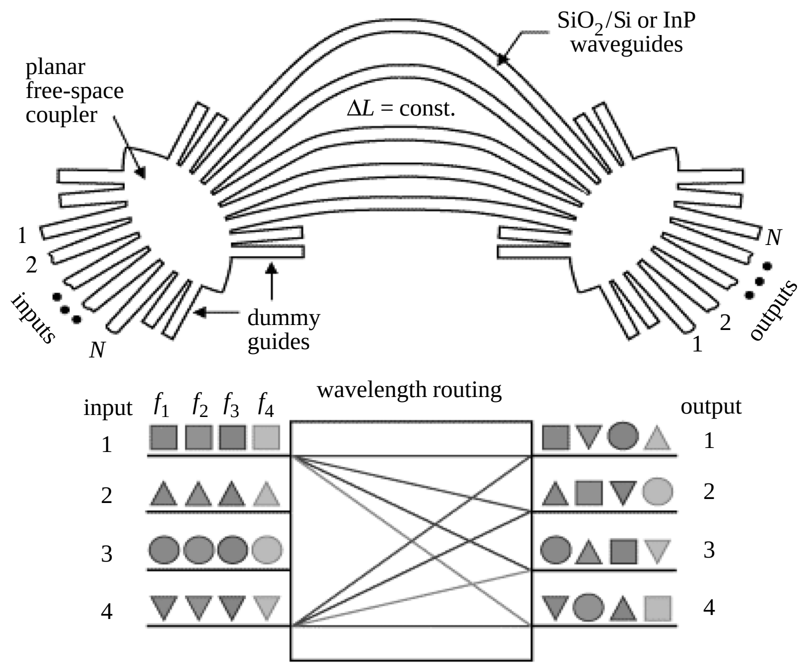

Figure 7. Integrated $N \times N$ optical router fabricated in silica waveguides on a silicon substrate. Routers with over 80 inputs and outputs are readily fabricated.

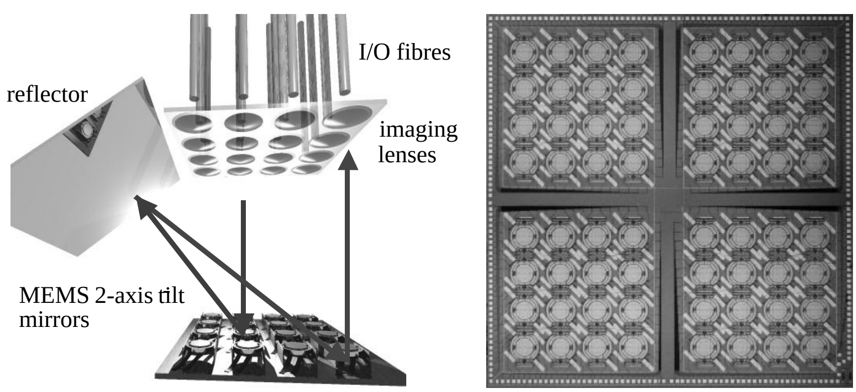

Figure 8. Large optical cross-connect fabric created with micro-electromechanical systems (MEMS) technology. The figure shows a 64 mirror array, which readily scales to over 1000 mirrors.

the device at multiple nodes. Because there is no electro-optic conversion of through traffic, such a device can support orders of magnitude more throughput capacity than an electronic TDM add–drop.

The optical cross-connect shown in figure 8 can likewise support orders of magnitude more throughput than conventional electronic cross-connects (Nielson *et al.* 2000). The device shown in figure 8 consists of a two-dimensional mirror array (approximately 1000×1000 mirrors) fabricated with MEMS technology. Wavelengths from input fibres are directed onto output fibres by steering the beams with the mirrors. For channels modulated at 40 $\mathrm{Gb\,s^{-1}}$ such a device is capable of a 40 $\mathrm{Tb\,s^{-1}}$ throughput!

6. Conclusions

It is evident that early in the 21st century continued progress at the optical-physical layer will result in multiterabit fibre-optic links, and flexible optical networks with many tens of terabits converging at large nodes. Optical devices will be low cost and ubiquitous. These networks will require continued advances in the optical elements including ultra broadband, gain and dispersion equalized amplifiers and wavelength-selectable lasers which cover the entire 50 THz window of the optical fibre, reconfigurable add–drop and optical cross-connects for scalability. Although traffic will be dominated by data, it is likely that the optical layer will remain connection oriented for the near future: that is, optical pipes with wavelength granularity rather than optical packets. These connections will be reconfigurable on a millisecond time-scale. Further into the century these will evolve to flexible, optical-packet-switched networks.

Fundamental considerations indicate that we will begin to realize the capacity limits of fibre-optic technology before AD 2010. Interestingly, this is a similar time-scale to that for the fundamental limits of silicon technology. Perhaps employing quantum effects in electronics and photonics may offer hope for continued progress further into the century. How people will use all the global bandwidth and processing power is the subject of much speculation. By the year 2010 at the current rate of progress in the fibre-optic infrastructure, each person in the world will have continuous (and simultaneous) access to 100 $\mathrm{Mb\,s^{-1}}$! History has shown that humans have an insatiable appetite for bandwidth and have always exceeded expectations in bandwidth consumption.

References

Bulow, H. *et al.* 1999 Adaptive PMD mitigation at 10 $\mathrm{Gb\,s^{-1}}$ using an electronic SiGe equalizer IC. In *Proc. Eur. Conf. on Optical Communication*, vol. 2, p. 138.

Doerr, C. R., Stulz, L. W., Gates, J., Capuzzo, M., Laskowski, E., Gomez, L., Paunescu, A., White, A. E. & Narayanan, C. 1999 Arrayed waveguide lens wavelength add–drop in silica. *IEEE Photon. Technol. Lett.* **11**, 557–559.

Eggleton, B. J., Rogers, J. A., Westbrook, P. S. & Strasser, T. A. 1999 Electrically tunable power-efficient dispersion compensating fibre Bragg gratings. *IEEE Photon. Technol. Lett* **11**, 854.

Forghieri, F., Tkach, R. W. & Chraplyvy, A. R. 1997 In *Optical fibre telecommunications* (ed. I. P. Kaminow & T. L. Koch), vol. IIIA, ch. 8, p. 196. Academic.

Li, Y. P. & Henry, C. H. 1997 In *Optical fibre telecommunications* (ed. I. P. Kaminow & T. L. Koch), vol. IIIB, ch. 8, p. 319. Academic.

Michalzik, R., Giaretta, G., Ritger, A. J. & Williams, Q. L. 1999 10 $\mathrm{Gb\,s^{-1}}$ VCSEL based data transmission over 1.6 km of new generation 850 nm multimode fibre. *IEEE, LEOS, Ann. Mtg, San Francisco, CA, USA, November 1999*, paper PD16.

Mikkelsen, B. (and 10 others) 1999 160 $\mathrm{Gb\,s^{-1}}$ single channel transmission over 300 km nonzero-dispersion fibre with semiconductor based transmitter and demultiplexer. In *Proc. Eur. Conf. on Optical Communication, PD2, Nice, September 1999.*

Nielsen, T. N. (and 18 others) 1999 3.28 Tb s^{-1} (82×40 Gb s^{-1}) transmission over 3×100 km non-zero dispersion fibre using dual C- and L-band hybrid Raman/erbium doped inline amplifiers. *Optical Fibre Communications Conf. Digest, Baltimore, USA, March 1999*, paper PD23.

Nielson, D. T. *et al*. 2000 Fully provisioned 112×112 micromechanical optical crossconnect with 35.8 Tb s^{-1} demonstrated capacity. *Digest of the Optical Fibre Conf., Baltimore, MD, USA, March 2000*, paper PD12.

Ouellette, F., Cliche, J. F. & Gagnon, S. 1994 All-fibre devices for chromatic dispersion compensation based on chirped distributed resonant coupling. *IEEE J. Lightwave Technol.* **12**, 1728.

Poole, C. D., Wiesenfeld, J. M., DiGiovanni, D. J. & Vengsarkar, A. M. 1994 Optical fibre-based dispersion compensation using higher order modes near cutoff. *IEEE J. Lightwave Technol.* **12**, 1746.

Srivastava, A. *et al*. 1999*a* Multiservice WDM transmission of 1.3/1.4/1.55 micron over allwave fibre. In *Proc. Eur. Conf. on Optical Communication, Nice, September 1999*, p. 200.

Srivastava, A. K., Zhang, L., Sun, Y., Sulhoff, J. W. & Wolf, C. 1999*b* System margin enhancement with Raman gain in multi-span WDM transmission. *Optical Fibre Conf. Digest, San Diego, CA, USA*, paper FC2, p. 53.

Suemura, Y., Takahashi, S., Araki, S. & Hemmi, N. 1999 Beyond Tb s^{-1} throughput WD/SD optical switch fabric technology and applications. In *Proc. Conf. on Lasers and Electro-Optics/Pacific Digest*, paper FT1, p. 1275.

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