Over the past decade, optical communications has penetrated deep into the telecommunications systems of most developed countries. Optical fiber has replaced copper to a large extent in the trunk network, bringing with it the benefits of increased regenerator spacings, lower cost, and improved reliability through the reduction in the amount of electronics. The use of optical communication technology has enabled much greater transmission speeds, with the result that 2.5 Gbit/s will become a standard transmission rate within the next few years.

As optical technology matured, however, it was recognized that the vast potential bandwidth of fiber (in the order of $10^4$ GHz) has not been efficiently exploited, i.e., there was a great mismatch between the capability of the medium and the bandwidth of the signals it was supporting. For this reason, the concept of optical wavelength division multiplexing (WDM) has been studied for many years.
different wavelength. The outputs of these lasers are combined at the transmitter, each individual data signal modulates a semiconductor laser, each of the lasers having a different wavelength. The outputs of these lasers are combined in a multiplexer and the combined signal propagates along the fiber. At some distance, depending on the fiber loss, the signal must be regenerated. At this point, a demultiplexer is required to separate out the individual wavelengths. The four signals are then independently regenerated before being recombined in a multiplexer for onward transmission to the next regenerator station. The diagram illustrates the unique attraction of WDM: additional capacity can be provided by adding wavelengths, and there is no need to install new fiber.

The deployment of such a system, however, has not been attractive economically. One reason for this relates to the transmitters. In the case where all the wavelengths lie within the same fiber window (for example in the low loss 1.5 µm window), each individual laser must have a carefully selected wavelength. This means increased cost and the need to carry a greater number of spares. This problem may be overcome by the successful development of tunable lasers. Another reason for the slow rate of deployment is that separate regeneration for each wavelength is needed at every regenerator site; thus the main saving is in the fiber itself and this has to be balanced by the need for multiplexers and demultiplexers and the insertion losses associated with these components. In the initial phase of fiber deployment, many spare fibers were available and so the incentive to use WDM was not so great. Traditionally, it has always been more cost effective to increase the bit rate than to use WDM.

In the past few years, however, the situation has changed in many respects. Developments in technology have improved the availability of sources and multiplexers. The commercial availability of all-optical amplifiers means that at a regenerator site all the signals can be amplified simultaneously by a single fiber amplifier. In addition, the growth in demand for capacity has meant that in many places, cities in particular, fiber has become scarce and the costs associated with cable installation have escalated. Fiber to the home is now an important issue for the future and WDM techniques are being considered as a means of providing future services. Local area networks employing WDM techniques are now being demonstrated in the laboratory and in field trials.

Classification of WDM Systems
As one might expect, there is a wide variety of WDM systems and a confusion of names. The types of system can be classified according to the wavelength spacing. One example of classification is as follows:

- **WDM:** Systems with channel spacings >1 nm. This generally covers systems with small numbers of wavelengths, e.g., 2-5.
- **HDWDM:** High density WDM, spacings of approximately 1 nm. Systems with the potential for up to 30 wavelengths.
- **UHDWDM:** Ultra high density WDM, spacings < 1 nm. Systems with the potential for 30-500 wavelengths. Generally associated with coherent transmission and detection techniques that allow high selectivity at the expense of an additional local oscillator laser at the receiver.

The multiwavelength systems currently in operation fall into the category of simple WDM. These systems provide a doubling of capacity by adding a 1.5 µm channel to an existing 1.3 µm system. Future WDM systems will use a number of wavelengths in the same transmission window, centered around 1.3 µm or 1.5 µm.

WDM Components
Developments in component technology are crucial to the successful deployment of WDM. There are many problems yet to be resolved, particularly in the area of tunable sources, but there has been significant progress in the past few years.

Sources: One of the main areas still needing considerable development is in the technology associated with the laser sources. The requirement is for cheap tunable sources, perhaps integrated with waveguides and a multiplexer. Although distributed feedback lasers (DFBs) can be fabricated with a grating designed to yield a particular lasing wavelength, it is much more convenient to have a common laser that can be tuned as needed. The distributed Bragg reflector tunable laser has the best performance to date, with a tunable range of approximately 10 nm. The ideal tuning range would correspond to the bandwidth of an optical amplifier (see below), which is in the order of 30 nm. These lasers have been successfully integrated with waveguides to form an integrated WDM transmitter.

Multiplexers/demultiplexers: The WDM system illustrated in Figure 1 uses a multiplexer to combine the signals in the fiber. Such multiplexers are available commercially and can combine and separate as many as 30 wavelengths with separations as close as 1 nm. These components are generally based on diffraction gratings. A signal incident on the grating is diffracted at an angle that depends on the wavelength. In the case of the demultiplexer, for example, the incoming signal contains all the wavelengths that are then diffracted at differing angles. The outgoing fibers are positioned at appropriate points corresponding to the specific
wavelengths. These devices are reciprocal and therefore can also be used as multiplexers. A commercial device for four wavelengths would have an insertion loss of approximately 5 dB.

Multiplexers may also be based on coupled waveguides (splitters/combiners)—for example fiber couplers or integrated waveguide couplers—but in this case the insertion loss would be at least 6 dB for four wavelengths. Because of the insertion loss (3 dB per two way split) splitters/combiners are not very attractive for large numbers of wavelengths.

**Tunable filters:** Tunable filters can also be used to select an individual wavelength from a wavelength multiplex. In this type of system, the filter is positioned at the input to each optical receiver. Thus, in the diagram of Figure 1, the multiplexer would be replaced by a simple fiber combiner and the demultiplexer by a splitter with a tunable filter in each branch. The filter is adjusted such that a particular branch corresponds to a particular transmitter wavelength.

The advantages of such an arrangement are that the fixed wavelength multiplexer/demultiplexers are removed and hence the need for precise matching of source wavelengths to fixed multiplexers is avoided. However, the tunable filters need to be controlled and are expensive. Recently, considerable success has been obtained with the use of fiber Fabry Perot filters. These components are based on the cavity formed by two closely spaced fibers. The ends of the fibers are coated to provide a high reflectivity and a piezoelectric drive enables the cavity gap to be varied. In operation, a tuning range of approximately 30 nm (the optical amplifier bandwidth) is possible with a filter bandwidth of <1 nm. Insertion loss is <3 dB. Thus, these components can be used for WDM and HDWDM systems.

**Optical amplifiers:** In recent years, the development of fiber based optical amplifiers has been rapid and successful. These components change the economics of WDM deployment by allowing simultaneous amplification of a number of wavelengths. The component itself comprises a short (10-20 m) length of silica fiber doped with the rare earth erbium (for operation in the 1.5 µm region). A fiber coupler at the input is used to combine the signal with a high power optical pump (a semiconductor laser). In the amplifying fiber, a transfer of energy takes place and direct optical gains in the order of 30 dB are readily obtained. The characteristics of these amplifiers are such that their use is likely to be widespread by the end of this decade. Figure 2 shows the gain bandwidth characteristic of a typical amplifier. The wavelength range of 30 nm corresponds to a frequency bandwidth in the order of 4 THz. Gain bandwidths of this order are unmatched by any electronic component. Refinements of these components have allowed the variation in gain across the band to be less than 1 dB.

The replacement of a number of individual regenerators by a single optical amplifier is attractive both from an engineering and an economic viewpoint. However, optical systems using amplifiers as repeaters are very different in nature from stan-
standard systems; they are analog rather than digital. This poses additional problems; for example, noise generated within the amplifiers will accumulate along the link and eventually limit the number of amplifiers that may be cascaded. However, the noise figure of an individual amplifier is very low (e.g., 4 dB) and hence is often not the limiting factor. For some applications (e.g., undersea links), the dispersion associated with the long system length is a major challenge.

The most developed fiber amplifier—the erbium amplifier—will operate only in the 1.5 µm window. There has been considerable progress recently, however, in the development of doped fiber amplifiers at 1.3 µm. Although there are many problems yet to be overcome, the future looks promising. (See related article, page 14).

### WDM Applications

Wavelength division multiplex techniques are now being considered for a number of major application areas, both in telecommunication and computer networks. Some of the main areas are:

**ACCESS networks**: In recent years, there has been considerable activity in studying the deployment of optical fiber in the subscriber loop. The motivation is to provide a broadband pipe that can carry future broadband services such as video to the home. A particular challenge is to reduce the cost of provision such that, in the case of the UK, it can be supported initially by telephone only. In the UK, British Telecom has proposed a particular architecture called TPON (telephony over passive optical networks) and a broadband upgrade strategy BPON (broadband over passive optical networks). Similar architectures are being considered in other countries.

The concept is illustrated in Figure 3. A single wavelength (at 1.3 µm) is used to carry telephony services from the central office to a street cabinet, where a first level of splitting occurs. From this point, a fiber is taken to a distribution point (for example, a pole in a street) and then on to the subscriber premises. A subscriber filter is included to ensure that only telephony wavelengths are received, unless other services are required. At a later date broadband services would be added by means of a second wavelength at 1.5 µm. Additional services might be added by increasing the multiplex of wavelengths within both the 1.3 µm and 1.5 µm windows.

A key to the cost effectiveness of this type of approach is that one exchange fiber is shared between many customers. It is likely that optical amplifiers will also be used in these networks to overcome splitting losses and increase the number of customers sharing a fiber.

**Main Network**: The use of WDM in the main telecommunications network is being considered at a number of levels. Much research has been focussed on its application to the long haul section of the network, both undersea and terrestrial, but more recently attention has been paid to its role in the development of all-optical network layers.

In the upper layers of a telecommunication network, high capacity transmission is often required over long distances. Currently this is achieved through the use of standard terminal and regenerator equipment, operating, for example, at bit rates up to 1.8 Gbit/s. The concept of long distance interconnections using multi-wavelength transmission together with optical amplifiers has many attractions (the upgrade capability being one, in particular). However, optical amplifier repeaters are linear amplifiers and hence simply amplify rather than regenerate the signal; thus, fiber dispersion can cause major problems in such systems.

In the past five years, there has been considerable research effort devoted to the study of coherent transmission and detec-
tion techniques. Coherent systems employ spectrally pure sources and hence minimize the problems associated with dispersion and allow very close wavelength spacings (5 GHz is quite practical). At the receiver, a local oscillator laser is mixed with the incoming signal. This results in a high degree of discrimination and sensitivity. Studies have demonstrated the possibility of transmitting 100 channels over a distance of 200 km using optical amplifier repeaters. More recently, experiments in which an optical amplifier combined with a highly selective filter is used to replace the local oscillator have been demonstrated very successfully.

For undersea systems, distances in the order of 6000 km have to be considered. The commercial attractiveness of being able to upgrade capacity by adding wavelengths is obvious; each undersea system costs a large amount of money. Additional problems become apparent over these distances; nonlinear effects limit performance and great care must be taken with the system design.

At present, many of the world networks are moving to a new standard. This is known as the Synchronous Digital Hierarchy in the UK and as SONET in the United States. These networks employ digital crossconnect switches that enable the network to be remotely reconfigured from a network management center. At the upper levels of the network these switches support the higher transmission levels of 2.5 Gbit/s. Although the transmission between switches is optical, within each node the crossconnect switch is purely electronic. As traffic increases with time, therefore, these switches will be required to operate at ever increasing bit rates. Such switches may become difficult to realize.

The optical layer concept is shown in Figure 4. At the top of the network, an optical WDM layer carries the traffic on a number of wavelengths and fibers. Within the node, local traffic can be selected by choosing a particular wavelength or fiber and dropped off into the local electronic crossconnect switch. The through traffic is routed through the node without any electronic conversion. Optical switching is achieved by a combination of wavelength selective elements (such as tunable filters) and optical space switches. Thus, the required crossconnect switching is divided between the optical and electronic domains. The optical switching provides for the through connection of large blocks of traffic, the electronic switching provides the fine grain selection required for local distribution. By this means, the load on the electronic switch is considerably reduced.

Local area networks: WDM technology is also being considered seriously for use in multiple access computer networks. In this application, multiple channels can be simultaneously in operation using different wavelengths and associated switching allows appropriate connections to be selected. Advantages to be gained over conventional networks are reduced speed requirements and improved reliability through the reduction in electronic hardware.

Figure 5 illustrates an architecture of the type demonstrated recently by IBM. Each station transmits on a fixed wavelength and the transmissions from all stations are combined and then broadcast to all stations by using a passive star coupler. At each station, a tunable filter (the switch) selects one of the channels for reception. In practice, when a connection is required, the transmitter repeatedly transmits a connection request specifying the required receiver. Receivers not busy repeatedly scan all wavelengths (by means of the tunable optical filter). When it detects a request, the receiver locks the filter. In the IBM demonstration, a 32X32 coupler was deployed with four operational nodes. Interconnection was successfully demonstrated at bit rates of 200 Mb/s and 275 Mb/s (video) and the time for switching between wavelengths was in the order of 1 msec.

Other architectures have also been studied. The Lambdanet experiment demonstrated 18 channels in the 1.5 µm window with spacings of approximately 2 nm. A star architecture was used as in the IBM experiment, but at the receive terminal a bank of optical receivers was used to detect all the channels; electronic switching was then used for channel selection.

Conclusions

WDM technology has developed rapidly in the past few years. Applications to telecommunication and computer networks are now being seriously studied. It is likely that deployment of the technology will be gradual and depend to some extent on the growth in demand for new services.

REFERENCES