Transparent Single-Mode Fiber Optical Networks

D. B. PAYNE AND J. R. STERN

Abstract—**For the first time in the history of communications technology, single-mode fiber offers the possibility of truly transparent communications systems. In this paper we consider the application of single-mode fiber technology to optical networks and the evolution of the technology to all optical networks based on space or wavelength switching. Also discussed is the progress towards some early experimental networks.**

I. Introduction

THE WIDER APPLICATION of optical technology to telecommunication systems such as LAN's, MAN's, cable TV Systems and more broadly, future wideband local networks, has been the subject of increasing interest in recent years. Early thinking in these areas was usually centered around "cheap" 850-nm optical device technologies with multimode-graded-index fiber. The optical technology is used only to provide point-to-point communications links within the network, all other functions being provided electronically. In recent years however, there has been an increasing interest in the application of single-mode technology to optical networks [1].

The major advantages of single-mode fiber technology over multi-mode graded index are: lower losses, enormous bandwidth (in practice limited only by the transmitter and receiver technologies rather than the fiber), lower cost fiber, and the fact that single mode can open the way to a much fuller exploitation of optical technology to achieve complete optical networks. In such networks switching/routing, and in time other signal-processing functions, in addition to transmission, could be carried out in the optical domain. Thus although multimode fibers may find early application in particular circumstances, the main thrust for future advanced networks will be on the basis of single-mode technology, which allows access to the widest range of optical component technologies (including planar lithographic waveguide processes).

Single-mode fibers are already becoming cheaper than multimode fibers, in part due to their dominance in the long-haul transmission applications, but also reflecting the fact that they are intrinsically cheaper to make. An additional factor in favor of single-mode fiber is apparent when the shorter distances of many network applications are combined with the low transmission losses of the medium. For distances of up to approximately 5 km, the fiber losses would only amount to 2–3 dB and a substantial portion of the optical power budget would be available for exploitation in ways other than simply providing geographical range. Thus on the basis of the typical fibers/components used in standard long-haul single-mode systems operating at 140 Mbit/s [1], a margin of around 35 dB could be available for network functions such as power splitting, extensive wavelength multiplexing, and/or optical switching/routing.

In the shorter term, the combination of low fiber losses and relatively short range (<5 km) can be used to allow the early economic introduction of single-mode technology into junction and local networks by the exploitation of lower cost 1300-nm LED or ELED multimode optoelectronic technology [2]. Although the launched power levels from such devices into single-mode fiber is only between -25 and -30 dBm there is still sufficient power available to cope with the short distances involved in many network environments. Such optical systems can only be used for point-to-point links, but will be invaluable in allowing the early establishment of a single-mode fiber infrastructure that can later be enhanced into full optical networks when low-cost laser and other optical components become available.

II. Optical Networks

The establishment of all optical, fully transparent networks will depend on the economic development of a wide range of new optical components. It is likely that the installation of networks to provide new and enhanced services will be required before a full range of single-mode component technologies are commercially viable. Rather than install multimode technology with limited capability for future enhancement, single-mode fiber networks could be installed on an evolutionary basis, initially providing no more capacity than an equivalent multimode network, but by the later addition of optical components and new terminal equipment could develop into complete optical networks. These optical networks could be completely transparent both in terms of the bandwidth or bit rate capability and the modulation format employed, analog or digital.

The first stage of a possible evolutionary approach to local network systems using single-mode fiber is shown in Fig. 1. In this system traffic from a small number of subscribers would be electrically multiplexed on to a single-mode fiber transmission system employing low-cost LED technology. These optical links would be short range and low-bit rate (8–34 Mbit/s) and would be well within

Manuscript received November 25, 1985.

The authors are with British Telecom Research Laboratories, Martlesham Heath, Suffolk, UK.

IEEE Log Number 8609001.

0733-8724/86/0700-0864$01.00 © 1986 IEEE

Authorized licensed use limited to: British Telecommunications via the BT Library. Downloaded on September 19,2025 at 10:13:41 UTC from IEEE Xplore. Restrictions apply.

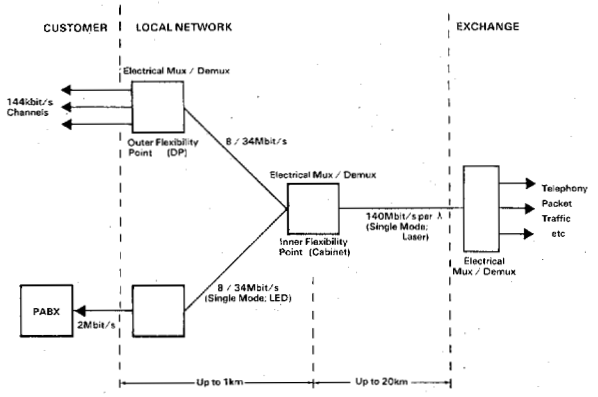


Fig. 1. Single-mode local network using LED's.

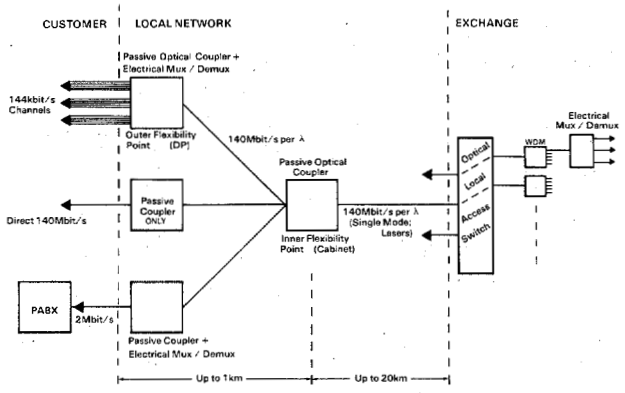


Fig. 2. Single-mode local network using wavelength multiplexing.

the capability of single-mode fiber LED systems. Further electrical multiplexing of several of these links to 140 Mbit/s could occur up to a few kilometers from the small subscriber multiplexers. The 140 Mbit/s links would have sufficiently concentrated traffic to justify the cost of laser transmitters and hence ranges comparable with trunk distances could be considered between these remote multiplexers and the central switching centers.

In the network shown in Fig. 1, optical technology is only being used to provide point-to-point transmission links between the various nodes in the network. Besides the relatively limited capacity of such a network, a major operational disadvantage is the requirement for electronic equipment to be out in the field with all the attendant power feeding and maintenance problems. A natural evolution, when the cost of the optical technology makes it economically viable, could be to replace the remote multiplexer with a passive optical splitter and use wavelength multiplexing to provide enhanced channel capacity between the small subscriber multiplexers and the switching centers, such a network is shown in Fig. 2. In the exchange or switching center wavelength multiplexers and demultiplexers are provided, and at the subscriber multiplexer a filter to select the appropriate wavelength would be incorporated. An optical path has now been created between the subscriber multiplexer and the exchange, the capacity of this path being limited only by the transmitter and receiver technology employed. The optical local access switch in the exchange, would in the first instance be no more than a flexibility point between the wavelength multiplexing equipment and the external fibers.

III. Switched Optical Networks

As optical technology develops, the next evolutionary step would be towards all optical networks where optical switching/routing will be carried out in addition to transmission and multiplexing. With optical technology there are three possible types of switching function that could be implemented: time switching, space switching, and wavelength switching. Although time switching has become a dominant switching technique for digital electronic communications systems, it does not follow that it is at all an optimum technique for optically switched systems. Time switching requires rigidly formatted and synchronized (both in time and phase) digital data. This invariably means a restricted transparency in terms of the maximum data rate per channel and the modulation format used. If optical circuit switching is employed then this transparency bottleneck can be avoided.

Optical technology can in principle be used to realize forms of circuit-switched networks where traffic is routed from terminal to terminal in the optical domain regardless of modulation format (analog or digital) and bandwidth would be limited only by the level of sophistication of the optoelectronic terminal equipment.

A. Optical Space Switching

An obvious optical circuit-switching option is space switching using optical cross points that are the analog of electrical crosspoints. In this way, fully transparent optical switching systems could be constructed that are parallels of existing space-switched electrical systems but without the bandwidth limitations of the electrical technology.

An additional space-switching option available with optical technology is optical beam-steering switching. This relies on the fact that in an optically linear medium, such as air, photons can pass through the same space without interference. A beam-steering switch conceptually consists of a two-dimensional (2-D) array of optical beam-steering elements that can scan another array of output element (see Fig. 3). The attraction of 2-D beam steering is the potential for large (maybe 10 000 × 10 000), single-stage nonblocking full-availability switches. One interesting approach to this form of switching is being pursued by J. P. Herriau *et al.* of Thompson-CSF [3]. Their technique is to write holographic diffraction gratings in BSO crystals. The pitch of the gratings and hence the diffraction angle of the optical beam is changed by writing the grating in the BSO crystal at a different wavelength and incidence angle, in this way steering of the optical beam is achieved.

B. Wavelength Switching

An interesting option available with optical technology is the ability to route traffic in the wavelength domain.

Authorized licensed use limited to: British Telecommunications via the BT Library. Downloaded on September 19,2025 at 10:13:41 UTC from IEEE Xplore. Restrictions apply.

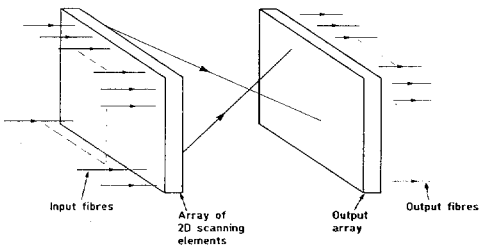


Fig. 3. Schematic of beam-steering optical switch.

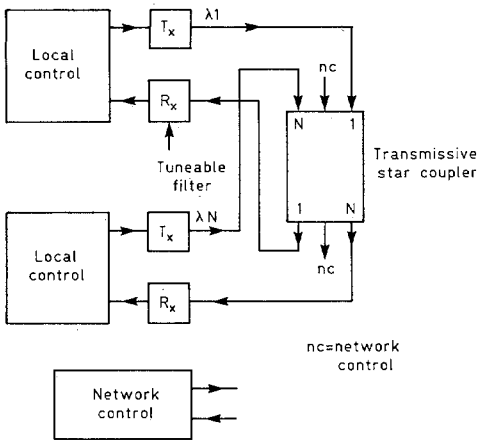


Fig. 4. Wavelength-switched local network.

Networks using wavelength routing could be entirely passive apart from the terminals.

One example of a wavelength-switched network is shown in Fig. 4. All terminals on the network are interconnected by a transmissive star coupler. In one realization, each terminal on the network (including the network control) has a different but fixed wavelength source for the transmitter (e.g., an individual DFB laser [4]), and a tunable filter in the receiver. The receiver tunable filters are tuned to the network control wavelength when in the free state. The network control polls each terminal in turn. When polled free terminals respond with a "request for service" or "service not required" command, busy terminals will not respond until free. On receiving a request for service (which will contain information on called terminal address) the network control will check its memory map and/or poll the called terminal to see if it is free. If free the network control will signal the called terminal to tune its receiver wavelength to the transmission wavelength of the calling terminal and then signal the calling terminal to tune its receiving wavelength to that of the called terminal transmitter. Completion of call setup would then be carried out by the terminal local control systems.

Two other versions of this network are possible. In the first, each terminal would have tunable rather than fixed wavelength optical sources [5] but fixed and different wavelength filters at the receivers. The network would operate in a very similar manner with call setup again controlled by the network control terminal operating at a designated control wavelength. The other, and more flexible version, would depend on the use of both tunable sources and receivers. This form would allow much more economical use to be made of the optical spectrum in that the network control could allocate wavelengths on a traffic demand basis, i.e., terminals not in use would not have a wavlength permanently reserved for them, allowing a given number of wavelengths to sustain many more terminals.

IV. Experimental Network

In order to illustrate the principles outlined above, a small experimental network (Fig. 5) has been constructed at BTRL, Martlesham Heath. The network has an 8 × 8 transmissive star coupler as a central passive node. This coupler was fabricated as a matrix of 2 × 2 fused biconical taper couplers without the need for splicing [6]; the configuration is shown in Fig. 6. To this coupler are connected various terminals including one video source connected via a 30-km cabled fiber link installed between Martlesham and the nearby town of Ipswich. This terminal serves to illustrate the power budget still available for further expansion of the network and also simulates, for example, a remote CATV head end. Terminals 1 and 2 each have a laser transmitter and a receiver with a tunable optical filter. The tuning range of the filters is 1200–1600 nm with bandwidths of approximately 10 nm. The tunable filters are continuously variable holographic reflection filters in dichromated gelatin [7]. The other terminals are video sources employing PFM modulators and one terminal transmitting 280 Mbaud data illustrating the transparency of the network and the ability to handle mixed traffic situations.

Also connected to the coupler node is a small 4 × 4 optical space switch using optomechanical crosspoints. This switch is controlled by a commercially available Monarch PABX [8]. The use of the Monarch means that the expensive development of the system management software can be avoided. The space switch in the experimental network can be considerd as a PABX connected to a wider wavelength switched network or as a switching node interconnecting a number of wavelength switched networks. In this latter case the space switch could be located in the switching center (as the service access switch in Fig. 2) with the passive star coupler replacing the optical splitter in Fig. 2.

V. Network Performance

The key factors determining the size (range and number of terminals) of wavelength routed networks [9] are: the launched power and spectral line width of the laser transmitters; the efficiency, bandwidth, and selectivity of the tunable filters; and the losses and spectral performance of the transmissive star couplers. The experimental network described above uses commercially available multilongitudinal mode lasers with spectral widths of about 5 nm. The tunable holographic filters in the network have half max bandwidths of less than 10 nm but have a side lobe structure in their spectral characteristics that limits channel spacing (using the above lasers) to about 15 nm.

Authorized licensed use limited to: British Telecommunications via the BT Library. Downloaded on September 19,2025 at 10:13:41 UTC from IEEE Xplore. Restrictions apply.

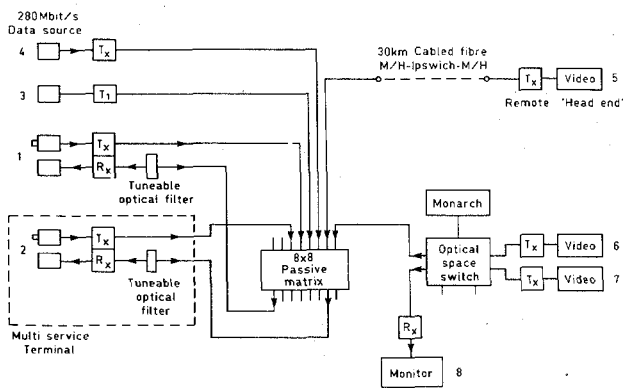


Fig. 5. Experimental network.

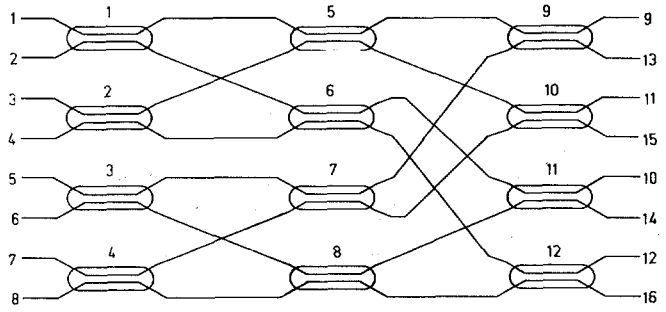


Fig. 6. Structure of 8 × 8 star coupler.

The spectral characteristics of the standard 3 dB, 2 × 2 biconical taper-fused coupler used to fabricate the 8 × 8 transmissive star matrix, has an insertion loss characteristic that can be closely approximated by

$$SL = -10 \log (0.5(1 + \cos (k\lambda + \phi c))) \quad (1)$$

and

$$(L = -10 \log (0.5(1 - \cos (k\lambda + \phi c))) \quad (2)$$

where SL is the insertion loss between the "straight" ports and CL is the insertion loss between the "crossed" ports. k is a constant that has a characteristic value for couplers fabricated from standard-matched-cladding single-mode fiber and ϕc is related to the wavelength at which 50 percent coupling occurs.

A general $N \times N$ transmissive star coupler requires $S = \log N/\log 2$ stages when constructed from 2 × 2 couplers. Any path through the star will, therefore, be via S couplers that could have combinations of "straight" or "crossed" states from all "straight" to all "crossed," each combination having a different wavelength characteristic. There are, therefore, $S + 1$ different wavelength characteristics for an $N \times N$ star. For example, Fig. 7 shows the four insertion loss characteristics of an 8 × 8 transmissive star coupler. Also shown in Fig. 7 is the transfer matrix for the complete 8 × 8 star, each element of which refers to the wavelength characteristic A, B, C, or D. It can be seen from this transfer matrix that if full availability between terminals is required then none of the wavelength characteristics can be avoided. The wavelength dependence of the insertion loss of these star couplers has a direct bearing on the network power budget and on the dynamic range of the receivers. The power budget of the network can simply be expressed by

Output or input port

Input or output port	9	10	11	12	13	14	15	16
1	A	B	B	C	B	C	C	D
2	B	A	C	B	C	B	D	C
3	B	C	A	B	C	D	B	C
4	C	B	B	A	D	C	C	B
5	B	C	C	D	A	B	B	C
6	C	B	D	C	B	A	C	B
7	C	D	B	C	B	C	A	B
8	D	C	C	B	C	B	B	A

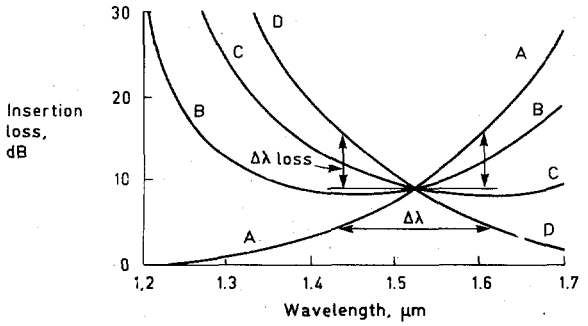


Fig. 7. Wavelength response of 8 × 8 star coupler.

$$T_x - R_x = L_f + L_c + M + (L_s + \Delta\lambda \text{ loss})$$

where T_x = launch power, R_x = receiver sensitivity, L_f = cabled and spliced fiber loss, L_c = loss of components other than the star coupler, e.g., connectors, tunable filter, etc.; M = system margin. The term in braces is the effective loss of the coupler, i.e., splitting loss $L_s = 10 \log N$ and $\Delta\lambda$ loss produced by the wavelength dependence of the star coupler.

For typical components and distances in local network environments it is estimated that the power budget available for the nett coupler insertion loss could be between 20 and 30 dBm for 140 Mbit/s systems [1]. The extreme spectral characteristics (curves A and D in Fig. 7) occur for paths through the coupler that are either all "straight," e.g., path port 1 to port 9 in Fig. 6, or all "crossed," e.g., port 1 to 16 in Fig. 6. These can be computed from (1) and (2) above and the number of stages S. The level of this loss and hence the number of terminals, is clearly dependent on the width of the optical window exploited by the network. Given the network components described above and a potential operating window from 1250 to 1600 nm then networks supporting up to 32 terminals could be constructed. Power budget considerations suggest however that several hundred terminals could be supported on such a network [9]. To realize these numbers of terminals, significant improvements in the performance of the network components is required. To reduce the limitation imposed by laser line width, single longitudinal mode sources will be required. A very promising laser for this application is the DFB laser, research samples are now available and it holds out the promise in

Authorized licensed use limited to: British Telecommunications via the BT Library. Downloaded on September 19,2025 at 10:13:41 UTC from IEEE Xplore. Restrictions apply.

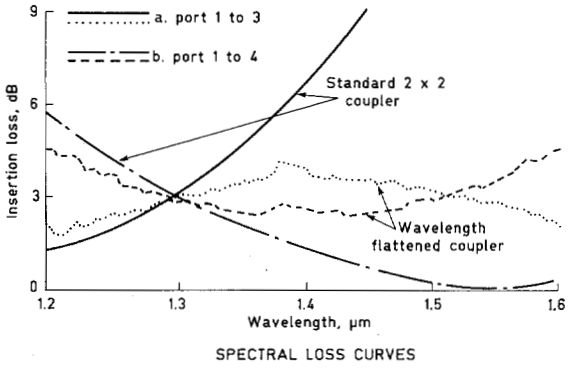


Fig. 8. Spectral response of 2 × 2 couplers.

the future of being a mass-produced low-cost source with well-defined central wavelengths. Such lasers should enable channel spacings of 1–2 nm, or less, to be realized. Such close channel spacings will need to be paralleled with a corresponding improvement in tunable filter performance. Currently research programs are underway to improve the performance of the DCG filters initially to <5-nm bandwidth with good sideband suppression and then as close to 1-nm performance as possible. In addition, other filter technologies are being investigated including thin-film interference filters [10] and tunable Fabry–Perot devices [11].

The realization that the performance of the star coupler would be a serious limitation to wavelength routed/multiplexed networks led to a research program at BTRL to investigate the possibilities of wavelength independent fused couplers. Recent work has shown that such couplers can be fabricated if, during manufacture of the elemental 2 × 2 couplers, an appropriate difference in propagation constant of the two modes in the coupling region is maintained [12]. Using this technique, four port (2 × 2) couplers have been fabricated with the spectral characteristics shown in Fig. 8. If transmissive star couplers are constructed using these couplers, then significantly greater numbers of terminals can be supported within a given power budget. This is shown in Fig. 9; here the number of terminals supported against the channel wavelength separation is shown for both types of couplers. It can be seen that for channel spacings around 7 nm the number of terminals supported increases from a maximum of about 32 for conventional couplers to about 64 for the wavelength-flattened type. In fact it can be seen that the number of channels, for this channel spacing, is limited not by the spectral behavior of the star coupler but by the assumed spectral window of the fiber. If the channel spacing is in the 1–2 nm region, the number of channels supported by networks using the new couplers increases significantly and networks of 256 terminals can be considered.

With the envisaged improvements in the key components, full-availability wavelength-routed networks supporting 150–300 terminals could be realized using conventional direct detection technology. In the longer term, coherent optical techniques with increased power budget and much enhanced channel capacity [13], could realize networks with several thousand terminals.

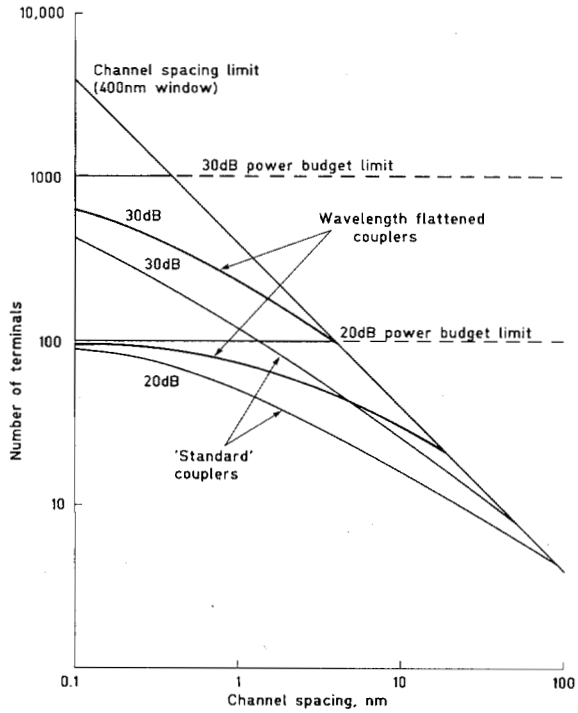


Fig. 9. Number of channels against channel spacing for transmissive star networks.

VI. Conclusion

In this paper we have discussed an evolutionary strategy for single-mode fiber networks. New network designs have been considered with potential for MAN's, cable TV, wideband local networks, and PABX applications. An early direct detection experimental network based on wavelength routing and optical space switching has been described and the performance requirements of the optical components have been outlined.

Acknowledgment

Acknowledgment is made to our many colleagues at BTRL involved in this project and to the Director of Research of British Telecom for permission to publish this paper.

References

[1] J. R. Stern, "Optical wideband subscriber loops and local area networks in the UK," *IEEE Intern. Conf. Comms. (ICC)* (Amsterdam, The Netherlands), May 1984.

[2] R. D. Hall, R. A. Betts, and J. P. Moss, "Bidirectional transmission over 11 km of single mode optical fiber at 34 Mb/s using 1.3-μm LED's and directional couplers," *Electron Lett.*, vol. 21, no. 14, pp. 628–692, 1985.

[3] J. P. Herriau, A. Delboulbe, J. P. Huignard, G. Roosen, and G. Pauliat, "Optical beam steering for fiber array using dynamic holography," this issue, pp. 905–907.

[4] L. D. Westbrook, A. W. Fiddyment, and P. J. Evans, "CW operation of 1.5 μm distributed feedback ridge waveguide lasers," *Electron Lett.*, vol. 20, pp. 225–226, 1984.

[5] R. Wyatt and W. J. Devlin, "10 kHz linewidth 1.5 μm InGaAsP external cavity laser with 55 nm tuning range," *Electron Lett.*, vol. 18, no. 19, pp. 110–112, 1983.

[6] D. B. Mortimore, "Low loss 8 × 8 single mode star coupler," *Electron Lett.*, vol. 21, no. 11, pp. 502–504, 1985.

[7] D. J. McCartney, D. B. Payne, and S. S. Duncan, "Position-tunable holographic filters in dichromated gelatin for use in single mode fibre demultiplexers," *Opt. Lett.*, vol. 10, no. 6, pp. 303–305, 1985.

Authorized licensed use limited to: British Telecommunications via the BT Library. Downloaded on September 19,2025 at 10:13:41 UTC from IEEE Xplore. Restrictions apply.

[8] M. H. Reeve *et al.*, to be published.
[9] D. B. Payne and J. R. Stern, "Wavelength switched, passively coupled, single mode optical networks," presented at IOOC/ECOC '85, Venezia, Italy.
[10] P. H. Lissberger, A. K. Roy, and D. J. McCartney, "Narrowband positioned tuned multilayer interference filter for use in single mode fibre systems," *Electron Lett.*, vol. 21, no. 18, pp. 798–799, 1985.
[11] S. R. Mallinson, "A fibre coupled Fabry–Perot wavelength demultiplexer," *Elec. Lett.*, vol. 21, no. 3, pp. 121–122, 1985.
[12] D. B. Mortimore, "Wavelength flattened fused couplers," *Elec. Lett.*, vol. 21, no. 17, pp. 742–743, 1985.
[13] D. W. Smith, T. K. Hodgkinson, D. J. Malyon, and P. Healey, "Demonstration of a tunable heterodyne receiver in a two channel optical FDM experiment," *IEEE Colloquium Dig.* (London, England) March 26, 1985, no. 1985/30.

D. B. Payne, photograph and biography not available at time of publication.

*

J. R. Stern, photograph and biography not available at time of publication.

Authorized licensed use limited to: British Telecommunications via the BT Library. Downloaded on September 19,2025 at 10:13:41 UTC from IEEE Xplore. Restrictions apply.