NEW DEVELOPMENTS IN OPTICAL FIBRE SYSTEMS

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Sufficient experience has now been gained with optical fibre systems to confirm that all the early optimism of the enthusiasts has been fully justified. Reliability and ruggedness are good, error rates are low and installation presents fewer problems than with coxial cables. The overall performance is excellent.

Research into the possibility of using cladded glass fibres as optical transmission lines began in the United Kingdom in 1966 at four laboratories, namely Standard Telecommunication Laboratories, Post Office Research Centre, Signals Research & Development Establishment and the University of Southampton. Initially, progress in what was then a tremendously challenging task — for example commercial fibre attenuations were 1000dB/km — was slow but steady and, indeed, increasingly promising. However over the past five years the pace of development has been rapid as, in the research laboratory at least, attenuations have dropped to as low as 0·15dB/km and extremely large bandwidths of over 20GHz km have been shown to be possible.

On the other hand the practising communication engineer and, more importantly, his potential customer are not so much interested in jam tomorrow but rather in bread today. In other words what is commercially available and practicable at present? A broad view of the current scene formed a major portion of the presentations in the 'Systems' sessions at the recent Fifth European Conference on Optical Communications in Amsterdam. This conference series is now a well-established feature of the international optical communications scene (the next in the series will be held at York, UK on September 16-18 1980) and attracted over 900 delegates from all parts of the world. The systems papers came from Germany, Italy, Japan, Netherlands and the USA. Rather surprisingly there were none from the UK but that does not indicate any lack of systems activity there; indeed the British Post Office has recently announced an extensive installation programme for the next five years and British work was described at the corresponding conference a year ago.

Most existing installations operate at a wavelength of 0·86μm for which gallium arsenide lasers and light-emitting diodes, together with silicon p-i-n and avalanche photodiodes, are commercially available. Laser lifetimes are now adequate for most applications although not yet as long as might be desired for widespread application, but are steadily being improved. At 0·85μm the installed cable attenuation is normally in the range 3 to 5dB/km and is not likely to be reduced much below the first of these figures for fundamental reasons. In graded-index multimode fibres the achievable bandwidth can be around 1GHz km although it often falls below this in practice. Strong moves are being made to produce sources and detectors suitable for operation at 1·3μm and 1·55μm where the lowest reported fibre losses are 0·5 and 0·15dB/km respectively. There is increasing interest in singlemode fibres since the spread in group velocities of the various propagating modes, which largely determines the bandwidth of multimode fibres, is no longer a limiting factor. In fact it has recently been shown that mode dispersion, material dispersion and profile dispersion can be mutually cancelled out at a wavelength which can be selected to be at 1·55μm thus giving extremely low losses and very large bandwidths at this wavelength. Repeater spacings of 100km can thus be predicted and indeed have already been achieved using a y.a.g. laser source. The line loss is likely to be determined by the joints in the cable and not by the fibre itself.

Subscriber Services

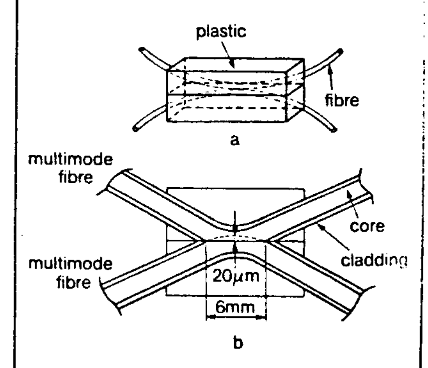
However, returning to the Conference, an invited paper was presented by H. Schüssler of AEG-Telefunken on the application of fibres to service integrated subscriber lines. In existing communication networks the subscriber lines account for as much as 40% of the total cost, thus if a saving can be achieved by changing to optical fibres then the subscriber end is where the maximum cost reductions can be made. In fact the Post Office in the UK expect that the major application of double-crucible fibres will be in this part of the system. Hitherto only narrow-band services have mainly been required but there will be an increasing demand for wideband services such as video, v.h.f., stereo sound, as well as multiple services such as telex, teletext, facsimile and so on. Thus, in addition to a change to digital transmission, the need for multiplexing will arise. It follows that both in the installation of new systems and the expansion of existing networks the subscriber line is a factor of major significance. In the case of fibres the requirements will be (i) duplex operation along one, or perhaps two, fibres; (ii) bandwidth ~100MHz; (iii) several narrow-band and broad-band services; (iv) local power supplied by the subscriber's equipment; (v) optical and monitoring techniques.

Optical fibre systems giving analogue bandwidths of 100MHz, extremely low harmonic distortion and a signal/noise ratio >50dB have been demonstrated over distances of 5km and digital transmission from 10 to 1000 Mb.p.s. over distances well beyond 10km at the lower bit rates. This is significant because the average distance between a subscriber and an exchange, in urban areas is less than 5km and 97% of all subscribers require a line length below 8km. Thus repeaters can be dispensed with. Changes in subscriber equipment can only be brought about over a long period so that the requirement for analogue transmission of sound and television will continue for some time. The high degree of linearity required can be provided and, for example, a harmonic distortion ratio of -50dB can be maintained at a laser output power of 1mW with a V-groove laser maintaining an output s/n ratio of nearly 60dB. An optical subscriber line was then described which allows telephone communication as well as two television and two stereo sound channels over two fibres. The second fibre can also be used for narrow band reverse transmission and can therefore provide a signalling channel, for the selection from a much larger range of services. At present the powering of subscriber services must be from the subscribers' premises since economic considerations rule out the incorporation of a copper circuit in the optical cable although optical power transmission is being considered. Similarly the development of wavelength-division multiplexing would obviate the necessity for two fibres. It is believed that in the late 1980s there will be large-scale application of fibres in the subscriber network with digital transmission of narrow-band services requiring digital exchanges but having the advantages of low capital expenditure, low operation and maitenance costs and an expansion in the number of services.

Multiplexed digital TV transmission

Work at the Heinrich Hertz Institüt für Nachrichtentechnik in Berlin is aiming at the simultaneous transmission of 16 television channels over a single optical fibre. Each channel requires 70Mb.p.s. leading to a total pulse rate for the 16 channels of 1·12Gb.p.s. The length of the graded-index multimode fibre is 3km and the individual pulse width is 0·3ns. There are four splices in the cable and two demountable connectors giving an overall attenuation of 5dB/km at a modest numerical

Fig. 1. A schematic diagram (a) and cross-section (b) of a fibre directional coupler.



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aperture of 0·17. Half the laser power is lost in coupling to the fibre and the transmitter is maintained at a temperature of 20°C. The receiver/regenerator for the RZ signals follows a conventional pattern but obviously required careful and ingenious design. The eye patterns measured at the link output are impressive and the measured error rate is better than 1 in 10^9. The link has successfully transmitted 16 TV channels which were sampled at about 8·2MHz and a linear 8-bit coding was applied, giving a pulse rate per channel of just below 70Mb.p.s. With suitable data compression the number of channels could be greatly increased and possibly even doubled. The system was demonstrated at the last Hanover Fair and future work will be concerned with a correlation between error rate and picture quality and with data compression.

Bi-directional operation

So far it has been customary, as indicated above, to use two separate fibres when bi-directional transmission is required. Small as fibres are, this is undesirable so various attempts have been made to use wavelength multiplexing involving two sources of different wavelength, two detectors, wavelength filters and so on, in order to avoid excessive crosstalk due to reflections at joints, connectors, receivers and other components. This whole problem has been re-examined at the Matsushita Electric Company where sources of only a single wavelength have been incorporated in a system transmitting multiplexed video, stereo, data and facsimile simultaneously in both directions along a single fibre. The fibre links the control centre and terminal of an interactive c.a.t.v. network. The key to successful operation is that reflections are minimised by careful design of all the relevant components.

The step-index fibre has a numerical aperture of 0·27 and core/cladding diameters of 100/150μm. The light source is a light-emitting diode with a 50μm diameter active area launching a power of -6dBm into the fibre. The detector is a simple p-i-n diode. Perhaps the most important element is the directional coupler which separates the transmitted and received signals at each end of the link. A sketch in Fig. 1 shows that it is composed of two fibres separately embedded in plastic and polished so that the cores are exposed and then fastened together. The excess insertion loss and directivity were measured as 0·36dB and 47dB, respectively which are impressive figures. A diagrammatic impression of the system is given in Fig. 2. All fibre ends, at splices, connectors and electro-optical components, were cut at an angle of 15° to reduce reflections and this represents a disadvantage since it is easy to cleave fibres perpendicularly but not at a specified and precise angle. With simultaneous transmission of two video signals the peak-peak signal/r.m.s. noise ratio was 56dB.

Another summary of results obtained with various television transmission systems came from Fujitsu. Simplicity has been the theme throughout with direct amplitude modulation of light-emitting diodes and detection by p-i-n diodes, except for long distances at an operating wavelength of 1·2μm when a germanium avalanche photodiode was necessary. Light-emitting diodes are more linear in response than might perhaps be expected but the residual non-linearity is compensated in the transmitter at the same time as emphasis is applied to the electrical input signal. Modulation depths of up to 75% are applied and the electrical supply power is quite modest at a few watts. Bandwidths are generally 6MHz but two systems operate at 22 and 30MHz. The celebrated Hi-OVIS system requires a received power of only -33dBm for a signal/noise ratio of 42dB. This system has been in full operation for about a year with good reliability and no particular problems. Also described was a portable television field pick-up equipment which can be used for distances up to 1km with four drums each containing 250m of cable. Various sports events have been covered in this way including the relaying of a ski event in quite severe cold.

Matrix coupler

Most effort in the application of optical fibres has been directed towards long-distance telecommunications, requiring lengths of fibre with an input at one end and an output at the other. However there is also a strong demand for multiple-access systems, often known as data buses. The first report on an attempt to make a data bus with single-mode fibres came from the US Naval Research Laboratory. The basic technique is relatively simple although producing rather large star couplers. The latter are based on a 3dB coupler in which power is transferred from one fibre to another via evanescent coupling through a thinned-down cladding. The loss of these components is less than 2dB. Star couplers are made by braiding a set of three fibres over a fixed length and then one or two of these fibres are braided with some from another set. Coupling from one particular fibre then takes place to each of the other fibres and is equalised over several braiding sections. In a star coupler formed from 10 fibres the uniformity of coupling from any one fibre to the other nine is ±2dB and is ±1dB between the best eight. Excitation is by a single-mode injection laser at 500Mb.p.s. In one 10-to-10 mixer the 'throughput' loss was 0·5dB. Unfortunately this factor was not defined but if it means the total transmission loss from one input port to the ten output ports the result is remarkable. The current version does not seem to be particularly stable since the output varies with time due to air currents and the device is not strictly a star coupler since each of the input ports couples to each of the output ports and not to the other input ports. Nevertheless the results are promising.

The next group of papers was concerned primarily with applications in the existing telephone network. The first, from the German Post Office, described the installation, and operational behaviour, of a 34Mb.p.s. link over 4·3km between two local exchanges in the local cable network of West Berlin. The cable duct route contained all the normal problems of bends and varying duct materials including concrete, steel and plastic as well as fairly severe environmental hazards comprising heavy road traffic with vibrations and electromagnetic fields from an underground railway. The optical cables were drawn into the ducts in lengths between a few hundred metres to 1km, at speeds of 10 to 20m/min at tensions up to 500N. Bends were negotiated using bicycle wheels as rollers, thus illustrating the relative ease of installation. Splices were made by the fusion technique in manholes and no precautions were taken to exclude dust which could be heavy with nearby traffic. The average loss over 70 splices was 0·15dB. Two cables of eight fibres could be spliced completely by two workers in one day. In a sense this presentation was uninteresting since there were no problems to report! The bit error rate was better than the planned 1 in 10^9 per kilometre of path, while over a period of 25 months there have been no interruptions of service due to faults in any of the optical components in the four systems tested.

Telephone link

Another 34Mb.p.s. system, albeit an experimental one, has been designed to meet optimum design and sensitivity conditions by Telettra Spa. It incorporates an l.e.d. (Plessey HR954) transmitter operating at 0·9μm. Since the attainable bandwidth is limited by material dispersion in the fibre there is a considerable

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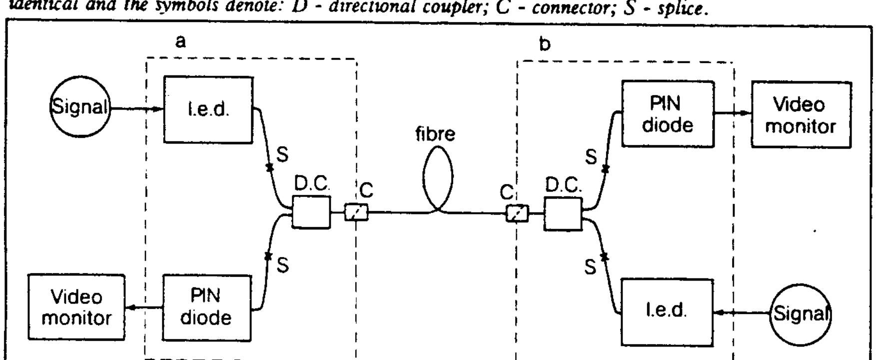
Fig. 2. Bidirectional transmission along a single fibre. The transmit/receive modules a and b are identical and the symbols denote: D - directional coupler; C - connector; S - splice.



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advantage in operating at 0·9μm rather than the more common 0·82μm. In the receiver front-end an avalanche photodiode (AEG-Telefunken BPLJ28) is followed by a high-impedance preamplifier. The a.p.d. gain is adjusted to compensate temperature variations of both transmitter and receiver so that the output level of the receiving is kept constant. The system operates with a 5B/6B code and has normal monitoring and alarm facilities. The l.e.d. linewidth is 15nm and a power of −16dBm is fed into the graded-index fibres which exhibit a material dispersion of 70ps nm^{-1}km. In a 5km length the losses due to pulse shaping connectors and splices is 5·5dB and the fibre attenuation is 4dB/km. A bit error rate of 10^{-10} gives a margin of 7·5dB but it is not clear which of these various figures are measured rather than calculated.

Demonstration of 140Mb.p.s. over 100km

An interesting laboratory demonstration of transmission at 140Mb.p.s. over a distance of over 100km has been carried out at Philips Telecommunication in The Netherlands. In the original system there were two cable sections each of 8km with six fibres per cable plus copper wire for power feeding and signalling. By looping at the ends a total length of fibre of 96km was available in which were inserted 11 repeaters of the fully-regenerative type. As in other systems 5B/6B coding was chosen. The cables were in 1km reels and spliced by the arc-fusion method, giving a loss of between 0 and 0·2dB per splice which is an excellent performance. All measurements were made with an equilibrium mode distribution in the fibre so that the measured total attenuation was within 0·5 and -1·5dB of the sum of the individual fibre and splice attenuations. This result is of considerable significance since it means that safe predictions can be made of total system attenuation from suitable measurements on separate components. On the other hand the section bandwidths of 0·9 to 1·0GHz km are appreciably larger than the corresponding values of 0·65 to 0·7GHz km in the separate installation lengths. Such an 'inverse Murphy's law' has previously been reported by the UK Post Office and may be due to successive lengths being alternately over-and under-compensated compared with the optimum refractive-index profile.

High efficiency

The optical sources were laser diodes, with a pherical lens for efficient coupling to the graded-index multimode fibres, biased at threshold and driven by NRZ pulses. The control circuit also keeps the output power constant at 0dBm mean value and 2mW pulse amplitude. For a bit error rate of 10^{10} the minimum received optical power is 32 to 38nW. The power margin is as high as 12 to 17dB. The receiver used avalanche photodiodes and both these and the lasers were provided with fibre pigtails terminated in connectors of loss below 0·5dB. The total receiver supply voltage was only 6V. A very sound piece of engineering.

1·12Gb.p.s. prediction

The German Post Office has predicted that digital links at rates up to 1·12Gb.p.s. will be introduced into future telecommunications networks and some experiments have already been reported. As an engineering step in this direction the design and operational characteristics of a 280Mb.p.s. transmitter and a receiver produced by AEG-Telefunken were described. The principal elements are a graded-index fibre permitting a repeater spacing at this pulse rate of 4km, a GaAlAs laser and a silicon a.p.d. (BPW28). The transmitter and receiver incorporate a scrambler or descrambler, respectively, to provide a sufficient mark density for clock regeneration. The NRZ p.c.m. input signal to the transmitter enters an eleven-stage scrambling circuit comprising ten e.c.l. shift registers. The NRZ format is converted to RZ before laser modulation. The transistor driver stage has a pulse transient time of 0·4ns and allows independent control of the bias and modulation drive. The laser emission is monitored by the emission from the rear face and a photodiode. A temperature change from 10° to 40°, with control applied, produced a change in peak light output of only 4%. The input to the receiver is a transimpedance amplifier with an f.e.t. input stage and transimpedance 5kΩ. The measured equivalent input r.m.s. noise current is $1{\cdot}5\times10^{-17}$A.

The final paper in this trend to higher bit rates was from the Siemens Company, this time describing tests on an experimental system operating at 560Mb.p.s. over a repeater spacing of 7·2km. T' . basic design is similar in many respects to those reported above. For example the electrical NRZ signals are converted to an optical RZ output in the transmitter and the laser emission is coupied via a micro lens into a fibre pigtail. The laser drive circuit has to be faster and requires 5GHz transistors working as emitter-coupled pairs. Again resonance peaks in the laser output at these high switching speeds have to be guarded against. Laser amplitude control is effected by applying a low-frequency modulation to the bias current and noting the zero-crossings of the resulting signal. With a threshold current of 150mA and a drive current of 50mA a tone modulation of only 0·5mA is sufficient.

7GHz bipolar transistors

The preamplifier in the receiver incorporates 7GHz bipolar transistors in a 1kΩ transimpedance amplifier. To maintain a large dynamic range the small-signal gain of the a.p.d. is made large and dependent on the signal amplitude whereas for larger signals the gain is constant. The input signal level required is −43dBm for an error rate of 1 in 10^9 and the receiver is linear up to -25dBm. Temperature variations from 10 to +50°C have no effect on the laser output. With a fibre of 1·2GHz bandwidth a transmission distance of 6·2km requires a power of −40·6dBm giving a margin of 6·2dB while the corresponding figures for 7·2km are −38·7dBm and 0·4dB.

Conclusion

It is clear from the papers presented at the Conference that the first-generation optical fibre communications systems have left the research laboratories and are progressing rapidly through the development phase towards routine installation and operation. Invaluable operating experience is being gained so that confidence in the reliability and simplicity of fibre links is building up. The presentations described are not representative of what is being done in all the major western countries — that would require an entire conference in itself — but nevertheless are typical of the general trend. Other aspects still being investigated, and which will form the basis of second generation equipments, are the twin moves to longer wavelengths and single-mode fibres. These are likely to encourage the development of underwater optical cables with the attraction that spans less than 100km will need no submerged repeaters. The future, as in so many facets of electronics, promises many exciting prospects, some of which it is only possible to speculate about.