Data transmission using optical fibres

The most critical system component in an optical fibre communications system is the fibre itself, write *F M E Sladen* and *S R Norman* who describe a 5 km link built at the University of Southampton

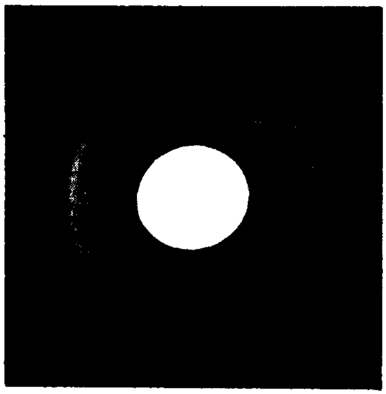
There are many applications such as in the field of medium-speed data communications where many of the inherent advantages of optical fibres can be used —in particular freedom from electromagnetic interference, light weight and greater bandwidth as compared to a copper wire system. Generally an optical-fibre link is capable of providing medium-speed (~1 Mb/s) data communications between local and remote terminals located from 10-20 km apart. Here we discuss a proposal for an unrepeatered optical-fibre link of this kind and will examine the optical transmitters, receivers and fibres that could be used. A feasibility study has shown the optical fibre to be the most critical system component for this application and the validity of this has been confirmed by the construction and successful operation of a 5 km link.

Fibre charactistics

The three principal fibre configurations which are possible are shown in Fig. 1. The type of fibre selected for a particular application will be largely governed by the allowable transmission losses and the bandwidth times length product of the fibre link. The step-index multimode fibre is simplest to fabricate but the group velocity differences between the fibre modes produce temporal spreading of the propagating pulse which severely restricts the fibre's bandwidth. A further limitation is imposed by material dispersion which arises from group velocity differences between the spectral components of the source. Thus, in a step-index silica-based fibre having a numerical aperture of 0,2 excited by a led operating at 0,9 μm with a 40 nm linewidth, the combined effects of intermodal dispersion (48 ns/km) and material dispersion (2,6 ns/km) limit the bandwidth to 10 Mb/s over a 1 kilometre link.

The severe restrictions of intermodal dispersion can be greatly reduced by employing graded-index multimode fibres. By radially varying the refractive-index distribution within the core in a parabolic manner, it is possible to nearly equalise the transit times of all modes. Pulse dispersion within the fibre is then dictated by material dispersion effects. If the fibre is operated with a led, the bandwidth can be 150 Mb.km.s^{-1}, whilst if a narrow linewidth (~4 nm) semiconductor laser is used the bandwidth can be as high as 500 Mb.km.s^{-1}.

The single-mode fibre has by far the greatest bandwidth because intermodal dispersion is totally eliminated, but its very small core size entails the use of a laser source to permit efficient coupling. Furthermore, the tolerances necessary for jointing and coupling are more severe than in multimode fibres. However, should system requirements demand the use of single-mode fibres, transmission rates in excess of 5 Gb.km.s^{-1} can be achieved.



Three fibre configurations are shown in Fig. 1.
Fig. 2 shows a cross-section of a graded-index fibre. (above)

Fibre fabrication

Although fibres exhibiting attenuation greater than 20 dB/km may be acceptable for short-distance links, most applications will require the use of silica-based fibres having losses below 5 dB/km. A simple and convenient method of producing all three types of fibre is the so-called homogeneous chemical vapour deposition (HCVD) technique, developed at Southampton University in 1974. The process involves the deposi-

The authors are with the Department of Electronics, University of Southampton.

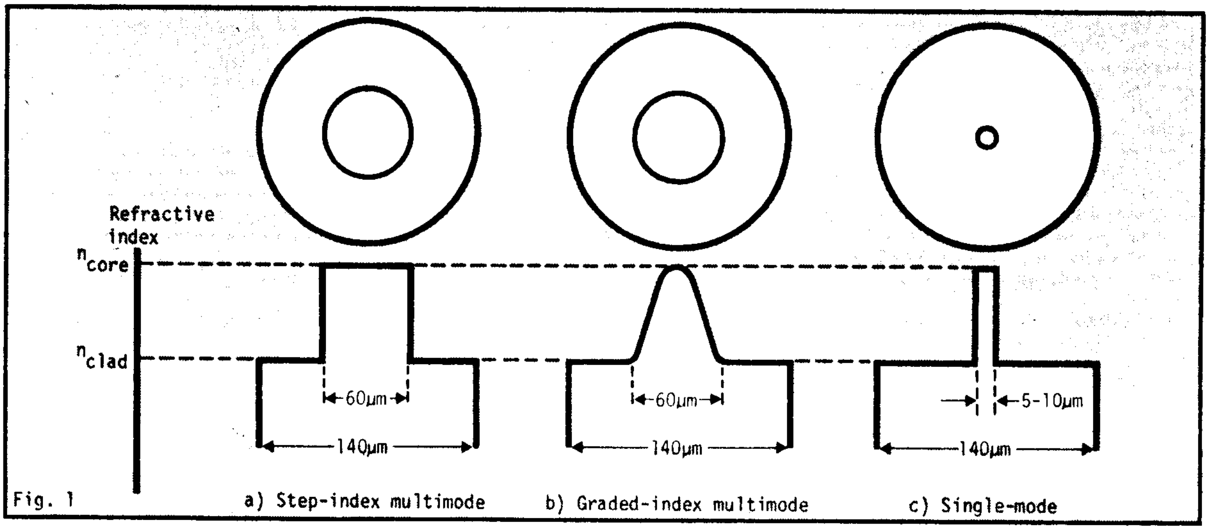


Fig. 1 a) Step-index multimode b) Graded-index multimode c) Single-mode tion of a number of layers of core glass on the inside of a silica tube which will form the fibre cladding. The composite tube is then collapsed at high temperature to form a solid rod which is subsequently drawn into a fibre. The core glass must be ultra-pure, chemically and physically compatible with silica, and must also have a refractive index about 0,8 % higher than that of silica.

We have found that by the high-temperature vapour-phase oxidation of the chlorides of silicon and phosphorus it is possible to produce a phosphosilicate glass which fulfills the above requirements. Because the starting materials (silicon tetrachloride and phosphorus oxychloride) are both liquids at room temperature, they are readily purified by distillation. To form the phosphosilicate glass, vapours of the two liquids are passed with oxygen through the silica tube along which a hot zone at about 1500°C is transversed. When they reach the hot zone, the chlorides spontaneously oxidise to form a dense soot of particles which fuse on the wall of the tube in a clear glassy layer. The composition of the glass is determined by that of the reactant vapours, and it is therefore possible to select the refractive index of the deposited glass by controlling the ratio of the reactants. Hence, to fabricate a step-index fibre several layers of glass of constant composition are deposited. To produce a graded-index fibre the phosphorus concentration in the vapour phase is increased layer by layer.

Borosilicate glass

Other materials which can be added to silica in a similar fashion are germania, boric oxide and fluorine. Whilst germania also increases the refractive index of silica, both boric oxide and fluorine decrease it. Thus, to increase the numerical aperture of a phosphosilicate-cored fibre it is common practice to deposit first several layers of low-index borosilicate glass on the inside of the silica tube prior to depositing the core glass. A numerical aperture of 0,25 can be achieved in comparison to a maximum of 0,18 for the silica-clad fibre. A further advantage of this configuration is that the borosilicate glass now acts as the cladding, and low-quality silica can be used for the support tube.

After a sufficient volume of glass has been deposited the reactant flow is stopped and the composite tube is collapsed into a solid rod by raising the temperature of the hot zone to about 1900°C. The preform, which is typically 8 mm in diameter and 50 cm long, is then drawn into a fibre, usually 140 µm in diameter, on a precision fibre-drawing machine. The freshly-formed fibre has a pristine surface free of stress-concentrating flaws, and it is therefore inherently strong. This strength is retained by applying a protective coating to the fibre as it leaves the drawing furnace. In this way, the fibre can be handled and cabled without significantly degrading its strength. For example a polymer-coated 140 µm fibre withstood in excess of 7,5 kg tension before failing compared to less than 1 kg for an uncoated fibre exposed to the atmosphere for 48 hours after drawing. Coated fibres can also be subjected to bend radii of approximately 2 mm without breaking.

Experimental results

A typical cross-section of a graded-index fibre having a phosphosilicate glass core with a borosilicate glass cladding is shown in Fig. 2. The overall fibre diameter is 140 µm, the core diameter is 55 µm and the cladding thickness is 8 µm. The fibre has a numerical aperture of 0,2. Fig. 3 shows the fibre's refractive index profile obtained by a near-field scanning technique. The decrease in refractive index on the fibre axis is due to outdiffusion of dopant during the collapse stage. Although the profile deviates from parabolic, the pulse dispersion measured in a 1 km length using a mode-locked He/Ne laser was only 0,6 ns/km; this corresponds to a bandwidth of 830 Mb/s over 1 km.

The spectral attenuation of the fibre over the wavelength range 0,45 µm to 1,0 µm is shown in Fig. 4. The minimum attenuation is 2,9 dB/km at 0,92 µm and 1,0 µm. It can be seen that the fibre exhibits a very broad window from 0,7 µm to 1,0 µm over which the loss is below 5 dB/km; extended measurements up to 1,2 µm in the infra-red show that the attenuation does not significantly increase. It is thought that the minimum loss could be reduced by increasing the cladding thickness to at least 12 µm in order to prevent differential mode attenuation; this is partly borne out by the fact that the numerical aperture after 1 km of propagation was only 0,16.

The refractive index profile of the fibre of Fig. 2 is shown in Fig. 3. The spectral attenuation is shown in Fig. 4.

Despite the fact that the fibre's refractive index profile departed from the ideal, and that the core was slightly elliptical, this fibre and four other similar samples were successfully employed in a 5 km data link described below.

Optical fibre systems

Many theoretical studies have been made to determine the performance of a digital optical-fibre transmission system. These studies have only taken into account the effects of quantum noise, thermal noise and pulse shape, although in a practical system additional factors such as external impulsive noise may considerably lower system performance.

Theory suggests the importance of reducing the thermal noise to increase receiver sensitivity and this has been approached in two ways, one via a high-impedance detector load circuit and the other via a trans-impedance amplifier. The high-impedance circuit has a large time constant due to component and stray capacitances and hence it integrates the signal. A differentiating equaliser restores the signal to its original form and although the method is

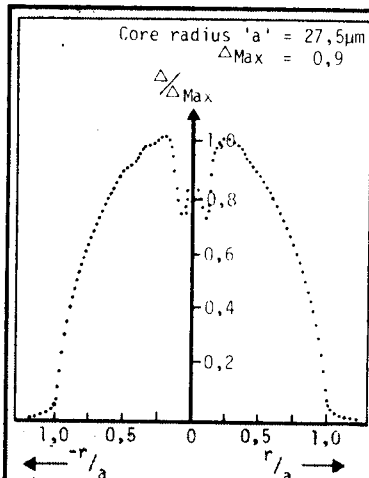


Fig. 3

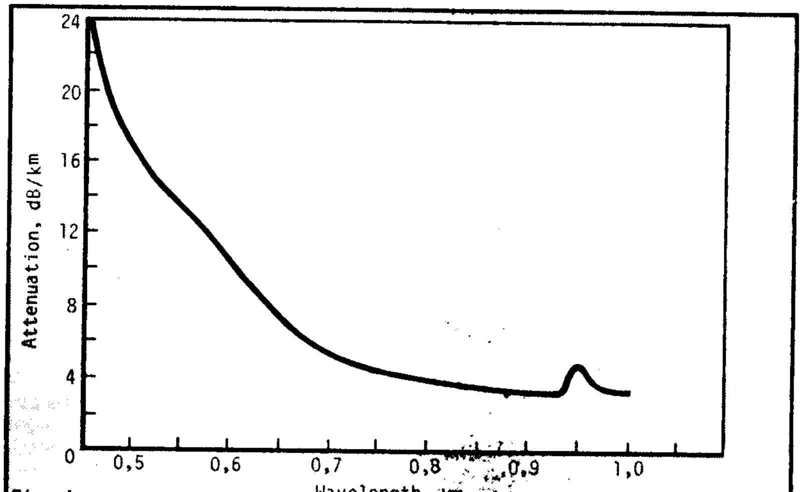


Fig. 4

simple and straightforward to apply, it tends to result in a limited receiver dynamic range. The trans-impedance amplifier, on the other hand, presents a low impedance to the detector and equalisation is either negligible or not required, thereby allowing a greater dynamic range. However the stability problems associated with feedback amplifiers can make this approach rather more difficult to implement. We have analysed a 1 Mb/s system using the characteristics of currently-available devices, and have found the optical fibre to be the most critical system component. For example, if an avalanche photodiode is used instead of a pin photodiode on a 20 km link, then the receiver sensitivity could be reduced by ~13 dB, an improvement that could also be achieved by a reduction in effective fibre loss of only 0,65 dB/km. The analysis indicates that a 20 km link using a led source would require a fibre with an effective attenuation ~2 dB/km, whereas a system using a semiconductor laser source could tolerate fibre losses ~4 dB/km. Fibres can currently be manufactured to these specifications but considerable effort should be devoted to the production of ultra-low-loss fibres for long-distance optical-fibre communications.

Test link

In order to test the validity of our analysis we have constructed a 5 km optical fibre link which has been successfully operated with an error rate of less than 10^{-9} at data rates of 1 Mb/s and it is anticipated that operation could be extended to over 7,5 km without a great deal of further development. The link, which comprises an optical transmitter, an optical receiver and 5 km of optical fibre, is shown in the photograph of Fig. 5.

The fibre consisted of five 1 km lengths of graded-index silica-based CVD fibre manufactured at Southampton and the five lengths were spliced together by a butt-joining technique developed in our laboratories. Briefly the joint consists of a triangular glass sleeve into which the fibres are inserted. Alignment is achieved when the fibres are forced into the apex of the triangular tube which is then filled with a cyanoacrylic adhesive to hold the fibres in place. It also acts as an index-matching medium. For low loss (~0,1 dB) this joint requires the cross-sectional dimensions of both fibres to be identical and since the fibres used in the experiment were not exactly matched in this way, losses of up to 1 dB per joint could be expected. Nevertheless the 5 km length of fibre had an overall attenuation of 22 dB at a wavelength of 0,9 μm, giving an effective fibre attenuation of 4,5 dB/km. The fibres had a core diameter of ~60 μm, a numerical aperture of ~0,16 and were wound on 0,5 m diameter drums. The characteristics of a 1 km length of this fibre are shown in Figs. 2-4 inclusive.

Sources and detectors

Gallium-arsenide leds are available operating at wavelengths of ~0,9 μm, and a useful high-radiance version known as the Burrus diode has been specifically developed for operation in fibre-optic systems. The led has the advantage of long life and reliability, is easily modulated by variation of the bias current and can be simply coupled into an optical fibre. However the high angular divergence of the light output produces a poor launching efficiency, and for systems requiring a wide bandwidth the large spectral linewidth (~40 nm) can give rise to relatively large material dispersion effects.

GaAlAs double-heterostructure semiconductor lasers are available operating on a 5% duty cycle and with a peak power of 150 mW at 0,85 μm. This duty cycle will probably be increased with future development even if cw operation does not become feasible at these power levels. However cw operation is now practical at output powers of 10-20 mW. When used to excite an optical fibre the semiconductor laser gives a coupling efficiency of 80% or more, allowing high powers to be launched, and the narrow spectral linewidth of about 4 nm gives low material dispersion. Currently-available devices exhibit short life-times when used at high duty cycles, but progress is expected in reliability, and developmental samples with life-times greater than 10 000 hours have been reported.

Silicon pin photodiodes operate in the spectral range 0,4-1,1 μm and exhibit short response time, high quantum efficiency, low capacitance and very low noise equivalent power (10^{-14}W/$\sqrt{}$Hz). The diode requires a simple low-voltage bias supply and its construction is mechanically rugged. It is also cheap and available with a large range of active areas.

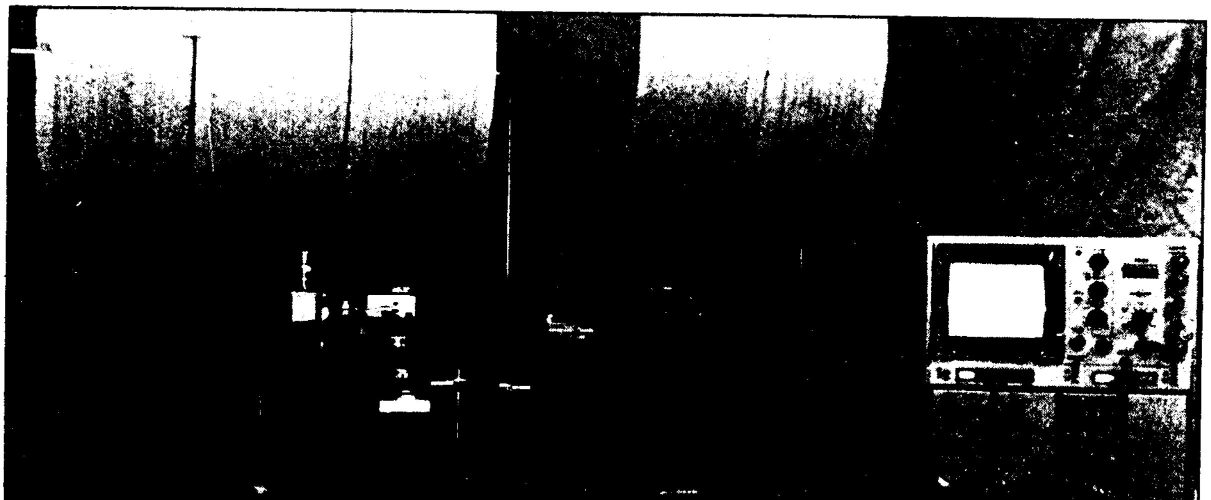
Avalanche photodiodes can provide a useful increase in system signal/noise ratio when the system is limited by preamplifier noise. The diodes exhibit a high gain-bandwidth product (~30-100 GHz), very fast risetimes (0,1-2 ns) and very low capacitance (~1 pF). However, they are expensive and require a complex biasing arrangement to stabilize the temperature-dependent operating point. A disadvantage of silicon detectors is their lack of response above 1,1 μm, and unfortunately germanium devices do not provide a comparable noise performance.

The transmitter

We have designed transmitters using both led and semiconductor-laser sources. For operation over ~5 km the led source is quite satisfactory but for longer distances ~20 km a semiconductor laser source would be required.

The led transmitter utilises a high-radiance Burrus diode with a radiance of approximately 10 W/st/cm² and operates at a wavelength of ~0,9 μm. The diode is modulated at 1 Mb/s with

The photograph shows the experimental 5 km link, Fig. 5



half-width, return-to-zero current pulses of 200 mA peak amplitude and for measurement purposes a pseudo-random bit stream is used as the data source.

The semiconductor laser transmitter utilizes a double-heterostructure, gallium-aluminium-arsenide, stripe-geometry, cw laser diode with a peak rated output of 10 mW, and operates at a wavelength of 0,85 μm. The diode is modulated at 1 Mb/s with half-width current pulses of 55 mA peak amplitude superimposed on a dc bias-current of 135 mA. The dc bias is set below the lasing threshold and is adjusted so that the laser operates at 5 mW (ie half its rated output) as it is very prone to catastrophic failure at high power levels.

During the transmission experiments coupling between the source and the fibre was achieved simply by accurately positioning the fibre end-face very closely to the emitting surface with an x-y-z micromanipulator.

The receiver

For the receiver design, there is the option of using either a high-input-impedance front-end or a trans-impedance amplifier. Both designs were built and comprehensively tested for noise performance, stability and impulsive noise immunity. From these tests the high-impedance design was found to be simpler to implement although it does appear to be very susceptible to the pick-up of impulsive noise. However, with careful screening of the first stage, it has been possible to virtually eliminate the pick-up of external impulsive noise. The calculated noise equivalent power of the receiver is −67,5 dBm at a wavelength of 0,9 μm, with the majority of the noise originating in the preamplifier.

The optical detector consists of a silicon pin photodiode with a very small active area (0,05 mm^2) and a very low noise-equivalent power ($1,4 \times 10^{-14}$ W/$\sqrt{Hz}$). The photodiode is reverse-biased at 24 V and feeds a 1 MΩ load resistor. The signal appearing across the 1 MΩ load resistor is amplified by a fet/bipolar transistor combination having a very high input-impedance and used in a common-source fet and shunt-feedback bipolar transistor configuration which has the advantage that it minimises the effect of the Miller capacitance of the fet at the input. The preamplifier has a voltage gain of 20 and a high-frequency roll-off at 10 kHz.

Equalisation

The equalisation of optical receivers having a high input impedance has hitherto relied on passive equalisers which, in the present application, would result in an insertion loss of ~40 dB. However, in this receiver a novel method for equalisation has been used which involves a careful choice of the emitter by-pass capacitor in a common-emitter amplifier stage. This overcomes many of the disadvantages of the passive equaliser and gives negligible insertion loss. Also the first stage of equalisation has been introduced immediately after the preamplifier in order to increase the dynamic range of the receiver. The latter property is particularly important when long streams of consecutive "1"s are being received. A similarly implemented second stage of equalisation is used to reduce the intersymbol interference to a negligible value.

The equalised signal is further amplified in the video amplifier before it is band-limited in the receiver output filter which consists of a two-stage R-C network followed by an fet source-follower output stage. A −3 dB bandwidth of 640 kHz was chosen as it results in a good compromise between minimum intersymbol interference and maximum signal/noise ratio at the receiver output. Threshold detection of the equalised and filtered signal was accomplished using an integrated-circuit differential comparator and re-timing was effected with the 1 MHz data-source clock, although in a final system the retiming signal would be extracted using a phase-locked loop.

Fig. 6a shows the pulse shape at the receiver output after transmission over 5 km of optical fibre. The source used was the Burrus diode transmitter modulated at 1 Mb/s with a pseudo-random bit stream. The corresponding eye-diagram of Fig. 6b shows that the intersymbol interference is negligible at the decision points (ie at the signal maxima). The noise equivalent power of the receiver was measured as −65,5 dBm at a wavelength of 0,9 μm and compares favourably with the calculated value of −67,5 dBm. The 2 dB difference is probably due to noise introduced by the second stage which is not accounted for in the theoretical calculations. The careful screening employed around the pre-amplifier stage appears to have completely eliminated the pick-up of impulsive noise which was found to be particularly troublesome in earlier prototypes. The error-rate performance of the 5 km link was measured for various values of received optical power. The led transmitter was used as it has a very stable optical output and the power launched into the fibre can be varied by altering the optical coupling between the transmitter and the fibre. The test signal was a 255 bit pseudo-random bit stream and the measured error-rate curve was within 2 dB of the theoretical curve. During these tests a visual observation was kept on the error counter in order to ascertain whether the errors occurred during error-bursts containing several errors or as single isolated errors. This visual test tended to show isolated single errors which suggests that they were caused by receiver noise and not by external impulsive noise. In a further measurement the transmitter/fibre coupling was adjusted for maximum signal at the receiver output and the measurement allowed to run for a period of 12 hours. During this 12-hour period no errors were recorded. □

Output pulse shape (6a) and eye diagram (6b) at the receiver output are shown in Fig. 6.