NEW LOW-LOSS LIQUID-CORE FIBRE WAVEGUIDE

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Low-loss liquid-core fibre-optical waveguides having a transmission loss of 10 dB/km has been made using commercially available glass tubing. The loss is less than 20 dB/km over a wavelength range of greater than 0·8–1·1 μm, and, at the semiconductor laser wavelength of 0·9 μm, has a value of 14 dB/km. This is the first low-loss fibre to be made using glass.

Introduction: In order to make a cladded fibre suitable for use as a transmission medium for optical communications, it is necessary to select two materials to act as core and cladding which ideally have low attenuation, scattering and dispersion at the wavelength of interest. In addition to the appropriate relative refractive indexes, they should have suitably matched thermal and mechanical properties and be chemically compatible, stable, flexible and strong. A suitable material which satisfies most of these requirements, with one major exception, is glass, but, unfortunately, none is yet available with a sufficiently low absorption coefficient. Using commercial glasses, we have achieved a transmission loss of less than 200 dB/km, which, to our knowledge, is the lowest value yet reported for a multimode cladded-glass fibre, but this is still much too high for practical application. In principle, it should be possible to obtain the desired attenuation by reducing the impurities to a sufficiently low level, typically about 1 part in 10^6, in the bulk glass from which the fibres are made, and, in fact, the loss in SELFOC graded-index fibre[†] has been improved to 60 dB/km. A material which is available in very pure form is silica, but its refractive index is too low, and its thermal and mechanical properties are too different from those of glass or similar compounds, to make a low-loss cladded fibre possible. By using silica doped with titania as the core material, and pure silica for the cladding, a single-mode fibre of 20 dB/km has been made,[1] but it has not become commercially available, has a long processing time, and is reputedly rather brittle.

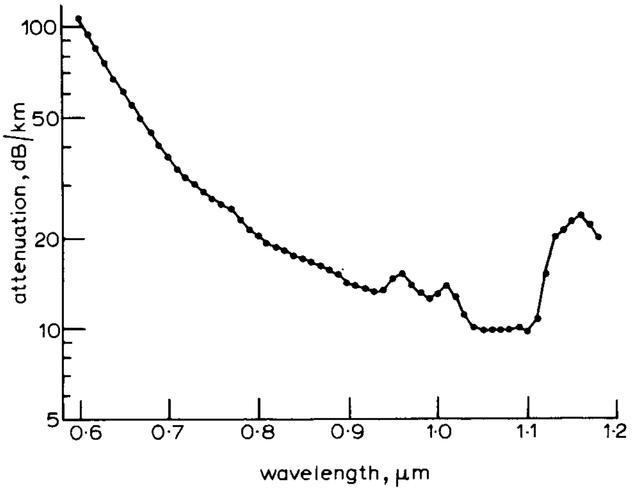

Fig. 1 *Attenuation of liquid-filled fibre as a function of wavelength*

Although suitable solid materials which are compatible with silica have not yet been found, there are some liquids of convenient refractive index which are relatively absorption-free. Two groups have independently produced low-loss multimode liquid-core fibres using the combination of tetrachloroethylene in a silica tubing. W. J. Ogilvi (CSIRO), using specially selected silica of low water content, has measured[2] a loss of 17·5 dB/km over lengths of several hundred metres, while J. Stone (Bell Telephone Laboratories) reports[3] figures of 20 dB/km or less between 0·84 and 0·86 μm and also between 1·04 and 1·10 μm for a fibre of 75 μm core diameter. In fact, the published curve in the latter paper seems to have a point at 1·10 μm which is near 15 dB/km. We wish to report a new[4] type of liquid-core fibre having an attenuation of 10 dB/km between 1·04 and 1·10 μm and which is below 20 dB/km from 0·8 μm to 1·13 μm. The tubing was made from cheap high-loss glass and we assume that, by purification and filtration of the liquid and by using glass of better quality, the attenuation may be reduced still further.

Method: The fibres were drawn from Chance-Pilkington ME1 glass tubing, having a bulk absorption loss in the region of 10 000 dB/km, by a precision pulling machine.[5] The tubing was of 14 mm outside diameter and 1·5 mm wall thickness, and was drawn into fibre, typically of 50 μm inner diameter and 27 μm wall thickness, in 5 km lengths, as a single layer on an aluminium drum 1·4 m in circumference. The fibre cross-section was accurately circular and the outer diameter constant to within 1 μm. The refractive index of the glass is 1·487, and, to achieve a guiding structure, it is essential that the liquid should have a higher index. For a high-loss cladding glass, the liquid should be as high as possible to avoid a significant cladding contribution to the overall fibre attenuation, i.e. the cladding contribution to the fibre attenuation may be reduced by having a large index difference.

It is also necessary that the u.v. and i.r. absorption bands of the liquid should be as far removed as possible from the wavelength region of interest (0·7–1·1 μm). This is because strong electronic transition bands in the u.v. may have a significant 'tail' into the region, and, whereas this effect does not show up in normal u.v. spectroscopy where the sensitivity is rarely better than 20 000 dB/km, the effect can be significant when considering a path length of 1 km or more. Molecular vibrations in the i.r. have overtones of decreasing intensity at submultiples of the main band. The strong C–H vibration at approximately 3·5 μm is particularly troublesome, eliminating many otherwise suitable liquids, such as methyl salicylate, which we have found to have strong overtones throughout the region of interest, although the peak values of 1000 dB/km would not be expected to show on an infrared spectrometer.

In addition, the liquid should have low optical scatter, low toxicity and should be stable and nonvolatile, with low viscosity to assist in fibre filling.

A fully halogen-substituted aliphatic liquid satisfies the above requirements, having no C–H bonding and thus avoiding the 3·5 μm i.r. vibration. The liquid should preferably contain no ethylenic linkages with the associated close u.v. absorption band. We have chosen hexachlorobuta-1,3-diene, which has the following properties:

$$n_d = 1{\cdot}5563$$

$$\text{melting point} = -19^\circ\text{C}$$

$$\text{boiling point} = 212^\circ\text{C}$$

In fact, this liquid has two ethylenic linkages which are conjugated, giving rise to a u.v. spectrum shifted to longer wavelengths and hence nearer the region of interest than would otherwise be the case. The tail of the absorption band dominates the fibre attenuation at wavelengths below 0·6 μm.

The liquid was of normal commercial spectroscopic quality,[*] and was used directly from the bottle. The fibres have been filled under a hydrostatic pressure of up to 1400 atmospheres and lengths of 200 m can be filled in a few hours.

Measuring technique: The fibre attenuation was measured using a stabilised quartz/iodine lamp and chopper disc in conjunction with a *p–i–n* photodiode and a phase-sensitive detector. The fibre was wound on an 11 cm-diameter drum and the input end was held in a suitable mount.[6] The input beam, after passing through a wavelength-selecting monochromator, was launched into the fibre via a microscope with a × 5 objective, corresponding to an input-beam semiangle of 6·9°. Visual observation ensured that the light entered the core centrally. The output end of the fibre was placed perpendicularly on a known spot on the horizontal detector surface in a drop of core liquid. For each measurement, the fibre end was removed and replaced on the detector surface three or four times and recordings made only when successive readings of the output voltage agreed to within 1%. After noting the output at the appropriate wavelengths, the fibre was shortened by a known amount, usually about 200 m, and further readings taken. The estimated accuracy of loss

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[†] MATSUMURA, H. (Private communication)

[*] Supplied by British Drug Houses Ltd.

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measurement is within ± 0·5 dB.

Results: The results of the attenuation measurements, given in Fig. 1, show that the loss in the fibre is below 20 dB/km over the rather wide wavelength range 0·8–1·13 µm. The low values of attenuation are repeatable and have been obtained with core diameters ranging from 42 to 75 µm. It is too early to draw any firm conclusions, but preliminary indications are that high quality and uniformity of the internal fibre surface are necessary if the transmission loss is to be low. In the region 0·8–1·1 µm, the loss varies relatively slowly with wavelength. Stone[3] observed a peak of about 85 dB/km at 0·96 µm, which he attributes to the presence of water vapour; our results indicate only a slight rise in attenuation at this wavelength, with a 'peak' of between 12 and 15 dB/km, depending on the fibre, and hence semiconductor lasers and gallium-arsenide lamps can be used satisfactorily with these fibres. At the wavelength of the helium–neon laser, 0·633 µm, the attenuation is 75 dB/km, although values as low as 50 dB/km have been measured.

We are in the process of measuring the scattering and light distribution in the fibres, but an upper estimate of the former may be obtained by assuming that the entire loss at, say, 0·633 µm is due to scattering and has a Rayleigh dependence. Applying the λ^{-4} law, the upper limit of scattering loss at 1 µm is found to be 8 dB/km.

Conclusions: In conclusion, our fibre waveguide has a lower loss over a wider wavelength range than any previously reported. In particular, the peak previously observed[3] covering the region 0·86–1·00 µm is almost absent. The tube material is considerably cheaper than quartz, and may be drawn with high precision at a much lower temperature. In fact, this is the first low-loss fibre of any configuration to be made using glass. The lowest losses so far reported in liquid-filled glass fibres are 130 dB/km[7] for tetrachloroethylene in Pyrex, and 140 dB/km[8] for bromobenzene in flint-glass tubing.

The importance of liquid-core fibres lies in showing that low attenuations can be achieved, in enabling the development engineer to gain experience in using low-loss fibres and in measuring such parameters as bandwidth over practical lengths of 1 km or so. Our fibres are easily handled, and can be rewound quite simply from the winding drum of the fibre-drawing machine onto other drums for filling, handling, assessment etc. A solid core would be more convenient for practical application in avoiding problems of evaporation, effects of temperature changes and the necessity for having small liquid reservoirs at the fibre terminations. The long-term stability of the liquid has also to be determined. For example, hexachlorobuta-1,3-diene comes from a family of organic chemicals which tend to polymerise, and we have observed this effect, with the resulting rise in attenuation due to a shift in the ultraviolet band edge, when the fibres are irradiated with u.v. radiation. An outer covering of black glass can prevent this happening, but other long-term effects may arise.

Another important consequence of these fibres lies in showing that the effect of cladding attenuation on the fibre loss is small. We have not measured accurately the bulk attenuation of ME1, but it is not less than 10^4 dB/km. The effect of the cladding has been estimated,[*] using a modal analysis,[9] by calculating the loss of each of the modes excited by the 6·9° launching beam and integrating over all modes. Using a value for the bulk cladding loss of 10^4 dB/km, the contribution of the cladding to the fibre loss is found to be 3·3 dB/km. This is not inconsistent with the upper estimate for the scattering loss of 8 dB/km. Thus, in multimode fibres, the prime need is to reduce the core loss and prevent interdiffusion at the core/cladding interface.

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D. N. PAYNE
W. A. GAMBLING

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Department of Electronics
University of Southampton
Southampton SO9 5NH, England

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[*] ROBERTS, R. (Private communication)