SOME EXPERIMENTAL ASPECTS OF PROPAGATION IN OPTICAL FIBRES

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If a microwave engineer were asked to predict the performance of an overmoded waveguide some 100 wavelengths in diameter, 10^{10} wavelengths long (60cm x 60,000km at 50GHz) and made by straightforward techniques then he would expect the attenuation to be high and the bandwidth poor. However cladded glass fibres of comparable dimensions are eminently suitable for practical application. The object of this paper is to discuss the various kinds of structure available and the experimental results which have been achieved.

The simplest form of optical fibre is straight, has a lossless, cylindrical core of uniform refractive index and is surrounded by a lossless cladding. Both core and cladding are uniform and homogeneous. In this simplified structure both the transmission loss and mode conversion are zero and the energy distribution over any cross-section as well as the pulse dispersion, and hence the bandwidth, can be predicted unambiguously if the launching conditions are known. If, in addition, launching from a Gaussian beam is assumed than a simple ray analysis[1] is sufficient to predict the near- and far-field intensity patterns as well as the output pulse shape for a given input pulse.

The nearest approach that has yet been achieved to an idealized fibre of this type is that comprising a liquid-core in a silica[2] or glass[3] capillary. The core is homogeneous and can be made accurately circular and uniform over lengths of hundreds of metres. Due to Rayleigh scattering in the core and losses in both core and cladding the attenuation is not zero,although a minimum of 5dB/km has been obtained[4], but mode conversion effects are virtually absent when care is taken to remove all sources of external stress. Thus single-mode propagation over appreciable lengths has been reported[5]. On the other hand when distortion of the fibre is introduced by transverse pressure or by winding tightly on a drum a certain amount of mode conversion occurs. To some extent this can be counteracted by a mode reduction process whereby a lossy cladding can be used to attenuate preferentially the higher-order modes. Propagation is then a balance between the two competing processes of mode conversion and mode filtering. Even so the ray propagation model can be used with success, at least in fibres which are not fully excited, and excellent agreement can be obtained between theory and experiment also in the presence of a high cladding loss[6].

In solid-core fibres there may be additional mode conversion even in a fibre to which no external stress is applied. In a fibre which is not fully excited the simplest method of observing mode conversion is to compare the far field angular

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distribution of intensity at the output with that at the input. It is seen that the power initially concentrated in the lower modes diffuses outward to higher-order modes as it propagates down the fibre. The pulse dispersion per unit length increases with fibre length since it is dependent on the number of modes excited. Eventually, at a distance dependent on the degree of mode conversion,an equilibrium power distribution amongst the modes is reached after which the pulse dispersion attains a half power dependence on fibre length. In the presence of mode conversion the response of a fibre to a short input pulse changes from that exhibiting a steeply rising leading edge to a more symmetrical distribution.

While it is sometimes straightforward to obtain a qualitative indication of mode conversion effects,quantitative results are more difficult to obtain. However a technique for use with stepped-index fibres has been developed whereby a numerical value for the mode conversion coefficient is derived from an observation of the angle of incidence of a collimated input beam at which the far-field output pattern changes from a solid circle to a ring. Values of the coefficients D, for various solid-core and liquid-core fibres under different degrees of stress are given in Table 1. The method is based on an analysis derived from the power flow equation of Gloge[7] which assumes that coupling occurs only to adjacent modes. The same assumption is made in several analyses and the above experiment provides a comforting confirmation of this result. The theory of propagation in a curved fibre due to Matsumura, as well as its experimental verification, leads to the same conclusion[8].

In a stepped-index multimode fibre the major factor leading to pulse dispersion is group delay dispersion due to the differing group velocities of the various modes. A number of suggestions have been made for circumventing this difficulty. The first is to eliminate all but a few modes by either partially exciting a multimode fibre or, more easily, by the use of a fibre with single-or nearly-single-mode properties. Some of the difficulties in this latter approach lie in the attendant launching and jointing problems although low-loss single-mode fibres can be made. Another possibility[9] is to introduce a controlled power exchange between the propagating modes but in any practical fibre the danger of coupling to radiation modes, with a consequent energy loss, is obvious. A third, and relatively successful, method is to equalize as far as possible the group velocities of the modes.

The first attempt to do this resulted in the Selfoc fibre[10] which has a parabolic radial variation of refractive index. The group velocities of paraxial rays are certainly equalized but those for skew rays are not, so that while the pulse dispersion is very low under axial launching conditions it is still dominated by the spread in group delays if the launching conditions are not optimum. More recently Gloge and Marcatili[11] have suggested that under conditions where all propagating modes are equally excited a somewhat different profile is preferable, giving a minimum dispersion of $Ln_0\Delta^2/8c$

where L is the fibre length, n_o the axial refractive index and Δ is the relative refractive index between axis and cladding. The precision required in the index profile to achieve this result is probably unattainable in practice. For example if $\Delta = 2\%$ and $n_o = 1.5$ the minimum broadening is ¼ns/km but is doubled by an index deviation of only 10^{-4}. Nevertheless considerable reductions in dispersion are possible even with non-optimum profiles and values below 1ns/km have been obtained. This is probably due to the fact that in practice all modes are not equally excited, and power is concentrated in the lower-order modes which are more effectively equalized. The commonly observed preferential attenuation of higher-order modes results in a similar power concentration[6].

An additional factor which may cause calculations of pulse dispersion to be pessimistic is the presence of mode conversion. In practice it has been shown[12] that a root length dependence of pulse broadening occurs after a length of the order of one kilometre.

At least in theory it would seem that multimode graded-index fibres are capable of transmitting information in excess of 1GBit/km. This may appear to be an optimistic estimate for the capabilities of real waveguides in view of the difficulty of obtaining the correct profile. However it has already been shown that experimental fibres often perform better than theoretical considerations would indicate. This is because there are several factors not normally included in the theory, and all of these tend to reduce the pulse dispersion. Differential mode attenuation, launching conditions which preferentially excite lower-order modes, and mode mixing each improve fibre bandwidths to a varying degree, although often at the expense of attenuation. These factors may be deliberately introduced for applications requiring maximum fibre capacity, provided the trade-off between bandwidth and attenuation is acceptable.

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TABLE 1

Mode Coupling Coefficients, D, for Optical Fibres

Sample	Origin	Type		Core dia (μm)	N.A.	D (rad^2/m)
1	Southampton U	Liquid-core	Increasing stress ↓	100	0.47	$3.0x10^{-6}$
2	"	"		"	"	$7.0x10^{-6}$
3	"	"		"	"	$2.5x10^{-5}$
4	"	"		"	"	$4.1x10^{-5}$
5	Sheffield U	Lead glass core Borosilicate cladding		87.5	0.63	$4.0x10^{-4}$
6	Sample 5 after heat treatment			"	"	$7.4x10^{-4}$
7	Southampton U	F7 core ME1 cladding		56	0.65	$4.1x10^{-4}$
8	Pilkington Glass Works	Not known		77.5	0.54	$3.0x10^{-4}$