ZERO-MODE DISPERSION IN SINGLE-MODE FIBRES

Indexing terms: Optical dispersion, Optical fibres

Near cutoff the loss of the LP_{11}-mode in cladded optical fibres becomes very high in the presence of even slight bends. Single-mode operation can thus be achieved with zero-mode dispersion as well as zero material dispersion, thus promising enormously large bandwidths.

Introduction: The bandwidth of optical-fibre transmission lines is ultimately limited by waveguide dispersion and material dispersion. It is possible to operate at a wavelength ($\approx 1\cdot3\ \mu m$) where the material dispersion coefficient is zero[1] and the attenuation is low.[2] Waveguide dispersion then predominates and multimode effects can be removed by using single-mode fibres. The remaining dispersion arises from the variation in group velocity v_g with wavelength λ of the HE_{11}-mode. Unfortunately $dv_g/d\lambda$ is always finite in the true single-mode regime ($V < 2\cdot4$) but falls to zero at a normalised frequency $V \approx 2\cdot9$ where the LP_{11}-mode propagates. If the LP_{11}-mode can be removed, and if mode conversion from the HE_{11}-mode can be prevented or reduced to a tolerable level, then a fibre of $V \approx 2\cdot9$ will operate at $\lambda \approx 1\cdot3\ \mu m$ as a quasi-single-mode fibre of zero mode and material dispersions and hence of enormous bandwidth.

Propagation of the LP_{11}-mode: We have observed that the loss of the LP_{11}-mode at frequencies above cutoff is very sensitive to applied pressure and slight bends. Thus fibres operating at $V = 2\cdot8$ have far-field radiation pattern indistinguishable from that of a single-mode fibre even over lengths as short as 1 m. Over longer lengths, similar fibres may therefore exhibit single-mode behaviour at even higher frequencies.

Consider a step-index single-mode fibre having a radius of curvature $R(z)$ that varies along its length. The loss due to curvature is given[3] by

$$\alpha = \int_0^L A\{|R(z)|\}^{-1/2} \exp\{-B|R(z)|\} dz \tag{1}$$

where

$$A = (\pi/W^3 a)^{1/2}\, U^2/\{V^2 K_0(W) K^2(W)\}$$
$$B = (\tfrac{2}{3})(W^3/V^2 a)\{1 - (n_2/n_1)^2\} \tag{2}$$

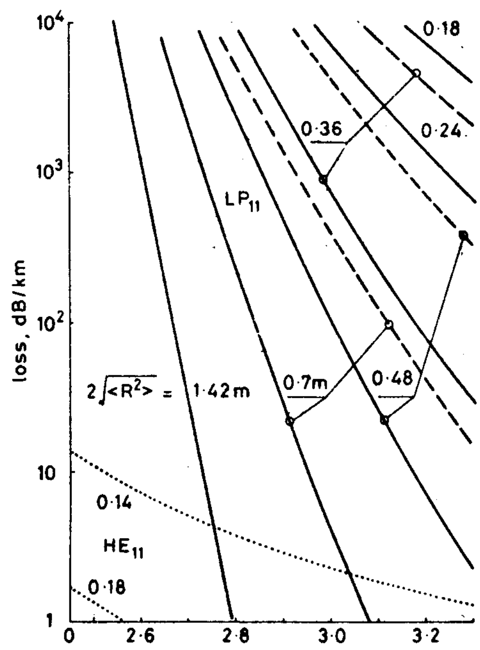

Fig. 1 *Loss of the LP_{11}-mode due to random bending as a function of V for various r.m.s. deviations of the bend radius at numerical apertures of 0·1 (solid curves) and 0·08 (dashed curves) with λ = 1 μm. Dotted lines show the corresponding loss of the HE_{11}-mode*

and the symbols have their usual meanings. Assume that the probability of a random bend of radius R occurring is given by

$$P(1/R) = (\tfrac{1}{2}\bar{\delta}) \exp(-|1/R|/\bar{\delta}) \tag{3}$$

where $\bar{\delta}\sqrt{2}$ is the r.m.s. deviation of $1/R$. The mean value of α is then

$$\langle\alpha\rangle/L = (\pi B)^{1/2} A\{1 + (\bar{\delta}/B)^{1/2}/2\} \exp\{-2(B/\bar{\delta})^{1/2}\} \tag{4}$$

Fig. 1 shows that $\langle\alpha\rangle$ depends strongly on V and $\bar{\delta}$. It is difficult to estimate $\sqrt{(2)}/\bar{\delta}$ for a practical situation, but taking a value of 40 cm, which may not be untypical, the loss of the HE_{11}-mode is negligible and the fibre therefore behaves effectively as a single-mode fibre even at $V = 3$. If the n.a. is decreased then the loss rapidly increases still further, as indicated by the dashed curves for n.a. = 0·08, and effective single-mode operation is obtained at even higher V values.

For a single-mode fibre in which the microbending loss of the HE_{11}-mode is reduced to a low level by selecting n.a. = 0·1 and at a wavelength where the material dispersion parameter[1] is zero, say 1·3 μm, the core diameter is 13 μm at $V = 3$ and this simplifies launching, splicing and coupling problems considerably.

As indicated above, either natural or induced random bending could cause an undesirable loss to the HE_{11}-mode by mode conversion to the LP_{11}-mode. However, the effect is small because the two propagation constants are sufficiently different to prevent appreciable coupling (see below). Such

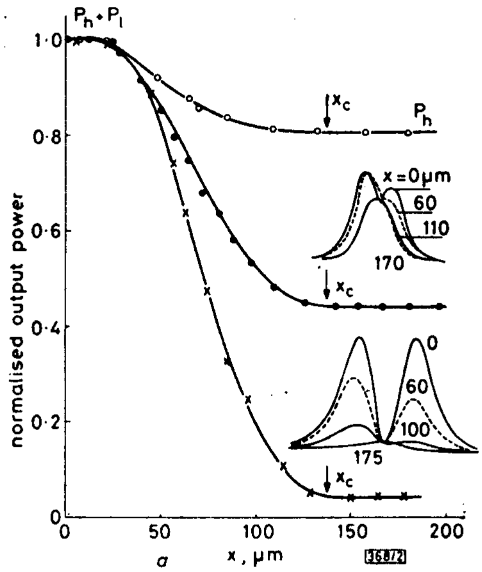

Fig. 2a *Normalised output power as a function of the amplitude x of deformation for V = 2·76, n.a. = 0·12 and f = 15 mm for three different positions of the input Gaussian beam*

The power is constant for $x > x_c$ in each case. The insets show typical intensity distributions for the values of x shown on the curves for two of the launching conditions

coupling would not affect the bandwidth but only α. Thus a curvature of 3·2 (1·6) cm at $V = 3$, n.a. = 0·1 produces an LP_{11}-mode loss of 3 (50) dB/cm while hardly affecting the fundamental mode.

Experiment: A fibre of $V = 2\cdot76$, n.a. = 0·12 and length 300 m was wound on a drum of 30 cm radius. When excited with a Gaussian beam of wavelength 0·633 μm the output far-field and near-field patterns were indistinguishable from those of the HE_{11}-mode at all lengths down to 2·5 m. Thus, due to the high LP_{11}-mode loss, a fibre of $V = 2\cdot76$ behaves effectively as a single-mode fibre.

A more quantitative result was obtained by introducing modulations into the fibre (see inset to Fig. 2*b*) of pitch $2f$ and depth $2x$. Fig. 2*a* shows the normalised output power measured as a function of x for three different excitation conditions. In each case the relative powers in the HE_{11} and the higher-order modes, P_h/P_l, at $x = 0$ is not known. As x is increased the output power falls, but after a critical depth $x_c \approx 140\ \mu m$ there is no further decrease up to the breaking point of the fibre. Since x_c is independent of the launching condition, i.e. of the initial power levels in the modes, this result clearly indicates that between $x = 0$ and $x = x_c$ the higher-order modes are suffering a power loss and at $x > x_c$ only the HE_{11}-mode remains. The constant level for $x > x_c$ thus denotes the fundamental mode power P_h as verified by the near-field patterns shown alongside the corresponding power curves. For $x = 0$ both modes are present, but P_l falls with increasing x whereas P_h remains constant (as indicated by the constant level of the central peak and the falling level of the side peaks). Hence the loss of the LP_{11}-mode is very sensitive to bending whereas the HE_{11}-mode is unaffected. The loss coefficient α_l of the LP_{11}-mode can be obtained directly from these curves by subtracting the constant value and is almost independent of the launching conditions (i.e. of the transverse offset and angular misalignment of the input beam).

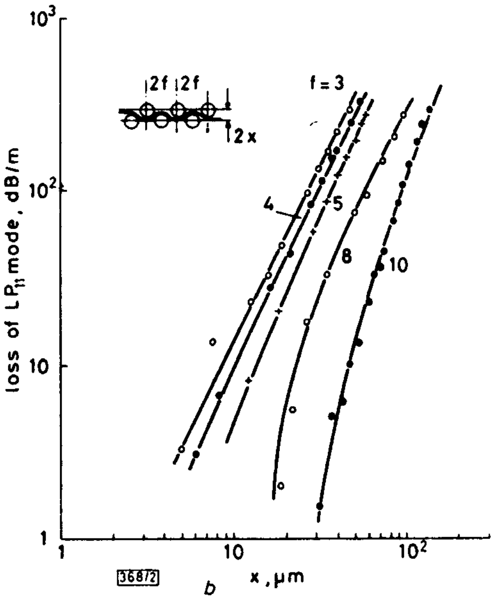

Fig. 2b Variation of attenuation coefficient of the LP_{11}-mode with fibre deformation amplitude for various deformation periods, as shown by inset

The measured LP_{11} loss (Fig. 2*b*) increases very rapidly with x, and for small f is given by

$$\alpha_l = 1{\cdot}6 \times 10^6 (x/f)^2\ \text{dB/m} \qquad (5)$$

Because the LP_{11}-mode intensity is zero at the core axis, the constant intensity at the centre of the near-field pattern shows that the HE_{11}-mode, which has a maximum at the axis, does not lose any appreciable power with increasing x. This fact has already been used to produce the curves of Fig. 2*b* but it also shows, further, that there is no observable mode conversion from the HE_{11} to higher modes.

Conclusions: The loss of the LP_{11}-mode near cutoff is considerably increased by slight bends. In any practical cable installation some bending is inevitable, or could be introduced artifically, for example by the helical lay in normal cable manufacture. Operation is thus possible at $V \approx 2{\cdot}9$ where the mode dispersion $dv_g/d\lambda$ is zero, as well as at a wavelength, for example with fibres having a phosphosilicate core and a silica cladding, where the material dispersion parameter is also zero. In this way the already considerable bandwidth potential of single-mode fibres can be greatly increased. The limitation is then imposed by higher-order effects and other, practical, factors such as ellipticity of the core, although preliminary indications are[4] that an ellipticity as high as 10% causes a pulse dispersion of only 5×10^{-13} s/km. A further advantage is that the permissible core size is also increased and diameters of perhaps up to 15 μm can be contemplated. We therefore propose this technique as a method of achieving fibre bandwidths considerably greater than any yet contemplated.

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31st July 1978

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