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Zero total dispersion in graded-index single-mode fibres — Source link

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ZERO TOTAL DISPERSION IN GRADED-INDEX SINGLE-MODE FIBRES

Indexing terms: Optical dispersion, Optical fibres

The combined effects of composite material dispersion, profile and waveguide dispersion can be made zero at a wavelength which depends on core diameter, refractive-index profile and composition. Wide bandwidths over large repeater spacings are therefore possible although close fabrication tolerances may be required.

Introduction: The primary causes of pulse dispersion in single-mode fibres are

(*a*) material dispersion due to the wavelength (λ) dependence of the refractive index n

(*b*) waveguide dispersion due to the variation of group velocity with wavelength

(*c*) profile dispersion $d\Delta/d\lambda$ due to the variation with wavelength of the relative refractive-index difference Δ between core and cladding.

We have previously indicated that the sum of these three components can be made equal to zero[1] and we show here how the wavelength of zero total dispersion can be changed in fibres of any arbitrary α-profile. The conditions under which this technique can be applied are also discussed.

In the past the material dispersion of a fibre has been calculated only in terms of a plane wave propagating with phase constant $\beta = n_1 k$ in the bulk material n_1 of the core. This approximation is acceptable for modes of a multimode fibre far from cutoff, but in single-mode fibres, as well as for modes in a multimode fibre near cutoff, the dispersive properties of both core and cladding must be considered.[2] We have therefore introduced a new parameter called composite material dispersion (c.m.d) which accounts for the combined dispersive effects of both the core and the cladding as well as waveguide effects. Previous calculations have assumed that the profile dispersion is negligible, but we have shown[2] that it cannot be neglected. Thus we define a composite profile dispersion parameter (c.p.d.) which includes core, cladding and waveguide properties. Thirdly, our waveguide dispersion (w.d.) term embraces material dispersion terms as well as the usual waveguide dispersion terms.[3]

Another factor which must be considered is the radial (r) variation of the refractive index.[4] Most studies of single-mode fibres have assumed a stepped refractive-index distribution, but in practice some degree of grading is inevitable. The refractive index is therefore assumed to be of the form

$$n^2(r) = n_1^2\{1 - 2\Delta'(r/a)^\alpha\} \qquad 0 \le r \le a$$
$$= n_1^2(1 - 2\Delta') = n_2^2 \qquad r > a \qquad (1)$$

where

$$\Delta' = (n_1^2 - n_2^2)/2n_1^2 \qquad (2)$$

Propagation of the HE_{11}-mode: The normalised propagation constant β/k of the HE_{11} mode and its relation to both the field intensity and field amplitude in a single-mode fibre has been considered in detail[2] and may be expressed as

$$\beta/k = \{n_2^2 + b(n_1^2 - n_2^2)\}^{1/2}$$

where[5]

$$b = 1 - (U/V)^2$$

$U = U(V, \alpha)$ is obtained by solving the characteristic equation.[4]

As expected, $n_2 k < \beta < n_1 k$, and at short wavelengths (large V), $\beta/k \simeq n_1$. However, in the single-mode region, the variation of β/k is not so obvious. For example, at cutoff of the LP_{11} mode ($V_c = 2{\cdot}4$ for $\alpha = \infty$), more than 80% of the total power is carried in the core. It might therefore be expected that β/k would be close to n_1, but in fact it is nearer n_2, and only reaches the midway value $\beta/k = (n_1 + n_2)/2$ when $V > V_c$ at any profile. This is because β depends[2] linearly on the ratio of the integrated fields in the core and cladding, and not on the power ratio. Therefore, even near cutoff, when the bulk of the power is carried in the core, the cladding has an effect on the propagation constant which is equal to that of the core. It is therefore essential to include the cladding properties in any calculation of the dispersive properties of a single-mode fibre.

Pulse dispersion: The pulse dispersion arising from an optical source of spectral width $\delta\lambda$ is

$$T = \frac{2\pi}{c\lambda^2}\frac{d^2\beta}{dk^2}\delta\lambda$$

where $c = 3 \times 10^8\ \mathrm{ms^{-1}}$. By considering the dispersive properties of both the core and cladding this equation can be written[2] as

$$T = \delta\lambda(T_{cmd} + T_{wd} + T_{cpd})$$

where

$$T_{cmd} = \frac{\lambda}{c}\left[A(V)\frac{d^2 n_1}{d\lambda^2} + \{1 - A(V)\}\frac{d^2 n_2}{d\lambda^2}\right]$$

$$T_{wd} = \frac{n_2\,\Delta}{c\lambda}B(n)V\frac{d^2(bV)}{dV^2}$$

$$T_{cpd} = -\frac{n_2}{c}C(n)D(V)\frac{d\Delta}{d\lambda}$$

$$A(V) = \frac{1}{2}\left\{\frac{d(bV)}{dV} + b\right\}$$

$$B(n) = \left[1 - \frac{\lambda}{n_2}\frac{dn_2}{d\lambda}\right]^2$$

$$C(n) = 1 - \frac{\lambda}{n_2}\frac{dn_2}{d\lambda} - \frac{\lambda}{4\Delta}\frac{d\Delta}{d\lambda}$$

$$D(V) = V\frac{d^2(bV)}{dV^2} + \frac{d(bV)}{dV} - b$$

and

$$\Delta = \Delta'(n_1^2/n_2^2)$$

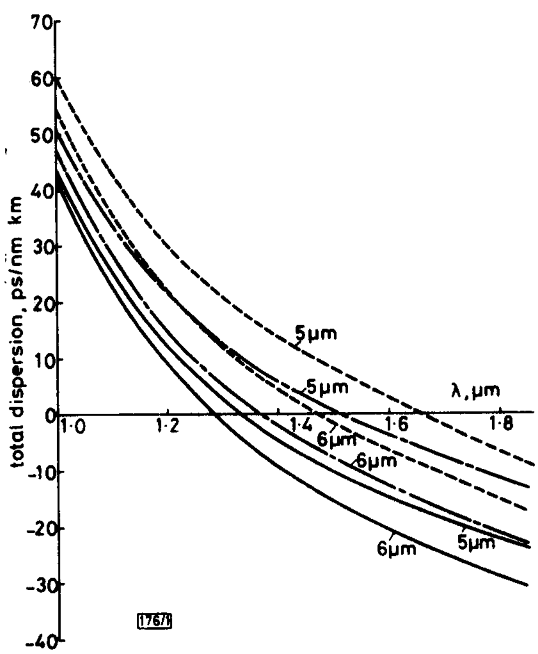

Fig. 1 *Total dispersion for the core diameter shown on the curves*
For profiles
$\alpha = \infty$ (———) $\alpha = 2$ (- - - -)
$\alpha = 4$ (-·-·-·-)

The total dispersion T is shown in Fig. 1 for several profiles and two core diameters, in a fibre having a core with 11·1 moles % concentration of GeO_2 in SiO_2 and a cladding of pure SiO_2. It is seen that the total dispersion falls to zero at a wavelength which depends on the profile and the core diameter. The wavelength of zero total dispersion can be tuned by altering these parameters or, of course, the numerical aperture. An attenuation of 0·2 dB/km has been reported[6] at $\lambda = 1{\cdot}55$ μm, and if zero dispersion could be simultaneously achieved then repeater separations of several hundred kilometres at appreciable bandwidths should, in principle, be possible. The bandwidth would then obviously be limited by other, higher-order, effects such as core ellipticity, birefringence, etc.

Fig. 2 indicates the wavelength λ_0 at which $T = 0$ as the core diameter is changed for $\alpha = 2, 4, \infty$. Thus λ_0 can be varied, for this fibre composition, from about 1·27 μm to more than 1·6 μm and lies at 1·55 μm for core diameters in the range 4–5·6 μm depending on the profile.

It is interesting to note that for a given dopant level in a fibre there is both a maximum and a minimum wavelength at which zero total dispersion can be achieved.[2] The maximum λ_0 occurs at a normalised frequency $V_0 \simeq 1{\cdot}2$ where the $Vd^2(bV)/dV^2$ curve, and hence the waveguide dispersion, has a maximum.[3] Thus at smaller V (long wavelengths) the increasingly negative material dispersion cannot be balanced out by the positive waveguide dispersion which begins to decrease again below V_0. For fibres with $\alpha > 2$, a similar effect occurs at short wavelengths, i.e. the waveguide dispersion is a minimum at $V_0 \simeq 6$ and there is another turning point, this time a minimum value of λ_0. However for $\alpha \leq 2$ no such minimum occurs[7] and the minimum wavelength for zero total dispersion is asymptotic to a value given approximately by the wavelength needed for zero material dispersion of the core material.

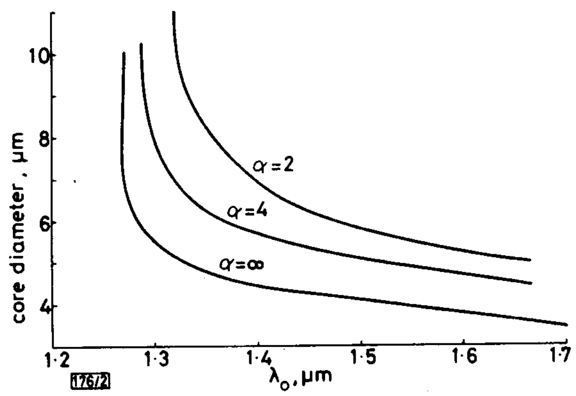

Fig. 2 *Core diameter required to give $T = 0$ for the α profiles shown*

Conclusions: In a single-mode fibre the effects of both core and cladding must be taken into account, and the complete expression for pulse dispersion is complex. However, it can be expressed in the form of three components, namely composite material dispersion, composite profile dispersion and waveguide dispersion, each of which contains crossproduct terms. Profile dispersion has a significant effect on the wavelength of zero total dispersion and cannot be neglected.

The total dispersion, as defined by the sum of the three component terms, is strongly dependent on the refractive-index profile, for a given numerical aperture. The wavelength of zero total dispersion can be varied over a wide range by suitable choice of core diameter or index profile, but there are well defined limits to this range. Unfortunately, in the true single-mode region and at the important wavelength of 1·55 μm, strict control of the core diameter is required if λ_0 is to be kept constant. As an illustration of the degree of constancy required, Fig. 2 shows that, for $\alpha = \infty$, if the core diameter fluctuates by as little as ± 2 μm, then λ_0 can vary between 1·48 and 1·6 μm. Operation in the quasisingle-mode region where higher-order modes are easily suppressed is much less restrictive.

If the combined dispersion of the three components considered here can be made zero then obviously limitations will be imposed by other mechanisms. Nevertheless, bandwidths considerably larger than any yet contemplated over more than 100 km will be possible, especially at wavelengths of 1·3 μm and 1·55 μm. Further, by operating above cutoff, larger core diameters can be tolerated[8] and diameter control is less critical.

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