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Zero Dispersion Optical Fibres for High Data Rate Systems

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Abstract. The different dispersion parameters that contribute to the pulse spreading in a single mode fibre are discussed with particular reference to the possibility of reducing the total dispersion to zero and increasing the bandwidth and repeater spacing.

1. Introduction

The intrinsic loss and dispersion of the optical fibre are two main factors, which limit the bandwidth of the fibre and determine the upper limit of data rate and repeater spacing. During the last decade considerable progress has been made in reducing the transmission loss of the fibre. It has been shown that the lower limit of fibre attenuation is restricted by Rayleigh Scattering at shorter wavelengths and by vibrational absorption at longer wavelengths and that the minimum[1] loss can be expected to be 0.2 dB/km at 1.6 μm. Using GeO_2 doped silica core and SiO_2 cladding, low loss fibres, approaching the lower limit of minimum loss, have been prepared by the chemical vapour deposition technique and a loss figure of 0.2 dB/km at 1.55 μm has been attained[2] for single mode fibres. Long lengths ($\sim$10 km) of low loss fibre have also been made with the chemical vapour deposition technique by using $P_2O_5 - GeO_2 - SiO_2$ core and B_2O_3/P_2O_5 doped silica cladding and minimum losses of 0.6 to 0.7 dB/km have been achieved[3] in the wavelength range of 1.1 to 1.7 μm. However, merely minimising the loss is not enough. To realise the full capacity of the optical fibre the total dispersion at the wavelength of operation has also to be minimised. Simultaneous minimisation of loss and dispersion at the transmission wavelength can lead to a very large figure of merit (10-20 Gbps km) giving a repeater spacing of 100-200 km at 100 Mbps or a data rate of $\sim$1Gbps at 10-20 km. The other factors that limit the figure of merit at the wavelength of minimum loss and zero total dispersion is the loss due to microbending and ellipticity of core[6] and the loss due to defect centres in the guide caused by the nuclear radiation[7]. Microbending losses arise due to the physical positioning of fibre i.e. cabling and wrapping on drums etc. This causes coupling of guided modes among themselves and to the radiation modes and is calculable. The nuclear radiation acts as the ionizing radiation and causes defect centres. This loss is wavelength dependent—it decreases from 0.8 to 1 μm and increases from 1 to 1.7 μm. These external factors, however, depend upon the environment in which the fibre is used and can therefore be reduced by taking proper precautions in the use of the fibre.

2. Pulse Dispersion

The pulse spreading in time, of the propagating optical pulse in the fibre, arises due to the group delay caused by the group velocity difference between the various modes and the wavelength dependence of group velocity for a given mode. For multimode operation, where diameter and numerical aperture are sufficiently large to allow a large number of modes to be launched and propagated, the different modes propagate along the fibre with different path lengths. This path difference causes a delay spread which can be estimated by ray tracing. This kind of intermodal dispersion is most significant for multimode fibres and is the limiting factor for determining the bandwidth capability of the fibre. Typical values of $\sim$ 50 ns/km are obtained for an index difference of 1% between the core and cladding for a step index fibre. Efforts to reduce this dispersion have resulted in the fabrication of graded index fibres in which the core index n_1 is varied along the radius r in the manner

$$n(r) = n_1(1 - \Delta (r/a)^{\alpha})$$

where $2a$ = core dia. and $\Delta = (n_1^2 - n_2^2)/2n_1^2$

$$\approx \frac{n_1 - n_2}{n_1} << 1 \tag{1}$$

It has been shown that the optimum value of profile gradient $\alpha = (2 - 2\Delta)$ which is nearly parabolic. The effect of this index gradient is to reduce the delay spread by making the modal velocities nearly equalised. This near equalisation of modal velocities also helps in reducing the differential modal loss. Due to this, the graded index modal dispersion is reduced by the factor Δ compared to step index so that for $\Delta = 1$ percent, the modal dispersion of optimally graded index fibre is nearly two orders of magnitude less than that for step index fibre. In the single mode fibre, only the lowest order mode propagate so that the intermodal dispersion is avoided. In this fibre, the diameter is sufficiently small so that at a given wavelength λ, the modal V number, given by

$$V = ak(n_1^2 - n_2^2)^{1/2} = (2\pi\, a/\lambda)\ (\text{N.A.}) \tag{2}$$

is $\leqslant Vc$. Vc defines the cut off regime and $V > Vc$ leads to multimode operation. The value of Vc depends on the profile[8] gradient α and for HE_{11} mode, $Vc = 3.5$ for $\alpha = 2$ (parabolic) and $Vc = 2.4$ for $\alpha = \infty$ (step index). In the case of $V < Vc$ the optical field is not confined to the core alone but it penetrates the cladding as well. While estimating the extent of dispersion in this case, the effect of cladding on propagation parameters has also to be considered. Further, the intermodal velocity difference is not present but there is an intramodal effect caused by the wavelength dependence of group velocity which leads to the three types of dispersion[9].

(i) *Material dispersion*

This arises due to the variation of refractive index with λ and is inherent in the material out of which the fibre is made. This, however, is easily calculable if the refractive index of the fibre core and cladding and also the linewidth of the source are given. For a relatively large diameter fibre (i.e. $V > Vc$ when the wave is strongly guided within the core), $d/d\lambda$ of the cladding index can be ignored so that $dn_1/d\lambda$ of the core is the only important term for the estimation of group delay due to material dispersion. For small dia. fibres (i.e. $V < Vc$ weekly guided waves in the single mode regime) the fields penetrate the cladding and therefore it is desirable to consider both $dn_1/d\lambda$ and $dn_2/d\lambda$.

(ii) *Waveguide dispersion*

This type of dispersion results due to the very structure of the waveguide for the reason that in the single mode regime it is both core and cladding which partake in the propagating of the wave. The effect of the core and cladding on the propagating mode is considered by the index difference Δ. This is important when $\Delta << 1$ and the energy is propagated as a weakly guided mode in the fibre. This dispersion arises due to the wavelength dependence of the group velocity of this weakly guided propagating mode.

(iii) *Profile dispersion*

This dispersion results from terms like $d\Delta/d\lambda$ where the index difference is dependent on wavelength. In many cases it is considered as a part of the waveguide dispersion but in situation like graded index fibres where core index assumes a certain profile, it is best to view it separately particularly when the profile gradient is far from the optimum. For a single mode fibre, the total group delay[10] is given by

$$\tau = \frac{L}{C}\frac{d\beta}{dk} \tag{3}$$

where

$$\beta = n_2 k(1 + b\Delta), \quad [b = (\beta/k - n_2)/(n_1 - n_2)]$$

L = Length of fibre

C = Velocity of light in vacua

$k = 2\pi/\lambda_0$, (λ_0 = wavelength in free space)

The dispersion D due to the dependence of group velocity on wavelength, is given by

$$D = \frac{d\tau}{d\lambda}$$

$$= \frac{2\pi L}{C\lambda^2}\frac{d^2\beta}{dk^2} \tag{4}$$

Combining Eqns. (2), (3) and (4) it can be shown that due to a source having linewidth $\delta\lambda$,

$$D = \frac{L}{C}\Big[\lambda\Big\{b\frac{d^2n_1}{d\lambda^2} - (1+b)\frac{d^2n_2}{d\lambda^2}\Big\} + \frac{n_2\Delta}{\lambda}V\frac{d^2(bv)}{dv^2}$$

$$+ 2\Delta\left(b - \frac{d(bv)}{dv}\right)\frac{dn_2}{d\lambda} + 2n_2\left(b - \frac{d(bv)}{dv}\right)\frac{d\Delta}{d\lambda}\Big]\delta\lambda \qquad (5)$$

$$= \frac{L\delta\lambda}{C}[X + Y + Z]$$

where

$$X = \lambda\left\{b\frac{d^2n_1}{d\lambda^2} - (1+b)\frac{d^2n_2}{d\lambda^2}\right\} \quad \text{material dispersion}$$

$$Y = \Delta\left\{\frac{n_2}{\lambda}V\frac{d^2(bv)}{dv^2} + 2\left(b - \frac{d(bv)}{dv}\right)\frac{dn_2}{d\lambda}\right\} \quad \text{waveguide dispersion}$$

$$Z = \left(\frac{d\Delta}{d\lambda}\right)\left\{2n_2\left(b - \frac{d(bv)}{dv}\right)\right\} \quad \text{profile dispersion}$$

and $\delta\lambda$ = linewidth of the source.

3. Results

To solve equation (5) one needs the values of $n_{1,2}$ and its derivatives w.r.t. λ and also the value of b and derivatives of (bv) as functions of v.

Values of refractive index for pure silica have been given by Malitson[11] while those for GeO_2 doped silica glasses have been given by Fleming[12,13] and Kobayashi *et al*[14]. The values of n_1, n_2 and their derivatives can therefore be known for particular situation i.e. whether pure silica is used as core and doped silica as cladding or vice versa. For step index fibres ($\alpha = \infty$) waveguide parameter b and the derivatives $d(vb)/dv$ and $vd^2(bv)/dv^2$ as functions of the normalised frequency v have been described by Gloge[10]. The effect of profile parameter α on total dispersion has been obtained by Gambling & Matsumura[8] and can be considered by considering b as a function of both v and α. In this case the wavelength at which total dispersion D equals zero becomes a function of fibre diameter $2a$ and the profile parameter α. In their extensive calculations, Gambling *et al.* have described the design parameters $2a$ and α as function of wavelength at which D vanishes.

Considering that both b and dbv/dv are $\leqslant 1$, their difference $(b - d(bv)/dv)$ will be < 1. The product of this with a small quantity like

Δ or $d\Delta/d\lambda$ will therefore be negligibly small,. Also

$$b\frac{d^2n_1}{d\lambda^2} - (1+b)\frac{d^2n_2}{d\lambda^2} \equiv -\frac{d^2n_2}{d\lambda^2} + b\left(\frac{d^2n_1}{d\lambda^2} - \frac{d^2n_2}{d\lambda^2}\right)$$

Since $b \leqslant 1$ and $\left(\frac{d^2n_1}{d\lambda^2} - \frac{d^2n_2}{d\lambda^2}\right) < \frac{d^2n_2}{d\lambda^2}$, $n_1 \approx n_2$, the product $b\left(\frac{d^2n_1}{d\lambda^2} - \frac{d^2n_2}{d\lambda^2}\right)$ can be neglected in comparison to $\frac{d^2n_2}{d\lambda^2}$.

By making these approximations, Eqn. (5) can be expressed as

$$D = \frac{L\delta\lambda}{C}\left[-\lambda\frac{d^2n_2}{d\lambda^2} + \frac{n_2\Delta}{\lambda} V \frac{d^2bv}{d\lambda^2}\right] \tag{6}$$

Since $n_2\,\Delta \approx (n_1 - n_2) = (\text{N.A.})^2/2n_2$,

the above equation matches will with the expression derived by Jeunhomme[15].

For given values of fibre dia, profile parameter, and refractive indices of core and cladding, the wavelength for $D = 0$ is fixed and can be estimated from the plot of Eqn. (5), vs λ. For calculating the various values in equation (5), use is made of the n vs λ values for the core and cladding material and the curves for $b\,.\frac{dbv}{dv}$ and $\frac{Vd^2\,bv}{dv^2}$ vs V as plotted for different values of α. For germanium doped silica core and pure silica cladding these curves have been plotted by Gambling[9]. Knowing $\lambda D = 0$, it is then desirable to operate at this wavelength to take advantage of full capacity of the fibre medium. Alternatively, if it is desired to operate at a given wavelength, then fibre dia and profile gradient can be adjusted to obtain $D = 0$ at this wavelength. These considerations results in very large bandwidth Km products. Feasibility of achieving values as large as 28 Mbps Km have been confirmed[4] by using 0.8 db/km GeO_2 doped silica core fibre, and In GaAsPdh laser as source and GeAPD as detector.

4. Discussion

Fig. 1 gives total dispersion D vs λ of a silica based single mode fibre for the particular case of core diameter $2a = 5\ \mu$m, $\Delta = 1$ percent, and $\alpha = \infty$. The fibre is made of GeO_2 doped SiO_2 core and pure Silica as Cladding.

Fig. 2 shows the plot for $\alpha = 2$, other parameters remaining same. The three terms X, Y, Z due to material dispersion, waveguide dispersion and profile dispersion corresponding to Eqn. (5) have also been separately plotted in order to show the contribution due to various terms. For the sake of comparison, points have also been plotted which correspond to the approximate expression Eqn. (6) and the complex expression due to Gambling *et al.* (Eqn. (13) of Ref. 9). It is seen that the difference between the three expressions (Eqns. (5), (6) and (13) of Ref. 9) is not significant though the expressions due to Gambling[9] *et al.* are quite complex. The approach utilised in this paper and in Ref. 9 is similar but the final expressions in Ref. 9 are quite complex. This is because the authors of Ref. 9 have expressed the three dispersion components (material dispersion, waveguide dispersion and profile dispersion) as composite terms rather than using the normal definitions for these quantities. For example, profile dispersion arises from terms such as $d\Delta/d\lambda$ whereas they have given an expression (Eqn. (16) of Ref. 9) which contains terms of the form d^2bv/dv^2 and dbv/dv which are generally considered as waveguide dispersion. Also their expression for material dispersion (Eqn. (14) of Ref. 9) includes terms involving dbv/dv whereas it should by definition only involve terms like $d^2n/d\lambda^2$. Their reason for doing so is only a mathematical convenience. We have on the other hand stuck to the well known definitions for the different dispersion terms and have given a simple expression

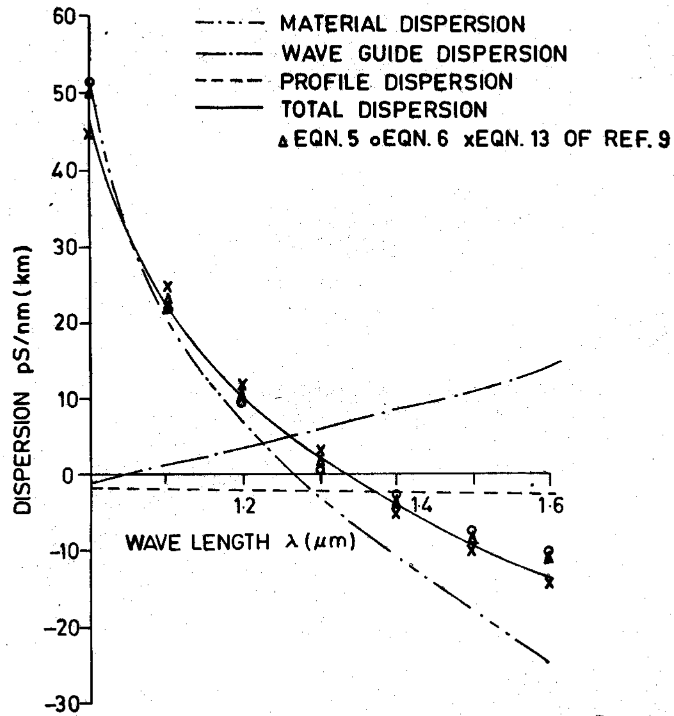

Figure 1. Dispersion vs wavelength of a silica based single mode fibre (2a = 5 μm, $\Delta = 1\%$, $\alpha = \infty$).

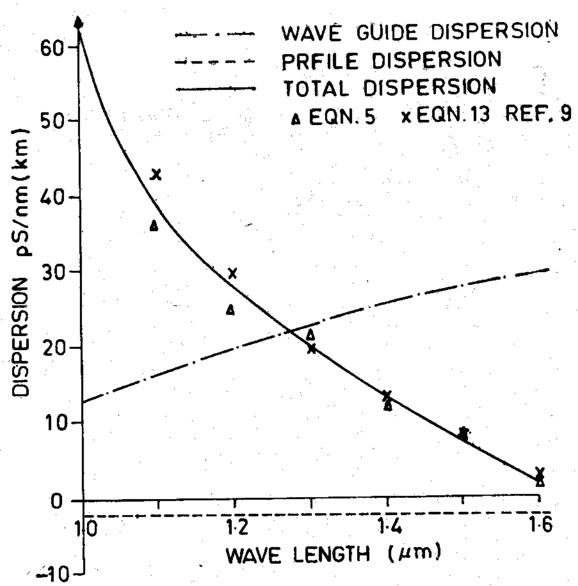

Figure 2. Dispersion vs wavelength graded index single mode fibre.

for the total dispersion Eqn. (5) which clearly includes the three well defined expressions for material dispersion $f(d^2n/d\lambda^2)$, waveguide dispersion f $(\Delta, dbv/dv, d^2dv/dv^2)$

and profile dispersion $f(d\,\Delta/d\lambda)$. The validity of Eqn. (5) is proved by the fact that it reduces to the approximate expression of Jeunhomme[15] Eqn. (6) by making valid approximations, and that the values of D based on Eqn. (5) closely correspond to the values obtained from the more complex expressions of Gambling[9] *et al.* The closeness of the values derived from Eqn. (5) with those of Eqn. (6) in Fig. 1 is in fact expected because the major contributions to the total dispersion come from the terms due to $d^2n/d\lambda^2$ and d^2bv/dv^2 as stated in Eqn. (6)., while the terms due to $\left(b - \frac{dbv}{dv}\right) dn/d\lambda$ and $\left(b - \frac{dbv}{dv}\right) d\,\Delta/d\lambda$, contribute only to the extent of nearly 2 percent and 10 percent of the total dispersion respectively.

5. Source and Detectors

The wavelength for $D = 0$ for silica based fibres falls in the range 1 – 1.7 μm. Semiconductor junction devices of the type GaInAsP, grown on InP substrates, have been used as source for operation in this range[16]. The exact wavelength of emission can be adjusted by adjusting the alloy composition and can be varied from 0.92 μm (1.35 ev) to 1.6 μm (0.78 ev). Both diode lasers and LEDs have been fabricated in this system and show promising performance. Recently the semiconductor devices of the type GaInAsP/InP have also been reported as p i n photodetectors[17] in the 1.0 – 1.6 μm range. However, for detection in 1.0 – 1.6 μm in the avalanche mode only GeAPDs have been usefully employed even though they are a little more noisy compared to the III – V compound devices. Hiroaki *et al.*[18] have discussed the use of GeAPD in the wavelength region 1 – 1.6 μm while Brain[19] has described its responsivity and noise characteristics in the 1.1 — 1.7 μm range.

6. Conclusion

Single mode fibre optic systems operating at a wavelength where intrinsic loss is minimised and total dispersion is reduced to zero assume importance because of the wide bandwidth available leading to large repeater spacing. This zero dispersion wavelength for the silica based fibres lies in the range 1 – 1.7 μm. System have been operated at 1.3 μm and 1.5 μm leading to very large figures of merit ($\sim$ 10 – 20 Mbps Km) for specific silica based fibres. III – V compound semiconductor devices are available as LED or laser sources and GeAPD detector can be used throughout 1 – 1.6 μm range.

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