SINGLE-MODE FIBRES WITH LOW DISPERSION AND LOW LOSS FOR LED-SIGNALS*

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Summary

Single-mode fibres for low loss and low-dispersion transmission of LED-signals near $\lambda = 1.3$ μm may be produced economically with only a few MCVD-cladding layers, when a second cladding of depressed index surrounding the inner cladding prevents outer cladding loss to add to the fundamental mode loss. The spotsize is large enough for LED excitation of the fundamental mode without rendering it too sensitive with respect to microbending.

Introduction

Recently it has been demonstrated that LED's, preferably in the form of edge emitting diodes, can be coupled to single-mode fibres with enough coupling efficiency to transmit high-speed pulses over medium distances [1]. The aim is for low-cost optical fibre systems with transmission-capacities per fibres of up to 300 Mbit/s and distances between terminals or regenerators of up to and even beyond 10 km. Instead of employing an expensive high-quality graded index fibre with an error-free refractive index profile of low mode dispersion, single-mode fibres are under serious consideration which, in principal, can be less expensive. They are lower in cost as compared to graded-index fibres because all they need is a simple step-profile of their refractive index. Their inner cladding layers must however be made out of extremely pure synthetic fused silica, free of any OH-contamination extending to an outer radius which is at least six times the core radius. Otherwise the radially evanescent cladding fields of the fundamental mode would reach into the more lossy substrate glass and this mode would suffer too much attenuation. On the other hand, the spotsize of the fundamental mode should be large enough for the coupling efficiency from an edge emitting diode into this mode to reach its largest possible and yet quite small value without any refined and expensive beam transformation. Despite of this large spotsize, the fibre should not be too sensitive with respect to bending.

* Dedicated to Professor Károly Simonyi on the occasion of his Seventieth Birthday

To meet all these requirements we consider a triple-clad fibre with a step-profile of its refractive index, according to Fig. 1. Its homogeneous core with a refractive index n_0 has a radius a and is surrounded by a first cladding of refractive index n_1 extending to the radius b. The second cladding has a refractive index n_2 and extends to the radius c, while the third and outer most cladding has the same refractive index n_1 as the first cladding.

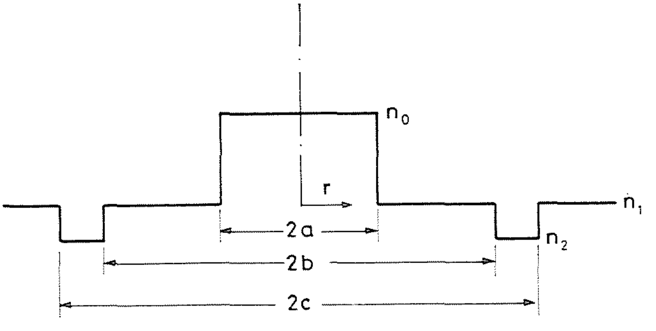

Fig. 1. Refractive index profile of a triple-clad fibre with depressed index in the second cladding

Such a fibre can be fabricated at low cost by starting for the preform with a substrate tube of ordinary, and hence relatively lossy quartz-glass. With the modified chemical vapour deposition (MCVD)-process a layer of synthetic quartz-glass doped with either boric oxide or fluor is first deposited on the inside of the substrate-tube. The doping depresses the refractive index to $n_2 < n_1$. Next, only a few layers of pure quartz-glass with the refractive index n_1 are deposited, to be followed, finally, by one or a few layers for the core which, by doping them with Germanium oxide, have their refractive index raised to $n_0 > n_1$.

The depressed index layer with its fluor or boric oxide doping serves as a diffusion barrier and prevents any contamination, particularly hydroxyl ions, to penetrate from the substrate glass into the inner cladding and the core. In addition, this depressed index layer presents a barrier to the radially evanescent cladding fields of the fundamental fibre mode, and prevents them from reaching into the outer cladding. Thus, that part of the fundamental mode attenuation, which the absorption and scattering of the outer cladding material causes, is kept low, even when the inner cladding consists only of very few MCVD-layers. At the same time this depressed index layer, by confining the fundamental mode fields through its strong radial evanescence, makes the fibre relatively insensitive with respect to bending. All these aims are achieved with a spotsize of the fundamental mode that is fairly large and makes it easier to launch sufficient power into this mode, even from an edge emitting diode.

Analysis

To compute a design for this triple-clad fibre, that allows as economical a fabrication as possible and has a large spotsize, as well as little bending sensitivity, and to determine how chromatic dispersion of the fundamental mode limits its transmission capacity, we can assume only small refractive index differences within the index-profile. We can then base the analysis on the scalar approximation to the solution of the vector-wave equation for the fundamental fibre mode and the modes of next higher order, as well as for those radiation modes, which the fundamental mode excites in the outer cladding, when the fibre is bent.

The solution of the boundary value problem yields as its lowest eigenvalue the effective index $N=\beta/k$ of the fundamental mode with β as the phase coefficient of this mode, and $k=2\pi/\lambda$ as the free-space wavenumber, where λ is the free-space wavelength. Once we know N as a function of λ, we can calculate the effective group-index of the fundamental mode according to

$$N'=N-\lambda\frac{\mathrm{d}N}{\mathrm{d}\lambda}. \tag{1}$$

N' as a function of λ yields in turn the dispersion coefficient of the fundamental mode according to

$$D=\frac{1}{c}\frac{\mathrm{d}N'}{\mathrm{d}\lambda} \tag{2}$$

with c as the vacuum velocity of light. The wavelength-dependence of the refractive index is very important in this dispersion analysis. It is taken into account here by a three-term Sellmeier equation with its various parameters following from reference [2], for pure quartz-glass, as well as for the doped quartz-glass in the core and the depressed-index cladding.

The attenuation of the fundamental mode by losses in the outer cladding is determined by a perturbational analysis, which we base on the solution for the fundamental mode of the loss-less structure [3].

For the effective spotsize w of the fundamental mode the following definition has proven to be quite useful

$$w^2=\int_0^\infty r^3E^2(r)\,\mathrm{d}r \Big/ \int_0^\infty rE^2(r)\,\mathrm{d}r. \tag{3}$$

It measures the radial extent of the electric field $E(r)$ of the mode by means of the second moment of $E^2(r)$ with respect to the radius. When the field depends on the radius as a Gaussian distribution the spotsize w from eq. (3) represents the radius at which the field has dropped to $1/e$ times the field maximum on the axis of the fibre. The spotsize w according to eq. (3) is at the same time a fundamental-Mode parameter, which, in case of random microbending of the fibre with a very short autocorrelation distance L_k, determines the added average fundamental mode loss with the following amplitude attenuation coefficient [3, 4]

$$\langle\alpha\rangle = \frac{1}{2}\left\langle \frac{1}{R^2} \right\rangle (n_0 k w)^2 L_k \qquad \text{for} \quad L_k \ll n_0 k w^2 . \tag{4}$$

In this formula $\langle 1/R^2 \rangle$ represents the mean square of curvature of microbending. In the limit of short autocorrelation the added curvature loss according to eq. (4) increases with the square of the spotsize from eq. (3).

Under practical circumstances, however, the approximation for the microbending loss according to eq. (4) is not applicable, because in cabled fibres the random curvature is correlated over distances too large for eq. (4) to hold. This equation, moreover, looses in accuracy the more, for finite autocorrelation distance of curvature, the radial field dependence $E(r)$ deviates from a Gaussian distribution [4]. The fundamental mode fields of multiple-clad fibres in some cases show little resemblance with a Gaussian distribution, in particular when they are designed for low dispersion over a wide spectral range [5]. To safely asses the bending sensitivity of such fibres it is therefore necessary to calculate their curvature loss more accurately also for practical curvature distributions.

For this curvature loss analysis we use the well established method of coupled wave equations [6] for which we must here consider the interaction between the fundamental mode and the continuous spectrum of radiation modes. First we approximate the vector wave equation for the field components by scalar wave equations. While this may not be accurate enough when the dispersion characteristics of the fundamental mode must be determined in detail, it is quite adequate for the curvature analysis. We then replace the curved fibre by an equivalent straight fibre with a refractive index distribution according to [7]

$$n_e^2 = n^2(r)\,(1 + 2x/R) \tag{5}$$

where $n(r)$ is the index profile of the fiber and $x = r \sin \varphi$ the projection of r on the plane in which the fiber is curved.

The fundamental mode, as the only guided mode of the fibre, is coupled by curvature to the continuous spectrum of those radiation modes which have a circumferential dependence of first order. It thus looses power by radiation. The average curvature loss is described by an attenuation coefficient for the fundamental mode amplitude according to [6]

$$\alpha = \frac{1}{2} \int_0^{n_1 k} C(\beta_r)\, \varphi(\Delta\beta)\, \mathrm{d}\beta_r \tag{6}$$

with $C(\beta_r)$ as the coupling coefficient between the fundamental mode and the respective radiation mode whose axial phase coefficient is β_r. $\varphi(\Omega)$ denotes the power spectrum of curvature $1/R$ and is given by

$$\varphi(\Omega) = \lim_{L \to \infty} \frac{1}{L} \left| \int_0^L \frac{1}{R} e^{-j\Omega z} \, dz \right|^2 . \tag{7}$$

In eq. (6) this curvature power spectrum must be evaluated at the spatial frequency $\Omega = \Delta\beta = \beta - \beta_r$, where β is the phase coefficient of the fundamental mode. The integration in eq. (5) ranges over all coupled radiation modes from $\beta_r = 0$ to $\beta_r = n_1 k$.

To evaluate eq. (5) we have chosen a curvature power spectrum according to

$$\varphi(\Omega) = K/\Omega^{2p} \tag{8}$$

and adjusted the exponent $2p$ so that the curvature loss as it obtains from eq. (6) corresponds in its wavelength dependence to experimental observations [8].

Results

LED's, also of the edge emitting variety, have an emission spectrum which in wavelength is up to 100 nm wide. If their radiation is to transmit pulses at rates up to 300 Mbit/s over fibres up to 10 km in length the dispersion coefficient of these fibres for linear chromatic dispersion according to eq. (2) must be smaller than 3 ps/(nm · km). Fundamental mode dispersion as low as according to this figure calls for an operating wavelength near a zero-crossing of the linear dispersion coefficient. The material dispersion of pure fused silica has this zero-crossing at $\lambda = 1.28$ μm. Doping fused silica lightly with Germanium oxide shifts this zero-crossing only slightly to longer wavelengths. Since the spotsize of the fundamental mode should be large enough to facilitate its efficient excitation from an edge emitting diode, the numerical aperture of the fibre can only be small. As a consequence the waveguide dispersion of the fundamental mode will remain quite weak. It can therefore shift the minimum of material dispersion also only slightly towards longer wavelengths.

Taking all these requirements into consideration, the operating wavelength must be chosen in the vicinity of $\lambda = 1.3$ μm.

With a refractive index of the core raised to a relative difference

$$\Delta_0 = \frac{n_0 - n_1}{n_1} \tag{9}$$

with respect to the outer cladding index of only $\Delta_0 = 0.3\%$, a core diameter of nearly $2a = 8$ μm will be required for the fibre to be still single-mode at $\lambda = 1.3$ μm. Such a small index difference requires only so little doping with Germanium oxide that the doping will increase neither absorption nor scattering loss significantly. The large core diameter, which is associated with this small numerical aperture, will lead to a correspondingly large spotsize of the fundamental mode.

The second cladding with its depressed refractive index n_2 will be limited here to a width of only

$$c - b = 1.6\ \mu\mathrm{m}\,.$$

With this narrow width it can be formed by only one or a few layers, deposited in the MCVD-process. For the same reason of fabrication economy the ratio of inner cladding radius to core radius will initially be limited to $b/a = 3$.

The index n_2 in the layer between $r = b$ and $r = c$ can readily be depressed to a relative difference

$$\Delta_2 = \frac{n_1 - n_2}{n_1} \tag{10}$$

with respect to the outer cladding index of up to $\Delta_2 = 0.3\%$ by doping the fused silica of this layer with fluor.

From a solution of the scalar wave equation for the fundamental mode, Fig. 2 shows its dispersion coefficient according to eq. (2) as a function of wavelength for three different triple-clad fibres, which were designed to obey all the above requirements. The relative index differences which are listed in Fig. 2 for the three different fibres are those for $\lambda = 1.3$ μm. But in the relatively narrow wavelength range of Fig. 2 their dependence on wavelength according to the Sellmeier equation effects only little change for them. Fibres 1 and 2 in Fig. 2 have cutoff wavelength λ_c for the next higher order mode which are below the respective zero-crossing of the linear dispersion coefficient. They are hence single-mode in the dispersion minimum. For fibre 3, however, this cutoff wavelength is somewhat longer than the wavelength of the zero crossing of its dispersion coefficient. Theoretically this fibre is therefore not single-mode in the dispersion minimum. For all practical purposes, though, the next higher order mode extends its fields so far into the outer cladding, and suffers so much cladding loss at the wavelength of minimum fundamental-mode dispersion, that the fibre is effectively still single-mode at this wavelength.

The effective spotsize according to eq. (2) is also listed in Fig. 2 for three wavelength values for each of the three fibres. It is larger than 4.5 μm at wavelengths longer than 1.25 μm. This is considered to be sufficiently large for efficient LED excitation.

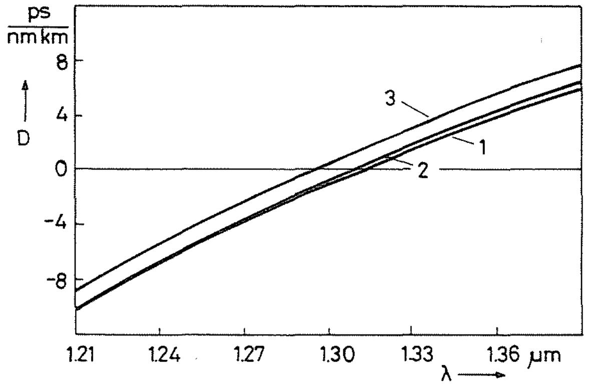

Fig. 2. Dispersion coefficient of the fundamental mode in tripleclad fibres with a depressed index in the second cladding due to fluor doping

Fibre	a (μm)	$\frac{b}{a}$	$c-b$ (μm)	Δ_0 % at $\lambda=1.3$ μm	Δ_2 % at $\lambda=1.3$ μm	λ_c (μm)	w (μm)	$\frac{\Delta\alpha}{\alpha_1}10^5$	at λ (μm)
1	4.1	3	1.6	0.32	0.32	1.244	4.52	1.5	1.25
							4.65	2.8	1.30
							4.79	5.1	1.35
2	4.5	3	1.6	0.25	0.32	1.21	5.04	2.1	1.24
							5.22	4.4	1.30
							5.42	8.6	1.36
3	4.8	3	1.6	0.3	0.32	1.41	4.86	0.23	1.24
							5.00	0.52	1.30
							5.15	1.1	1.36

The amount $\Delta\alpha$ by which the attenuation of the fundamental mode increases due to loss in the outer cladding has been computed by perturbational analysis and is listed in Fig. 2 relative to the bulk loss α_1 of the outer cladding material for three different wavelengths for each of the three fibre designs. If for example the bulk loss in the outer cladding amounts to $\alpha_1=100$ dB/km, then the fundamental mode of fibre No. 2 will suffer $\Delta\alpha=0.0086$ dB/km additional attenuation at $\lambda=1.36$ μm. For all other examples of Fig. 2 this added attenuation remains much lower in accordance with the smaller spotsizes in those cases.

Of much influence on this added fundamental mode attenuation due to outer cladding loss is the amount of index depression in the second cladding and the radial position of this depressed-index cladding. The fibre designs in Fig. 2 show that in case of $b/a=3$, $\Delta_2=0.32\%$, and at $\lambda=1.3$ μm, the fundamental mode suffers much less additional attenuation due to bulk loss in the outer cladding of $\alpha_1=100$ dB/km than the $\alpha=0.4\ldots0.8$ dB/km it suffers anyway in a regular low loss fibre. It is therefore possible to save on inner cladding layers and achieve low loss transmission also with a smaller ratio of b/a. Figure 3 illustrates this possibility by showing the added fundamental mode attenuation $\Delta\alpha$ relative to the bulk loss α_1 in the outer cladding as a function of the inner-cladding-to-core diameter ratio for values of a, $c-b$ and Δ_0 with which all the other requirements for these triple-clad fibres are met. These examples demonstrate that in order to keep the added fundamental mode attenuation due to an outer-cladding bulk loss of $\alpha_1 = 100$ dB/km below $\Delta\alpha = 0.1$ dB/km the inner cladding diameter needs only to be twice the core diameter.

As an alternative, that also simplifies fibre preform fabrication by the MCVD-process, the second cladding may be doped with less fluor, or with boric oxide instead of fluor. Less index depression in this cladding would be the consequence. Fig. 4 shows how the added fundamental-mode attenuation $\Delta\alpha$ relative to be bulk loss α_1 in the outer cladding depends on the amount of index depression in the second cladding. In order for this diagramm to be representative for a low-cost fibre with only few inner cladding layers, the diameter of the inner cladding was reduced here to 2.2 times the core diameter. The other fibre parameters, however, are the same as in Fig. 3.

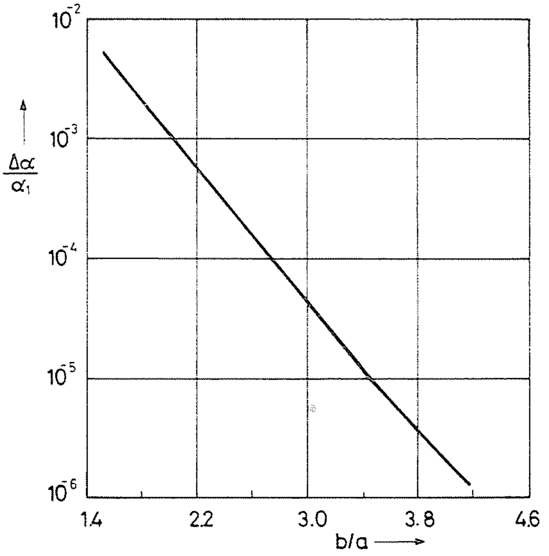

Fig. 3. Added fundamental mode attenuation $\Delta\alpha$ due to a bulk loss α_1 in the outer cladding of a triple-clad fibre as a function of the inner diameter 2b of the depressed-index cladding

$a = 4.1$ µm $c - b = 1.6$ qm
$\Delta_0 = 0.3\%$ $\Delta_1 = 0.3\%$ $\lambda = 1.3$ µm

According to Fig. 4 the amount of index depression does not change the added fundamental mode loss as drastically as does the radial position of this depressed index layer. Yet, for $\alpha_1 = 100$ dB/km it suffices to have 0.13% of relative index depression in order to keep the added fundamental mode loss lower than $\Delta\alpha = 0.1$ dB/km.

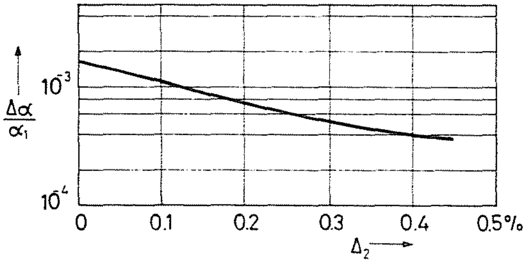

Fig. 4. Added fundamental mode attenuation $\Delta\alpha$ due to a bulk loss α_1 in the outer cladding of a triple-clad fibre as a function of the relative index depression in the second cladding

$a = 4.1$ µm $\quad b/a = 2.2$ µm $\quad c - b = 1.6$ µm
$\Delta_0 = 0.3\%$ $\quad \lambda = 1.3$ µm

Finally we need to know how sensitive the triple-clad fibre with its depressed index in the second cladding is with respect to bending. To find out, the average added loss $\langle\alpha\rangle$ to the fundamental mode due to microbending was calculated according to eq. (6) with a power spectrum $\varphi(\Omega)$ of the random curvature distribution according to eq. (8). The factor K and the exponent p of this curvature power spectrum were chosen as

$$K = 9.68 \cdot 10^{-19}\,(\text{dB/km})\,\mu\text{m}^{-2p} \qquad \text{and} \qquad p = 3.2\,.$$

Calculations of the microbending loss according to eq. (6) with these parameter values for the random curvature distribution and for simple step-index fibres give the same result as is measured in such fibres under practical conditions [8]. Therefore these parameter values should also be representative of practical microbending in triple-clad fibres.

Figure 5 shows the added average microbending loss as a function of the diameter ratio b/a. $\langle\alpha\rangle$ increases monotonically with b/a. For $b/a > 3.5$ it approaches asymptotically the limit which the corresponding step-index fibre without a depressed index cladding has as microbending loss. Even this limiting value amounts to only $\langle\alpha\rangle = 3 \cdot 10^{-4}$ dB/km and is therefore still much lower than what could be tolerated under practical conditions.

In Figure 6 the microbending loss is plotted as a function of the relative index depression in the second cladding. The ratio of inner-cladding-to-core diameter has been set at $b/a = 2.2$ for this diagram, and is hence large enough for

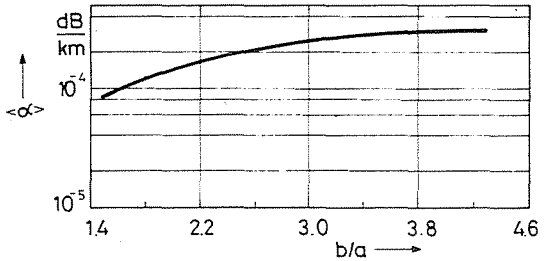

Fig. 5. Microbending loss $\langle\alpha\rangle$ of triple-clad fibres with a depressed index in the second cladding as a function of the diameter 2b of the inner cladding

$a=4.1\ \mu m$ $c-b=1.6\ \mu m$ $\Delta_0=0.3\%$
$\Delta_2=0.32\%$ $\lambda=1.3\ \mu m$

Curvature power spectrum according to eq. (8) with $K=9.68\cdot 10^{-19}$ (dB/km) μm^{-2p} und $p=3.2$

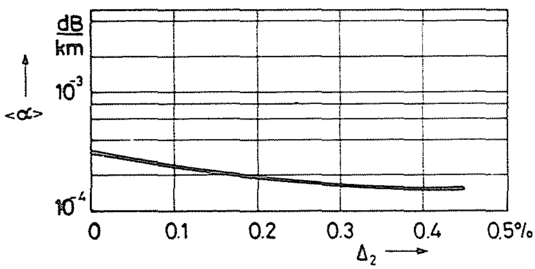

Fig. 6. Microbending loss $\langle\alpha\rangle$ of triple-clad fibres with a depressed index in the second cladding as a function of the relative index depression
$b/a=2.2$ all other parameter except for Δ_2 as in Fig. 5

the outer cladding loss not to add too much to the fundamental mode attenuation. Without any index depression $\langle\alpha\rangle$ amounts to $3\cdot 10^{-4}$ dB/km, which corresponds to the asymptotic limit in Fig. 5. Depressing the index in the second cladding reduces the microbending loss to still lower values.

Altogether the triple-clad fibre can stand normal microbending without any noticeable loss increase for the fundamental mode. Neither a radial displacement of the depressed index layer nor a change in its index depression will make the fibre too sensitive with respect to microbending.

Conclusions

A single-mode fibre with large spotsize and low loss and dispersion for LED signals near $\lambda=1.3\ \mu m$ needs only few MCVD-cladding layers if a depressed-index cladding between inner cladding and outer substrate glass prevents the outer claddig loss from adding to the fundamental mode loss. With nearly 8 μm core diameter, the inner cladding needs only to be 4 μm thick when the next cladding is 1.6 μm and has 0.2% relative index depression. Even 100 dB/km of bulk loss in the outer cladding will then add not more than 0.1 dB/km to the fundamental mode attenuation. The fundamental mode with its 5 μm of spotradius will then also be quite insensitive with respect to microbending.

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