

OPTICAL FIBRES

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Optical losses in single-mode and multimode fibres heavily doped with GeO_2 and P_2O_5

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***Abstract*.** **Optical losses in single-mode and multimode optical fibres heavily doped with germanium oxide and phosphorus oxide are studied. Optical losses in multimode fibres in a broad spectral range are found to be much lower than in single-mode fibres with the same concentration of dopants. The study of few-mode fibres showed that the core – cladding interface is the region of excess optical losses. The reasons for the observed relation between optical losses in single-mode and multimode fibres are discussed.**

Keywords: *fibre optics, heavily doped fibres, optical losses.*

1. Introduction

It is well known that single-mode optical fibres fabricated by the method of modified chemical vapour deposition (MCVD) and doped with germanium oxide up to molar concentrations of 15 % – 30 % have excess optical losses [1 – 4], which are much higher than the estimated fundamental losses (due to Rayleigh scattering and electronic and phonon absorption) and rapidly increase with the dopant concentration. Despite many attempts to establish the reason for a drastic increase in optical losses [1, 2, 5 – 11], this effect was not adequately explained so far. Also, it is not clear which regions in a fibre are sources of high optical losses. It was assumed in some papers [2 – 4, 10 – 12] that optical losses are high in the fibre core, whereas the authors of papers [5 – 9] considered excess losses at the core – cladding interface.

Because multimode heavily doped fibres did not find wide applications in communication systems, they were poorly studied. At the same time, a comparative analysis of optical losses in multimode and single-mode fibres and the study of few-mode fibres can shed light on the mechanism of excess losses in highly doped fibres. This work is devoted to the investigation of excess losses in fibres heavily doped with germanium or phosphorus oxides. We found that the dependence of optical losses on the dopant concentration and the fibre drawing temperature in multimode fibres was substantially different from that for single-mode fibres. Optical losses at the core – cladding interface in few-mode fibres were studied.

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2. Fabrication of experimental samples

Fibre preforms were fabricated by the MCVD method. High-purity fused silica tubes were used as supporting tubes. Preforms of two types were manufactured, which were doped with germanium oxide or phosphorus oxide. The reflecting cladding was made of fused silica doped with P_2O_5 (molar concentration 1 % – 2 %) and F (atomic concentration 0.1 % – 0.3 %). The core of germanosilicate and phosphosilicate fibres consisted of $F - GeO_2 - SiO_2$ and $P_2O_5 - SiO_2$, respectively. Multimode and single-mode fibres were drawn from the same preform. A part of the initial preform was inserted into a fused silica tube and collapsed in it. A preform fabricated this way was then drawn to produce a single-mode fibre. A multimode fibre was drawn from the remaining part of the initial preform. Single-mode and multimode fibres manufactured by this method had the same concentration of the dopant, the same refractive-index profile, and the same external diameter (125 μm). In some preforms, the collapse stage was modified to exclude almost completely the central dip in the refractive-index profile.

3. Optical losses in single-mode and multimode fibres

3.1 Dependence of losses on the dopant concentration

Our studies showed that in the case of low molar concentrations of germanium oxide (less than 5 % – 7 %), optical losses in multimode fibres in a broad spectral range exceed those in single-mode fibres. This fact is quite expected. The level of optical losses in glass doped with germanium oxide is higher than in pure fused silica [13]. Optical losses in slightly doped fused silica, of which the reflecting cladding is made, are comparable with losses in pure silica or even lower [14]. Because a part of the radiation power propagating in the fibre core is greater in multimode fibres, optical losses caused by fundamental mechanisms are higher in them.

The Rayleigh scattering coefficient in fused silica doped with phosphorus oxide at the molar concentration above 6 % is close to that in pure fused silica [14]. Therefore, we can expect that optical losses in multimode fibres doped with

P_2O_5 will be comparable with those in single-mode fibres.

However, our experiments showed that the relation between optical losses in multimode and single-mode fibres at high dopant concentrations differ from the assumed value. Figure 1 demonstrates optical losses in fibres doped with germanium oxide at the molar concentration of 5 % – 30 %. One can see that at GeO_2 concentrations exceeding 20 %, optical losses in multimode MCVD fibres are considerably lower than in single-mode fibres at the same dopant concentration. This relation between optical losses is independent of the refractive-index profile and the fibre drawing temperature. The same situation was also observed in a broad spectral range from 0.6 to 1.5 μm for samples doped with P_2O_5 at high molar concentrations (above 10 %) [15].

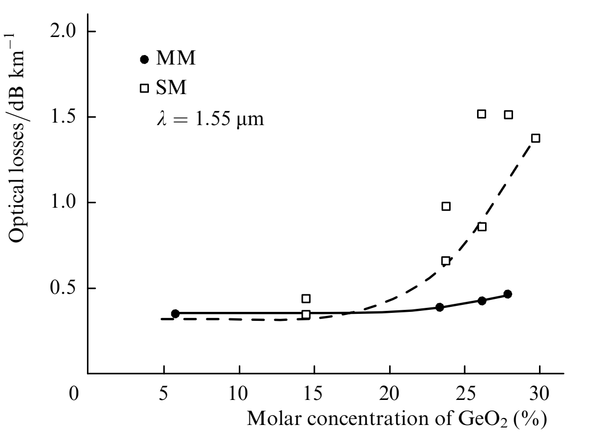

Figure 1. Optical losses in germanium-oxide-doped multimode (MM) and single-mode (SM) fibres with different index profiles.

3.2 Temperature dependence of optical losses

It is well known that optical losses in single-mode heavily doped fibres depend on the drawing temperature [1, 16]. We studied a number of single-mode and multimode fibres with different index profiles (step-index and graded-index fibres and fibres with or without a central dip in the index profile) heavily doped with germanium or phosphorus oxides. The dependence of optical losses on the fibre drawing temperature in multimode fibres was found to be an order of magnitude weaker than in single-mode fibres or absent at all. The spectra of optical losses in heavily doped (molar concentration of GeO_2 was 26 %) single-mode and multimode fibres drawn from the same preform at different temperatures are presented in Fig. 2.

3.3 Absorption bands of multimode and single-mode fibres

If an increase in optical losses is caused by losses in the fibre core, then the attenuation of a signal in a multimode fibre should be greater than that in a single-mode one because in multimode fibres a considerably greater part of the light power propagates in the core.

The IR absorption in phosphosilicate glass is higher than that in pure silica. This is explained by the appearance of new phonon IR absorption bands due to a change in the glass network [14, 17]. In addition, phosphosilicate fibres have the 1.55-μm absorption band of the OH group [18]. As a result, absorption in the core of heavily doped phosphorus fibres increases and optical losses in the spectral region above 1.5 μm in the multimode fibre are higher than in the single-mode fibre (Fig. 3).

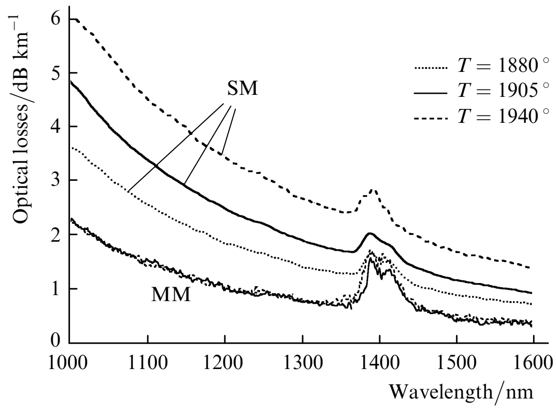

Figure 2. Dependences of spectra of optical losses on the fibre drawing temperature for SM and MM fibres containing 26 % of germanium oxide.

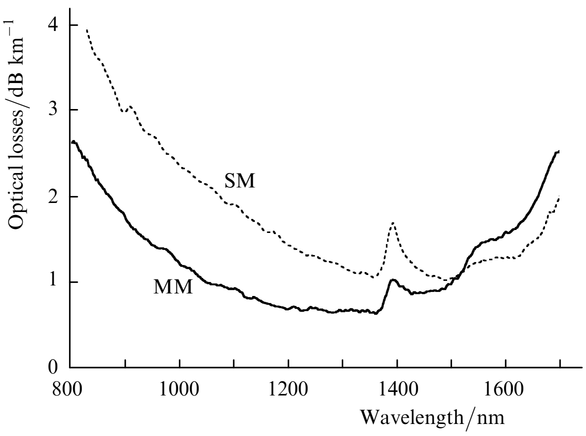

Figure 3. Spectra of optical losses in SM and MM fibres doped with phosphorus oxide up to a molar concentration of 10 %.

At the same time, the intensity of the 1.4-μm absorption band in the multimode fibre is lower. This band is related to the OH group in fused silica and its intensity decreases when phosphorus oxide is introduced into the glass network due to a change in the vibration frequencies of some bonds of Si – OH [18]. Because a part of radiation propagating in the fibre cladding is greater in the case of the single-mode fibre, the intensity of the absorption band in the multimode fibre should be lower than that in the single-mode fibre, as we see in Fig. 3.

4. Study of few-mode fibres

4.1 Description of the method

It was assumed in a number of papers [5 – 9, 19 – 21] devoted to the study of mechanism of optical losses in heavily doped fibres that excess losses appear at the core-cladding interface. To verify this assumption, we studied few-mode fibres. Note that the central dip in the refractive index profile can be also a source of optical losses [22]. Because of this, to establish the influence of only the core – cladding interface on optical losses, we performed an additional technological procedure during the fibre fabrication, which provided an almost complete elimination of the central dip in the refractive index profile. Fibres under study heavily doped with germanium or phosphorus oxides had the second-mode cut-off wavelength lying in the region between 0.98 and 1.1 μm. The fibres were studied with the help of a 0.63-μm helium – neon laser.

At this wavelength, up to four groups of modes with different sets of angular (l) and radial (m) indices: $m = 1$, $l = 0$, 1, 2 (Fig. 4a) and $m = 2$, $l = 0$, can propagate in fibres. The $LP_{02}(HE_{12})$ mode with $l = 0$ and $m = 2$ has the cut-off wavelength at 632.8 nm and can be readily coupled out of the fibre with a scrambler. We did not study this mode here. Modes with identical indices have the same radial distributions of the electric field amplitude and identical propagation constants. By varying the conditions of light excitation in a fibre, we managed to excite only one set of modes with indices $l = 0$, 1, 2 and $m = 1$ (Fig. 4b). Optical losses were measured for each of the excited modes by the cut-back method.

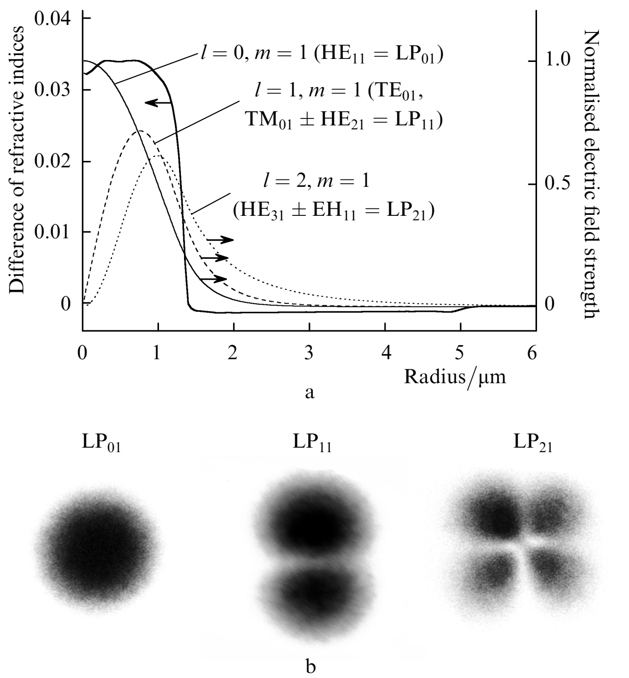

Figure 4. (a) Radial distributions of the electric field (field is normalised to the same power in all propagating modes) for modes with $l = 0$, 1, or 2 and $m = 1$ at a wavelength of 632.8 nm and of the refractive index profile in the Ge303 fibre (23.5 % of GeO_2). (b) Far-field photographs of modes coupled into the fibre.

Modes with the same indices l and m propagating in a fibre readily mixed even in fibres of length of a few metres, whereas the coupling between modes with different indices was insignificant due to a great difference between their propagation constants. Thus, upon excitation of one of the mode groups ($m = 1$, $l = 1$ or 2) in a fibre doped with phosphorus oxide ($\Delta n = 0.01$), which can propagate at a wavelength of 632.8 nm, the second group of modes was not visually observed at the output of the 500-m fibre. A mode excited in heavily doped germanate fibres of length ~ 50 m experienced a strong attenuation (by a factor of 1.5 – 2), and modes observed at the fibre output were different from the modes excited at the fibre input. It can be explained by a partial channelling of scattered radiation due to a great difference between the refractive indices of the fibre core and cladding ($\Delta n = 0.034$, Fig. 4a). Therefore, the length of fibres was selected so that to provide sufficiently high losses ($\sim 1 - 2$ dB) but without noticeable excitation of modes different from the mode excited at the fibre input. The cut-off lengths of modes under study were noticeably greater than the working wavelength (Fig. 5), which reliably demonstrates the absence of the mode leakage.

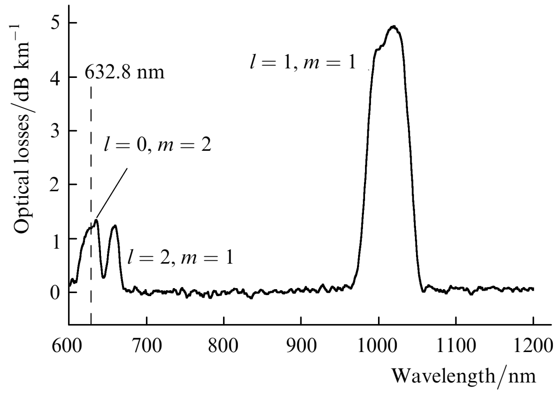

Figure 5. Measured cut-off wavelengths for the second ($l = 1$, $m = 1$), third ($l = 2$, $m = 1$), and fourth ($l = 0$, $m = 2$) modes in the Ge303 fibre.

4.2 Experimental results

Figure 6 shows the optical losses for three first modes with the radial index $m = 1$ and angular indices $l = 0$, 1, 2 in germanosilicate fibres drawn at two different temperatures. Each of the measurements was performed in four different parts of the fibre (of length ~ 25 m), and then the average value of optical losses and their rms spread were determined for each mode. Figure 4a shows the refractive index profile of the fibre and the distributions of the electric field for each of the modes.

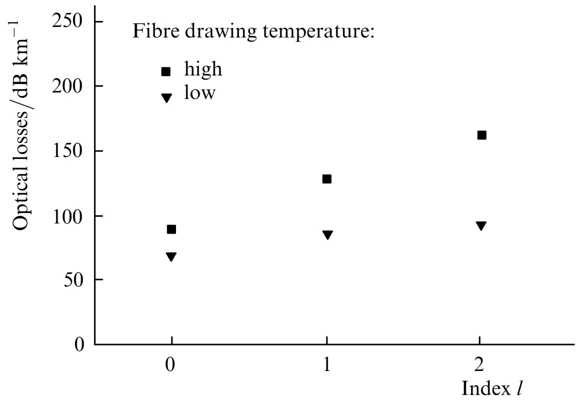

Figure 6. Optical losses in modes with $m = 1$ at a wavelength of 632.8 nm in the Ge303 fibre for two fibre drawing temperatures as functions of the index l.

Optical losses increase with increasing index l, a part of the radiation power propagating in the fibre core being decreased. This suggests that not only the fibre core make a significant contribution to optical losses. Optical losses in the reflecting cladding should be close to losses typical of pure silica [14]. This means that a significant part of optical losses in the fibres occurs at the core – cladding interface, which explains the increase in optical losses with increasing index l. Our calculations showed that the normalised radiation power in modes under study at the core – cladding interface was greater for modes with the higher index l.

The increase in the fibre drawing temperature leads to the increase in optical losses for each mode group, which correlates with a total increase in optical losses in single-mode fibres, the relative increase in optical losses being greater for groups of modes with a higher index l.

A similar situation was observed in fibres doped with phosphorus oxide at the molar concentration 12 % – 13 % and nearly step-index profile ($\Delta n_{max} = 0.0105 - 0.0115$). The measurements were performed for the two first modes. Optical losses in the $LP_{01}(HE_{11})$ fundamental mode proved to be lower than those in the $LP_{11}(HE_{21} \pm TM_{01}, TE_{01})$, mode for all fibres studied. They were 8 dB km^{-1} for the LP_{01} mode and 9.3 dB km^{-1} for the LP_{11} mode at a wavelength of 632.8 nm in the P236 fibre (molar concentration of P_2O_5 was 11 %).

4.3 Optical losses in the fibre core and at the core – cladding interface

The results obtained in Ref. [14] show that optical losses in fused silica, of which the reflecting cladding is made (molar concentration of P_2O_5 was 1 % – 2 % and the atomic concentration of F was 0.5 % – 1.5 %), are close to losses in pure silica and are ~ 6 dB km^{-1} at a wavelength of 632.8 nm. Assuming that total optical losses are caused by losses in the fibre core, at the core – cladding interface, and in the reflecting cladding, we can estimate from our results the average optical losses for each of these regions in germanosilicate and phosphosilicate fibres. The boundaries of the core – cladding region are determined by the fibre radii r_1 and r_2, for which $\Delta n(r_1) = 0.1\Delta n_{max}$ and $\Delta n(r_2) = 0.9\Delta n_{max}$. The fractions of power in the fibre core and at the core – cladding interface calculated for each of the modes are presented in Table 1. Average optical losses in the fibre core (α_{cor}) and at the core – cladding interface (α_{int}) were selected so that the rms difference between the measured and calculated mode losses would be minimal. The last but one column presents optical losses estimated for each of the modes from the obtained values of α_{cor} and α_{int}. One can see that they differ from measured optical losses (the last column) by no more than 5 %, which is virtually within the measurement error. It is interesting to note that optical losses in the core of germanosilicate fibres drawn at different temperatures are identical, although the coefficients α_{cor} and α_{int} were measured for different fibres independently.

Although the above estimates are rough, we can assert that optical losses at the core – cladding interface are several times higher than in the fibre core and their make a substantial contribution to optical losses for each of the modes studied. Note that it is losses α_{int} that depend on the fibre drawing temperature. The calculated attenuation of a signal in the core of germanosilicate and phosphosilicate fibres coincided with accuracy of ~ 35 % and 25 %, respectively, with the estimate of optical losses caused by fundamental mechanisms.

5. Discussion of results

The results described above suggest that the core – cladding interface is a source of additional optical losses, whereas losses in the core are mainly determined by fundamental mechanisms. Our results [22] showed that the central dip in the refractive index profile, which is typical of MCVD fibres, can be also a source of optical losses. Because both these regions contain the interface between weakly doped (reflecting cladding or the middle of the central dip) and heavily doped silica, the defects of the glass network [9, 23], fluctuations in the position and form of the interface due to the difference in viscosity [24, 25] or deformations caused by the difference in the thermal expansion of glasses can appear in them. The first mechanism can give rise to additional absorption of light at the core – cladding interface and in the region of the central dip in the refractive index profile. The second and third mechanisms will cause additional scattering of light. Indeed, studies of the angular dependence of light scattered in heavily doped single-mode fibres revealed the presence of anomalous (small-angle) scattering whose intensity is substantial only at small angles and greatly exceeds that of Rayleigh scattering [6, 8, 11, 19]. According to our estimates [19], such scattering can make a large contribution to total optical losses.

By using the results obtained, we can explain the observed relation between optical losses in multimode and single-mode fibres. At low dopant (germanium oxide) concentrations, optical losses are mainly determined by fundamental mechanisms, whose contribution is greater in the doped silica core. For this reason, optical losses in single-mode fibres are lower than or comparable to losses in multimode fibres. At high dopant (germanium oxide or phosphorus oxide) concentrations, optical losses in single-mode fibres are mainly determined not by fundamental mechanisms. A source of optical losses in this case is the core – cladding interface (see section 4). The contribution

Table 1. Estimates of optical losses in the fibre core (α_{cor}) and at the core – cladding interface (α_{int}). Optical losses α_{clad} in the cladding are assumed equal to 6 dB km^{-1} at 632.8 nm.

Fibre	Drawing temperature/°C	Index l ($m = 1$)	Fraction of power in the fibre core P_{cor} (%)	Fraction of power at the core – cladding interface P_{int} (%)	α_{cor}/dB km^{-1}	α_{int}/dB km^{-1}	$\alpha_{cor}P_{cor} + \alpha_{int}P_{int} + \alpha_{clad}(1 - P_{cor}P_{int})$	Measured optical losses/dB km^{-1}
		0	86	7.6			89	90 ± 2
Ge303 (23.5 % GeO_2)	1940	1	66	17.9	54 ± 0.6	547 ± 40	135	128 ± 2
		2	39	24.6			158	162 ± 5
		0	86	7.8			69	69 ± 2
Ge303 (23.5 % GeO_2)	1860	1	66	17.9	54 ± 1	288 ± 8	88	86 ± 3
		2	39	24.6			94	93 ± 5
P236 (11 % P_2O_5)	1905	0	92	6	6.56	28.3	7.85	7.85 ± 0.1
		1	79	13.3			9.4	9.4 ± 0.1

from this region to optical losses in multimode fibres is lower than in single-mode fibres for the following reasons:

(i) When power is uniformly distributed among all the modes, a fraction of the total power propagating at the core – cladding interface weakly depends on the number of propagating modes and is comparable with a fraction of the power at this interface in single-mode fibres [26]. However, the consideration of enhanced optical losses at the core – cladding interface in multimode fibres and contribution of intermode conversion [27] shows that, when the power distribution among the modes is established, a fraction of power falling on modes with a large generalised mode number $q = 2m + l$ is small. It is mainly these modes that carry power to the core – cladding interface [26]. Multimode fibres discussed in section 3 can support $\sim 50 - 80$ different modes (12 – 20 groups of modes with different indices l and m). Our far-field measurements (the angle of observation of the mode-power maximum in the far field is directly proportional to q [27]) confirmed the aforesaid and showed that, when the power distribution among the modes is established, the power is mainly concentrated in modes with a low mode number q. A fraction of the power of such modes falling within the core – cladding interface is lower than a fraction of power propagating along the boundary of single-mode fibres. Therefore, excess losses at the core-cladding interface for these modes should be lower.

(ii) The level of total [1, 28] and excess [19] losses in single-mode step-index fibres is considerably greater than in graded-index fibres (at molar concentrations of GeO_2 more than twice as much as 26 %). A small decrease in the average doping level over the cross section of the graded-index core cannot explain such a drastic reduction in optical losses. Our studies demonstrate quite convincingly that optical losses are reduced in this case due to the decrease in excess losses at the core – cladding interface. Mechanisms [9, 23 – 25] proposed to explain the appearance of excess losses at the core – cladding interface relate the increase in optical losses to a step-wise change in one of the parameters (viscosity, glass composition, thermal expansion coefficient) at the core – cladding interface. Because the region in a graded-index fibre where a step-wise change in the viscosity, thermal expansion coefficient, etc, takes place is several times greater than that in a step-index fibre, this change is less drastic in the former case, resulting in the reduction of excess losses at the core – cladding interface. The width of the intermediate region between the core and cladding in multimode fibres is three – four times greater than that in single-mode fibres. We can assume that, as in the case of single-mode fibres, this should reduce the contribution of losses at the core – cladding interface to total optical losses.

The above discussion suggests that optical losses in multimode fibres are close to those caused by fundamental mechanisms. For this reason, total optical losses in heavily doped single-mode fibres, where the level of excess losses is high, are much greater than those in multimode fibres.

Note that the calculated optical losses α_{cor} in fibre cores at a wavelength of 632.8 nm (Table 1) are comparable with losses α_{MMF} in multimode fibres. The calculated value of α_{cor} for germanosilicate fibres is ~ 54 dB km^{-1}, while optical losses measured in a multimode fibre drawn from the same preform were 77 dB km^{-1}. For phosphosilicate fibres, $\alpha_{cor} \simeq 6.56$ dB km^{-1} and $\alpha_{MMF} \simeq 8.6$ dB km^{-1}. The 30 % excess of optical losses in multimode fibres over the calculated losses in the core of few-mode fibres can be explained by the residual level of excess losses at the core – cladding interface in multimode fibres.

Our study can also explain a weak dependence of optical losses in multimode fibres on the fibre drawing temperature. Unlike excess losses [6, 19], optical losses caused by fundamental mechanisms weakly depend on the fibre drawing temperature [6, 19, 29]. The decrease in the contribution of excess losses to total optical losses in multimode fibres reduces this dependence.

6. Conclusions

We have studied optical losses in heavily doped single-mode and multimode fibres and have found that optical losses in multimode fibres in a broad spectral range are substantially lower than in single-mode fibres with the same dopant concentration. In addition, optical losses in multimode fibres are almost independent of the fibre drawing temperature.

We have developed the method for measuring optical losses in individual modes in heavily doped few-mode fibres and have found that modes for which a fraction of power propagating near the core – cladding interface is lower have lower optical losses. We have estimated optical losses in the fibre core and at the core – cladding interface. Optical losses in the fibre core are close to fundamental optical losses, whereas the level of optical losses at the core – cladding interface is very high and depends on the fibre drawing temperature. The behaviour of optical losses in single-mode and multimode fibres is explained based on the results obtained.

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