Contributed paper

OPTO-ELECTRONICS REVIEW 8(2), 161–170 (2000)

Process optimisation of the arc fusion splicing different types of single mode telecommunication fibres

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Calculation method and coefficient values of the GeO_2 dopant diffusion from the core to the cladding of spliced fibres in splicing temperature have been presented. Accepting different diffusion models, the intermediate area dimensions for various splicing parameters were calculated. A correlation between intermediate area parameters and splice loss of single mode fibres of different types including those designed for WDM has been discovered.

The analysis and usage of one–way OTDR measurement of splice losses of fibres with essential differences in cores diameters and numerical aperture has been presented. There also has been presented the influence of these parameters on one–way OTDR measurement of loss of splices of joined fibres.

Keywords: diffusion, diffusion models, splice loss, telecommunication fibres, OTDR measurements.

1. Introduction

Optimisation of standard single mode fibre (SMF) splicing processes with erbium doped fibre (EDF) [1] revealed that significant splice loss, from a few dB to ≈ 0.1 dB, is obtained if a intermediate area arises within a splice due to erbium diffusing, Fig. 1.

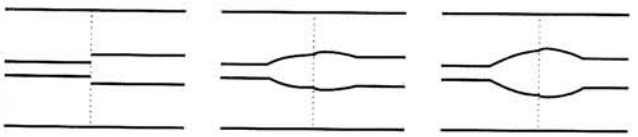

Fig. 1. Schematic presentation of dopant diffusion and arising of intermediate area.

EDF fibres are characterised by high numerical aperture (NA) ≈ 0.25–0.3 and a small mode field diameter (MFD) ≈ 4–6 μm for λ = 1550 nm. For SMF respectively MFD ≈ 10 μm for λ = 1550 nm, NA = 0.11–13. These parameters impose more difficult splicing condition than in case of splicing fibres: SMF, dispersion shifted – single mode fibre (DS-SMF), non zero dispersion shifted – single mode fibre (NZDS-SMF), depressed cladding – single mode fibre (DC-SMF), even though made according to different technologies. It is the result of smaller differences in NA of these fibres (from 0.11 to 0.17) as well as in MFD (from ≈ 8–11 μm for λ = 1550 nm).

Concepts connected with arising of an intermediate area became a base for the optimisation of splicing conditions of single mode fibres of different types, performed according to different technologies.

The main step of the splicing process is the basic splicing step (for the fusion splicer FSU 925RTC & FSU 975 it is the II step) in which the splicing temperature reaches the value ≈2000°C. For this temperature calculations of the intermediate area have been performed. Below the assumption for the optimisation for the optimisation process has been presented.

Different dopants (GeO_2, F) and their different levels of concentration in the core and the cladding cause the refraction coefficient change [2–4]. Higher GeO_2 dopant level in the core leads to a bigger refraction coefficient difference between the core and the cladding, to a bigger numerical aperture NA and to a smaller mode field diameter MFD.

In the front of head connection of two one–mode fibres optical energy losses occur

$$A = 20 \log \frac{\omega_1^2 + \omega_2^2}{2\omega_1\omega_2}, \tag{1}$$

where A is the two fibres splice loss (dB), ω_1, ω_2 are the spliced fibres mode field radii.

In case of connecting fibres with the same MFDs, according to the Eq. (1) the splice loss is equal to zero-assuming that the splice is centric splice loss. With this assumption of splice centricity and MFD adjusting, depends also on the difference in the numerical aperture NA, on the dopant type, its concentration in the cladding and the core [1]

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$$MFD = 2\omega = \frac{2a}{\sqrt{\ln[ka(NA)]}}, \qquad (2)$$

where 2a is the core diameter, NA is the numerical aperture, and

$$k = \frac{2\pi}{\lambda}.$$

Thus, in order to obtain levelling of mode fields for single mode fibres it is necessary to equalise diameters of the cores and numerical apertures of spliced fibres (dopant concentration) within the splice. Splice with low loss and good reflectance may be obtained when due to appropriate dopant diffusion in splice core, a proper intermediate area has been obtained, Fig.1 [1].

Obtaining an optical intermediate area is a function of time and splicing current [5].

Transient area optimisation as a function of splicing time and current may be performed knowing the GeO_2 in SiO_2 diffusion in splicing temperature.

2. GeO_2 w SiO_2 coefficient calculation method

In order to evaluate the diffusion processes GeO_2, a single mode fibre with NA = 0.217 and content of germanium in the in the core C_{GeO_2} = 10.4 mol %, [6] and a quartz rod with the diameter ≈130 μm were used. Diffusion coefficients were calculated on the basis of changes, along splices, of luminescence profiles of the above mentioned spliced fibres. The splice temperature was 2000°C [7]. The time of the second step of splicing was changed from 1 to 6 seconds (Fig. 2). Linear dependence of thermoluminescence on GeO_2 concentration in SiO_2 was assumed [8]. The curves of luminescence intensity changes for different splicing times as a function of the distance from the splice front have been shown in Fig. 3 [6,7].

For the purpose of calculation of the diffusion coefficient the below mentioned conditions and parameters have been assumed:

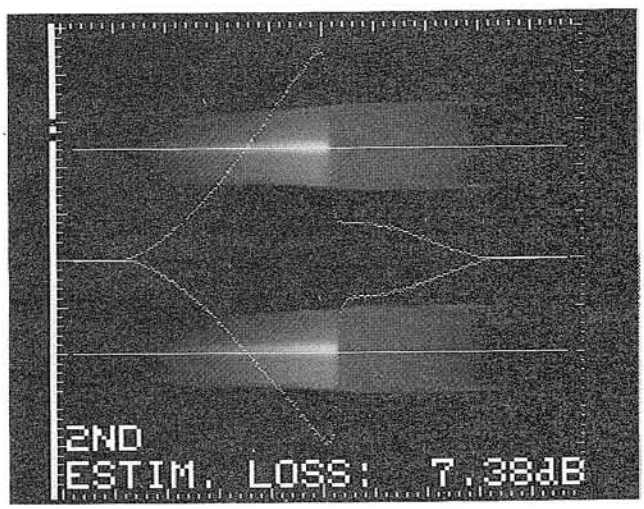

Fig. 2. Exemplary thermoluminescence intensity profile for t = 6 s.

- diffusion from unlimited dopant source, i.e., $N(0,t) = N_o$,
- initial concentration inside the quartz rod is small in comparison with N_o.

Thus, GeO_2 concentration in the quartz rod may be rendered by the following expression

$$N(x,t) = N_o erfc \frac{x}{2\sqrt{Dt}}. \qquad (3)$$

Density of SiO_2 ρ = 2.20 g/cm^2 has been assumed. Content C_{GeO_2} = 10.4 mol % corresponds with the concentration of GeO_2 in SiO_2, $N_o = 2.27\times10^{21}$ cm^{-3}. With N_o, x, t being known, N(x,t) being evaluated on the basis of luminescence, the diffusion coefficient values D for germanium in SiO_2 at the temperature ≈2000°C has been estimated. The coefficients were calculated for the distance x = 7.5 μm and x = 12.5 μm from the splice front. Values obtained were changing in the range from $D = 3\times10^{-7}$ cm^2/s to $D = 2\times10^{-6}$ cm^2/s. Higher coefficient values were obtained for shorter splicing times and smaller distances from the splice front. Dopant diffusion coefficients can be rendered by the following equation [9]

$$D = D_\infty \exp\left(\frac{-E_a}{kT}\right), \qquad (4)$$

where D_∞ is the diffusion coefficient for T = ∞, E_a is the dopant activation energy in SiO_2.

Having accepted theoretical values E_a [6,9] for interatomic dopants $E_{aI} \approx 1$ eV and diffusing dopants by means of substituting E_{aS} = 3.0 eV values of D_∞ where calculated. For E_{aS}: D_∞ = 20–130 cm^2/s, for E_{aI}: from $D_\infty = 1.2\times10^{-4}$ cm^2/s to $D_\infty = 8\times10^{-4}$ cm^2/s. The calculated values D_∞ for E_{aI} are close to the theoretical value $D_\infty = 1.7\times10^{-3}$ cm^2/s [9].

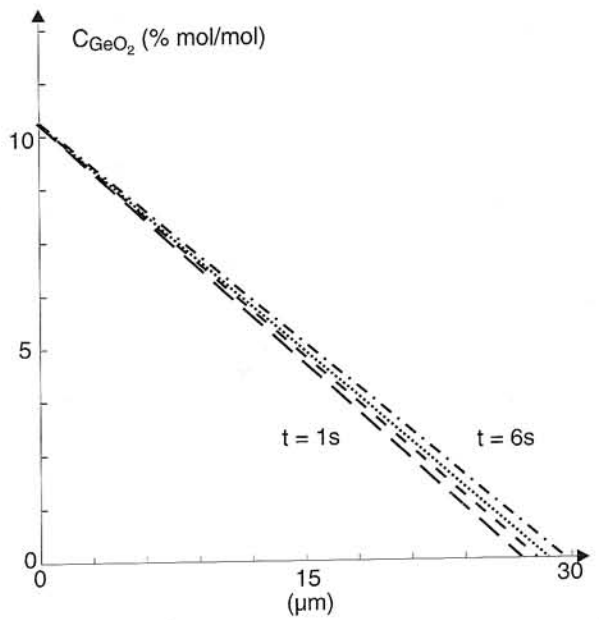

Fig. 3. Thermoluminescence intensity changes and assignment of GeO_2 in SiO_2 concentration for different splicing times in the distance from the splice front function.

In literature there is no information about values of diffusion coefficient GeO_2 in SiO_2 in temperature 2000°C. Theoretically foreseeable diffusion coefficient for interatomic dopant in SiO_2 for 1000°C is $D = 4.1\times10^{-7}$ cm^2/s [9]. Using Eq. (4) theoretical value of diffusion coefficient in temperature 2000°C is $D = 2.6\times10^{-5}$ cm^2/s and it is higher than estimated value of diffusion coefficient in this paper.

3. Simulation of diffusion process in splice intermediate area

In the intermediate area there occurs levelling of the dopant concentration in the core and partly in spliced fibres claddings. Literature and catalogue date for fibres do not contain information about GeO_2 concentration in the cores. Thus, an appropriate dopant concentration had to be assigned to numerical aperture NA so that the dopant concentration in the cores during splicing fibres with different NA could be known. It gives us a possibility to estimate the diffusion time needed for dopant concentration levelling in spliced fibres, subsequently the splicing time.

The results of this assignment have been shown in Fig. 4. For calculations, refraction coefficient values were accepted, n for $\lambda = 1310$ nm and $\lambda = 1550$ nm, depending on mole concentration of GeO_2 in SiO_2 presented in Ref. 4, Fig. 4. For not doped SiO_2 $n = 1.4468$ for $\lambda = 1310$ nm and $n = 1.4440$ for $\lambda = 1550$ nm have been accepted. It was estimated that 1 mol % GeO_2 in SiO_2 corresponds with GeO_2 dopant concentration equal to $No = 2.19\times10^{20}$ cm^{-3} and respectively 10 mol % GeO_2 in SiO_2 and $N_o = 2.19\times10^{21}$ cm^{-3}. Numerical aperture value NA was calculated from the expression

$$NA = n_1\sqrt{2\Delta}, \tag{5}$$

where $\Delta = (n_1 - n_2)/n_1$, n_1 is the core refraction coefficient, n_2 is the cladding refraction coefficient.

Figure 4 allows directly evaluating the GeO_2 dopant concentration in fibres, which significantly differ in respect of their parameters.

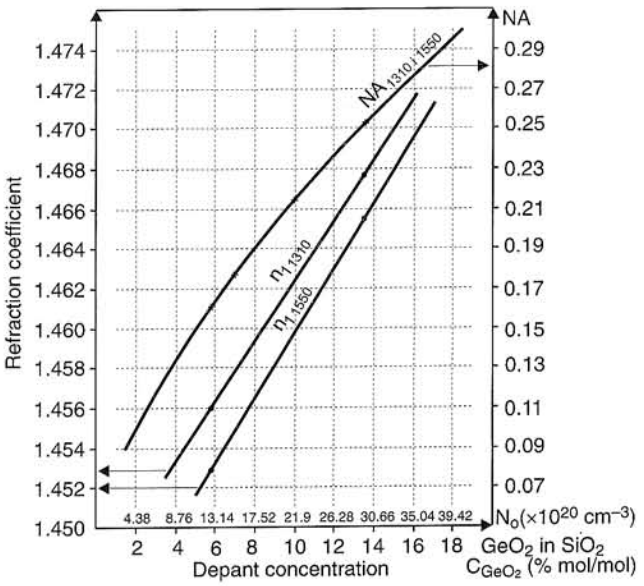

Fig. 4. Dependencies of refraction coefficient and numerical apertures NA on GeO_2 concentration in SiO_2.

3.1 GeO_2 in SiO_2 diffusion process simulation in intermediate area for diffusion from unlimited dopant source

If the following conditions are fulfilled [9]

- dopant concentration in the core during the diffusion process (splicing) is accepted to be a constant, that is

$$N(0,t) = N_o, \tag{6}$$

- initial dopant concentration in the cladding is small in comparison with N_o, i.e.,

$$N(x > 0,0) = 0, \tag{7}$$

then dopant concentration distribution is described by the following expression [9]:

x = 0–15 μm	
1. $N_o = 2.27\times10^{20}$ cm^{-3} (NA ≅ 0.08)	$D = 3\times10^{-7}\ \frac{cm^2}{s}$	t = 1,2,3,4,5 s
2. $N_o = 5.00\times10^{20}$ cm^{-3} (NA ≅ 0.105)		t = 1,2,3,4,5 s
3. $N_o = 1.00\times10^{21}$ cm^{-3} (NA ≅ 0.15)		t = 1,2,3,4,5 s
4. $N_o = 2.27\times10^{21}$ cm^{-3} (NA ≅ 0.22)		t = 1,2,3,4,5 s
5. $N_o = 2.27\times10^{20}$ cm^{-3} (NA ≅ 0.08)	$D = 7\times10^{-7}\ \frac{cm^2}{s}$	t = 1,2,3,4,5 s
6. $N_o = 5.00\times10^{20}$ cm^{-3} (NA ≅ 0.105)		t = 1,2,3,4,5 s
7. $N_o = 1.00\times10^{21}$ cm^{-3} (NA ≅ 0.15)		t = 1,2,3,4,5 s
8. $N_o = 2.27\times10^{21}$ cm^{-3} (NA ≅ 0.22)		t = 1,2,3,4,5 s
9. $N_o = 2.27\times10^{20}$ cm^{-3} (NA ≅ 0.08)	$D = 2\times10^{-6}\ \frac{cm^2}{s}$	t = 1,2,3,4,5 s
10. $N_o = 5.00\times10^{20}$ cm^{-3} (NA ≅ 0.105)		t = 1,2,3,4,5 s
11. $N_o = 1.00\times10^{21}$ cm^{-3} (NA ≅ 0.15)		t = 1,2,3,4,5 s
12. $N_o = 2.27\times10^{21}$ cm^{-3} (NA ≅ 0.22)		t = 1,2,3,4,5 s

$$N(x,t) = N_o erfc \frac{x}{2\sqrt{Dt}} \qquad (8)$$
$$erfc(x) = 1 - erf(x)$$

Calculations for the GeO_2 in SiO_2 distributions during splicing process for diffusion from an unlimited dopant source, have been performed for the data shown above.

Exemplary results of N(x,t) GeO_2 in SiO_2 dopant concentration distribution for diffusion from unlimited dopant source have been presented in Figs. 5 and 6.

3.2 GeO_2 in SiO_2 diffusion process simulation in splice intermediate area for diffusion from layer with limited thickness

For in the moment t = 0 the dopant concentration diffusion is described [9]:

$$N(x,0) = \begin{vmatrix} N_0 & -h < x < 0 \\ 0 & -h > x > 0 \end{vmatrix}, \qquad (9)$$

which means that the core diameter 2a = 0 – h = h, then after the time t dopant concentration distribution will be accounted for by the expression

$$N(x,t) = \frac{N_o}{2}\left[erf\left(\frac{x+h}{2\sqrt{Dt}}\right) - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right]. \qquad (10)$$

Expression (9) can be applied, e.g., for approximate dopant diffusion calculation from the so called finished layer, i.e., the dopant concentration distribution from the core to the cladding may be simulated, since the core may be treated as a specific "finished" layer SiO_2 + GeO_2 in pure SiO_2, that in the cladding. In this case the core is a limited dopant source which means that GeO_2 concentration decreases in the core which the diffusion time and temperature increase.

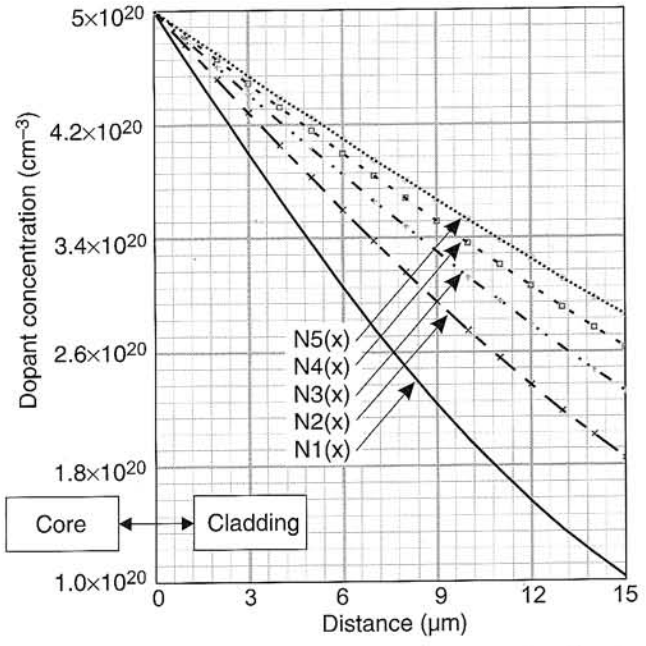

Fig. 5. GeO_2 in SiO_2 concentration distribution within the splice for diffusion from an unlimited source and parameters; x = 0 – 15 μm, t_1 = 1s, t_2 = 2s, t_3 = 3s, t_4 = 4s, t_5 = 5s, N_o = 5×10^{20} cm^{-3}, D = 7×10^{-7} cm^2/s.

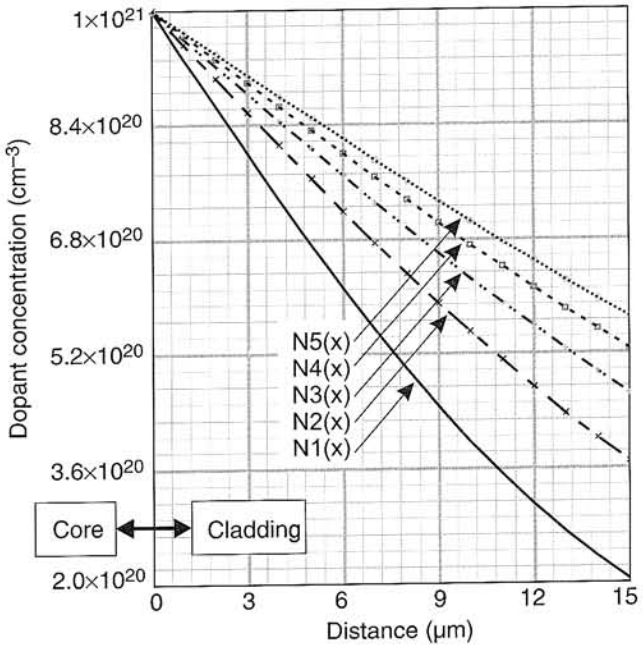

Fig. 6. GeO_2 in SiO_2 concentration distribution within the splice for diffusion from an unlimited source and parameters; x = 0 – 15 μm, t_1 = 1s, t_2 = 2s, t_3 = 3s, t_4 = 4s, t_5 = 5s, N_o = 1×10^{21} cm^{-3}, D = 7×10^{-7} cm^2/s.

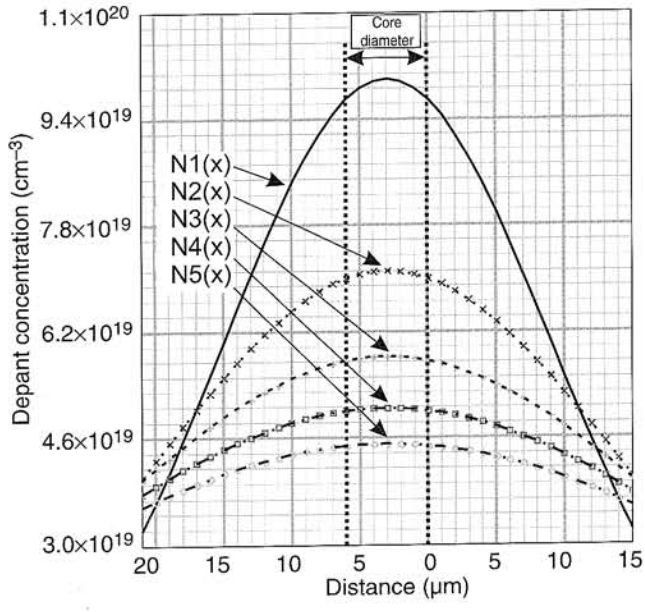

Fig. 7. GeO_2 in SiO_2 concentration distribution within splice for distribution from the layer with finished thickness and parameters; x = –21 – 15 μm, t_1 = 1s, t_2 = 2s, t_3 = 3s, t_4 = 4s, t_5 = 5s, h = 6 μm, N_o = 5×10^{20} cm^{-3}, D = 7×10^{-7} cm^2/s.

1. $N_o = 2.27\times10^{20}$ cm^{-3} (NA ≅ 0.08)		t = 1,2,3,4,5 s	
2. $N_o = 5.00\times10^{20}$ cm^{-3} (NA ≅ 0.105)	$D = 3\times10^{-7}\frac{cm^2}{s}$	t = 1,2,3,4,5 s	h = 6 and 9 μm
3. $N_o = 1.00\times10^{21}$ cm^{-3} (NA ≅ 0.15)		t = 1,2,3,4,5 s	
4. $N_o = 2.27\times10^{21}$ cm^{-3} (NA ≅ 0.22)		t = 1,2,3,4,5 s	
5. $N_o = 2.27\times10^{20}$ cm^{-3} (NA ≅ 0.08)		t = 1,2,3,4,5 s	
6. $N_o = 5.00\times10^{20}$ cm^{-3} (NA ≅ 0.105)	$D = 7\times10^{-7}\frac{cm^2}{s}$	t = 1,2,3,4,5 s	h = 6 and 9 μm
7. $N_o = 1.00\times10^{21}$ cm^{-3} (NA ≅ 0.15)		t = 1,2,3,4,5 s	
8. $N_o = 2.27\times10^{21}$ cm^{-3} (NA ≅ 0.22)		t = 1,2,3,4,5 s	
9. $N_o = 2.27\times10^{20}$ cm^{-3} (NA ≅ 0.08)		t = 1,2,3,4,5 s	
10. $N_o = 5.00\times10^{20}$ cm^{-3} (NA ≅ 0.105)	$D = 2\times10^{-6}\frac{cm^2}{s}$	t = 1,2,3,4,5 s	h = 6 and 9 μm
11. $N_o = 1.00\times10^{21}$ cm^{-3} (NA ≅ 0.15)		t = 1,2,3,4,5 s	
12. $N_o = 2.27\times10^{21}$ cm^{-3} (NA ≅ 0.22)		t = 1,2,3,4,5 s	

This model renders, in a better way, real processes that take place in splice fibres as in reality the core is not an unlimited GeO_2 dopant source.

Calculations have been made for the below-presented data

x = –21–15 μm
h = 6 μm (for DS-SMF) core diameter in figures from –6 to 0 μm
h = 9 μm (for SMF) core diameter in figures from –9 to 0 μm

Exemplary results of dopant N(t,x), i.e., GeO_2 in SiO_2 distribution calculation for diffusion from a layer with finished thickness for the data and h = 6 μm have been presented in Figs. 7 and 8.

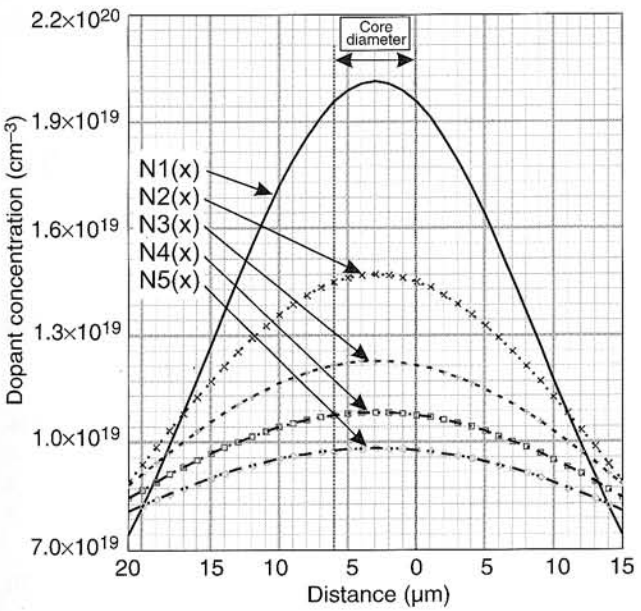

Fig. 8. GeO_2 in SiO_2 concentration distribution within splice for diffusion from the layer with finished thickness and parameters; x = –21 – 15 μm, t_1 = 1s, t_2 = 2s, t_3 = 3s, t_4 = 4s, t_5 = 5s, h = 6 μm, $N_o = 1\times10^{21}$ cm^{-3}, $D = 7\times10^{-7}$ cm^2/s.

4. Diffusion processes – summary

In splicing connecting practice extreme differences of core diameters (mode field) and numerical apertures are Δ(2a) ≅ 2–3 μm and Δ(NA) ≅ 0.05–0.06, and concerns spliced fibres with shifted dispersion DS-SMF to III optical window as well as standard SMF with zero dispersion in II optical window. It corresponds with dopant concentration $N_o = 5\times10^{20}$ cm^{-3} (NA ≅ 0.105) fibres SMF and $N_o = 1\times10^{21}$ cm^{-3} (NA ≅ 0.15) fibres DS-SMF. For these concentrations and different diffusion coefficient, long splicing times in II are the most advantageous during the main splicing step – diffusion model from an unlimited source. For long splicing times there occurs levelling of the dopant concentration in spliced fibres along distances which are differences in core diameters. Evidently splicing times can not be prolonged to infinity as it weakens the splice, and may as well lead to melting instead of splicing the fibres.

Diffusion takes place under the influence of dopant concentration gradient. Thus, diffusion within the splice of spliced fibres will be directed from the core to its claddings and from the core of the fibre with higher dopant concentration (in practice it refers to fibres with bigger NA and smaller core diameter 2a) toward the core of fibres with lower dopant concentration – this effect is not taken into account in the simulation process, Fig. 9.

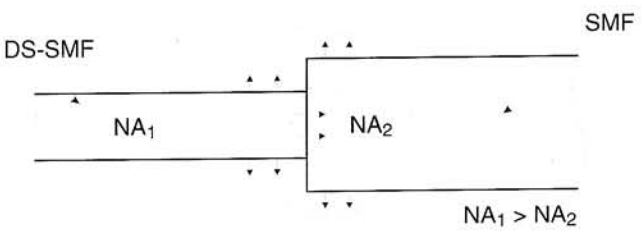

Fig. 9. Diffusion directions in spliced fibres within the splice.

This means that the dopant diffusion from the core in a fibre with lower dopant concentration will be in reality much smaller than it result from, e.g., Fig. 7, SMF fibres with NA ≈ 0.11 and $N_o \approx 5\times10^{20}$ cm^{-3} – a model of diffusion from a layer with finished thickness.

Therefore, the dopant concentration within the splice in a fibre with a lower NA will be comparable or not much lower (diffusion to the cladding) than the concentration level before diffusion, i.e., for short diffusion times then, the dopant concentration levelling conditions within the splice, e.g., for DS-SMF (NA ≈ 0.16, $N_o \approx 1\times10^{21}$ cm^{-3}, Fig. 8) and SMF (NA ≈ 0.11, $N_o \approx 5\times10^{20}$ cm^{-3}, Fig. 7) fibres occur as well – conclusions for the diffusion from an unlimited dopant source for times 4, 5 seconds and from $D = 3\times10^{-7}$ cm^2/s to $D = 2\times10^{-6}$ cm^2/s. That means, fundamental fusion time (step II for FSU 925 RTC) must be from 4 to 5 seconds with the splicing temperature assumption ≈2000°C. Our experience in splicing of SMF, DC-SMF, DS-SMF and NZDS-SMF fibres in different splicing combinations revealed that applying the above presented conclusions we may obtain repeatable splices with the loss A ≤ 0.08 dB and with unnoticeable reflectance [5].

5. Analysis of one-way OTDR measurements of splice loss for telecommunication fibre with different parameters

Analysis of one way measurement is an underestimated part of reflectometric measurements. Its importance will certainly increase since now we are going to have more frequent contacts with one-way accessible fibre routes. So far reflectometric one way values for splice loss of single mode fibres of different types have not been defined yet. Loss value A_{12} (A_{21}) for single mode SMF standard should not exceed 0.6 dB [10].

5.1. Real and apparent splice loss in OTDR measurements

According to Ref. 11, the backscattered power detected by OTDR from a point immediately preceding the splice is give by

$$P_1 = P_o S_1 \exp(-2\alpha_1 L_1), \tag{11}$$

where P_o is the initial power level (dBm), L_1 is the fibre length (km), α_1 is the attenuation coefficient (dB/km), S_1 is the backscatter coefficient, the latter being given by [2]

$$S_1 = 0.038\left(\frac{\lambda}{n_1\omega_1}\right)^2, \tag{12}$$

where λ is the wavelength, ω_1 is the mode field radius, n_1 is the core refractive index. The subscript 1 refers to the input fibre.

The backscattered power detected by OTDR from a point immediately following the splice is give by [11]

$$P_2 = P_o S_2 T_{12} T_{21} \exp(-2\alpha_1 L_1), \tag{13}$$

where T_{12} is the splice transmission value in the forward direction, and T_{21} the corresponding quantity in the reverse direction. With the assumption of central fibre connection fixing [11]

$$T_{12} = T_{21} = 4\left(\frac{\omega_1\omega_2}{\omega_1^2+\omega_2^2}\right)^2, \tag{14}$$

S_2 as the backscatter coefficient of fibre behind the splice is given by

$$S_2 = 0.038\left(\frac{\lambda}{n_2\omega_2}\right)^2, \tag{15}$$

where the subscript 2 refers to the output fibre.

One-way A_{12} fibre loss from 1 → 2 is

$$2A_{12} = 10\log\frac{P_1}{P_2}. \tag{16}$$

Thus, applying Eqs. (1), (2), and (4) we obtain

$$\frac{P_1}{P_2} = \left(\frac{n_2\omega_2}{n_1\omega_1}\right)^2 \frac{1}{T_{12}T_{21}}, \tag{17}$$

$$2A_{12} = 10\log\frac{P_1}{P_2} = 20\log\frac{n_2}{n_1} + 20\log\frac{\omega_2}{\omega_1} + 40\log\left[\frac{1}{2}\left(\frac{\omega_1}{\omega_2}+\frac{\omega_2}{\omega_1}\right)\right]. \tag{18}$$

Hence, one-way apparent splice loss in the direction 1 → 2 is

$$A_{12} = 10\log\frac{n_2}{n_1} + 10\log\frac{\omega_2}{\omega_1} + 20\log\left[\frac{1}{2}\left(\frac{\omega_1}{\omega_2}+\frac{\omega_2}{\omega_1}\right)\right]. \tag{19}$$

And similarly one-way apparent splice loss from 2 → 1 is

$$A_{21} = 10\log\frac{n_1}{n_2} + 10\log\frac{\omega_1}{\omega_2} + 20\log\left[\frac{1}{2}\left(\frac{\omega_1}{\omega_2}+\frac{\omega_2}{\omega_1}\right)\right]. \tag{20}$$

Real splice loss is an arithmetic mean of (9) and (10) including signs A_{12} and A_{21}

$$A = \frac{A_{12} + A_{21}}{2} = 20\log\left[\frac{1}{2}\left(\frac{\omega_1}{\omega_2} + \frac{\omega_2}{\omega_1}\right)\right]. \qquad (21)$$

Analysis of Eqs. (19), (20), and (21) lets us conclude that 10% difference of spliced fibre mode fields provides one-way $A_{12} \approx 0.45$ dB whereas in reality the loss in such a case is A = 0.05 dB.

In one-way measurements the component $10\log(n_1/n_2)$, even with extremely big refractive coefficient differences, e.g., $n_1 = 1.47$ and $n_2 = 1.45$, is 0.059 dB, and it slightly changes values A_{12} and A_{21}. However, differences in mode fields, e.g., $2\omega_{1_{1550\,nm}} = 8.5$ μm (for DS-SMF) and $2\omega_{2_{1550\,nm}} = 10.5$ μm (for SMF) give the following values A_{12} and A_{21} (components $10\log(n_1/n_2)$ and $10\log(n_1/n_2)$ have been left out): $A_{12} = 1.11$ dB and $A_{21} = -0.725$ dB. Whereas the real loss is A = 0.192 dB. Thus, one-way fibre splice loss values, which significantly differ in respect of their mode field diameters, may theoretically reveal values, which significantly exceed 1 dB.

5.2. Experimental results of one-way loss measurements of splice which differ significantly in respect of core diameters and numerical apertures

Non zero dispersion shifted single mode fibre NZDS-SMF of the TrueWave® type and standard single mode fibre SMF of Lycom have been used for testing. Both fibres were made (produced) according to MCVD technology.

For SMF – Lycom: NA ≈ 0.12,
2a ≅ 8 μm,
$2\omega_{1_{1550\,nm}} = 10.5$ μm.

For NZDS TrueWave®: NA = 0.154,
2a = 5.62 μm,
$2\omega_{2_{1550\,nm}} = 8.24$ μm.

Splices were performed with changing the second, basic splicing step for FSU 925RTC Ericsson fusion splicer, the following parameters have been changed:

1. $t_2 = 1.5$ s for $I_2 = 15, 16, 17, 18$ mA;
2. $t_2 = 2.0$ s for $I_2 = 15, 16, 17, 18$ mA;
3. $t_2 = 3.0$ s for $I_2 = 15, 16, 17, 18$ mA;
4. $t_2 = 4.0$ s for $I_2 = 15, 16, 17, 18$ mA;
5. $t_2 = 5.0$ s for $I_2 = 15, 16, 17, 18$ mA.

Results of one-way measurements A_{12} (from SMF–Lycom to NZDS TrueWave®) and A_{21} (from TrueWave® to Lycom), and real splice loss $A = (A_{12} + A_{21})/2$ for λ = 1310 nm and λ = 1550 nm were shown in Figs. 10–14.

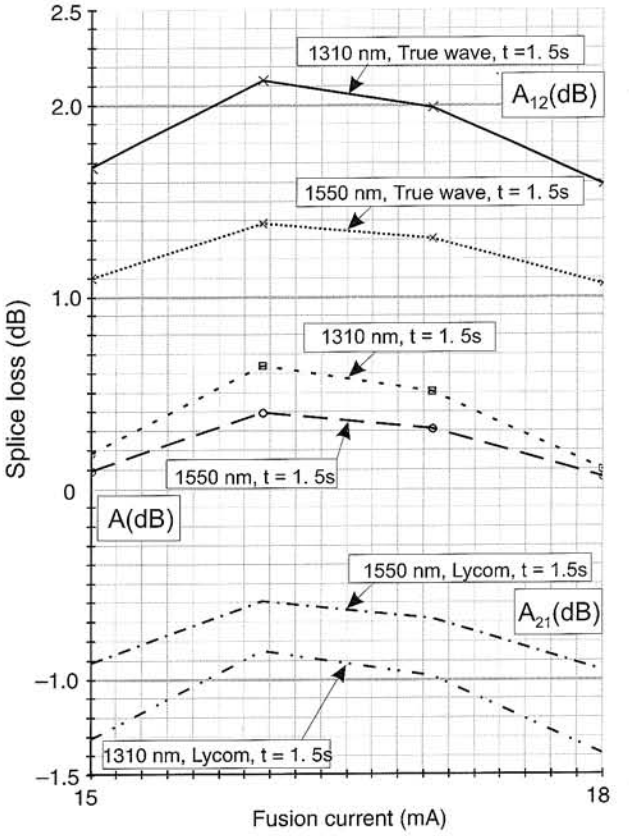

Fig. 10. Splice loss measurement results A_{12}, A_{21} and A for λ = 1310 nm, λ = 1550 nm in the fusion current function with $t_2 = 1.5$ s.

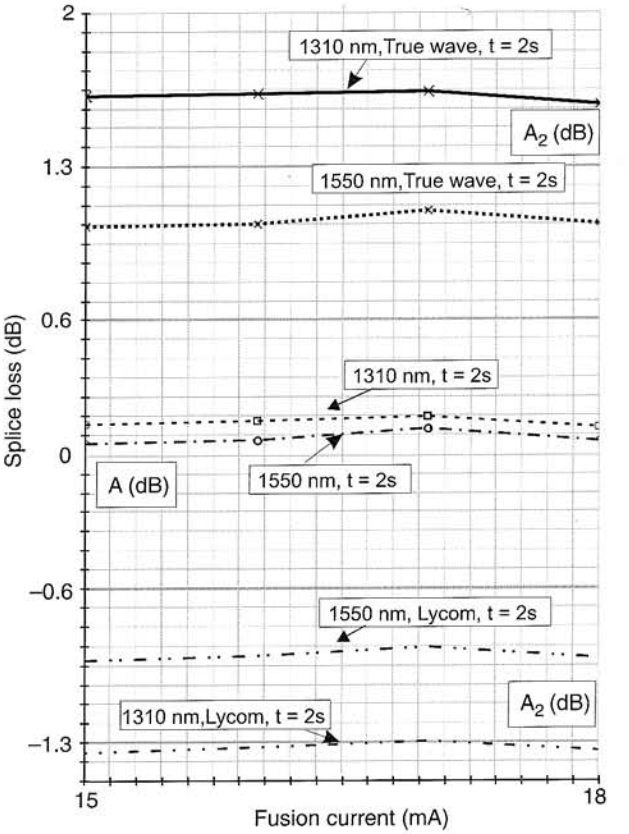

Fig. 11. Splice loss measurement results A_{12}, A_{21}, and A for λ = 1310 nm, λ = 1550 nm in the fusion current function with $t_2 = 2$ s.

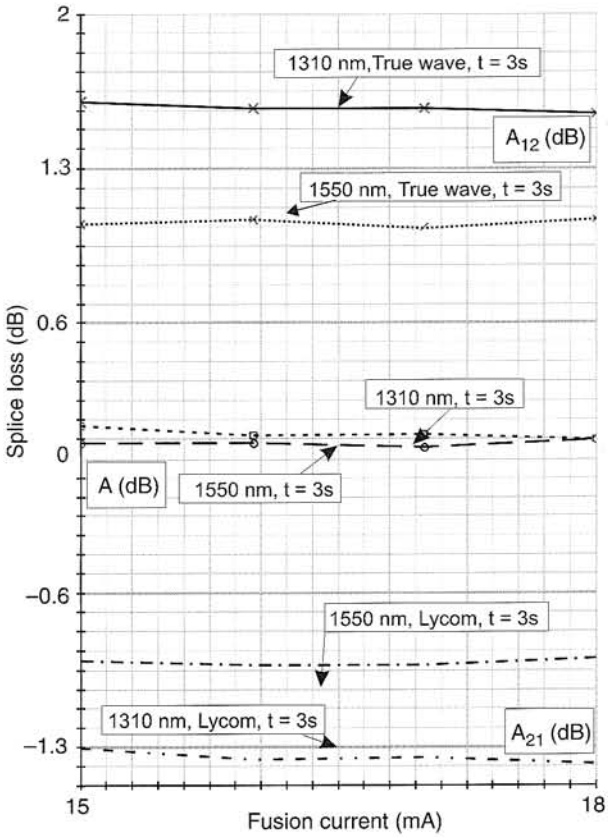

Fig. 12. Splice loss measurement results A_{12}, A_{21} and A for λ = 1310 nm, λ = 1550 nm in the fusion current function with t_2 = 3 s.

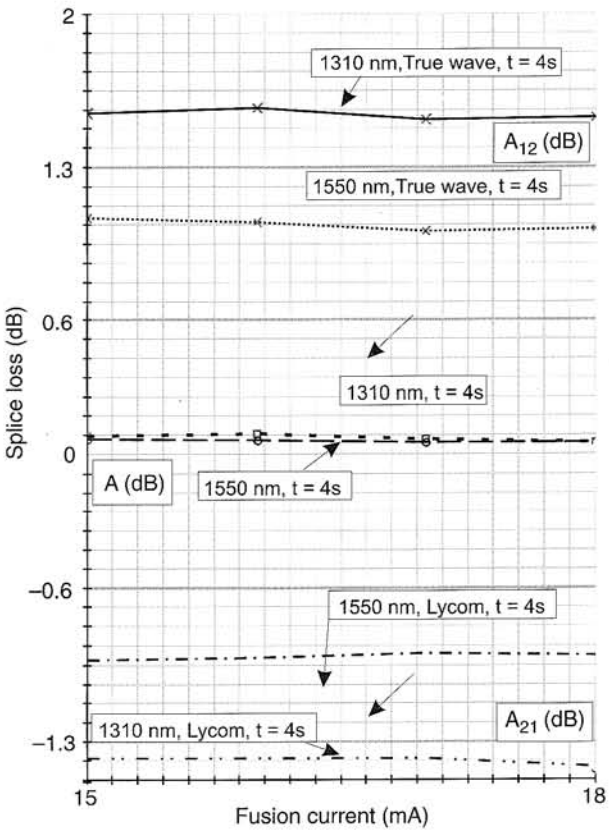

Fig. 13. Splice loss measurement results A_{12}, A_{21} and A for λ = 1310 nm, λ = 1550 nm in the fusion current function with t_2 = 4 s.

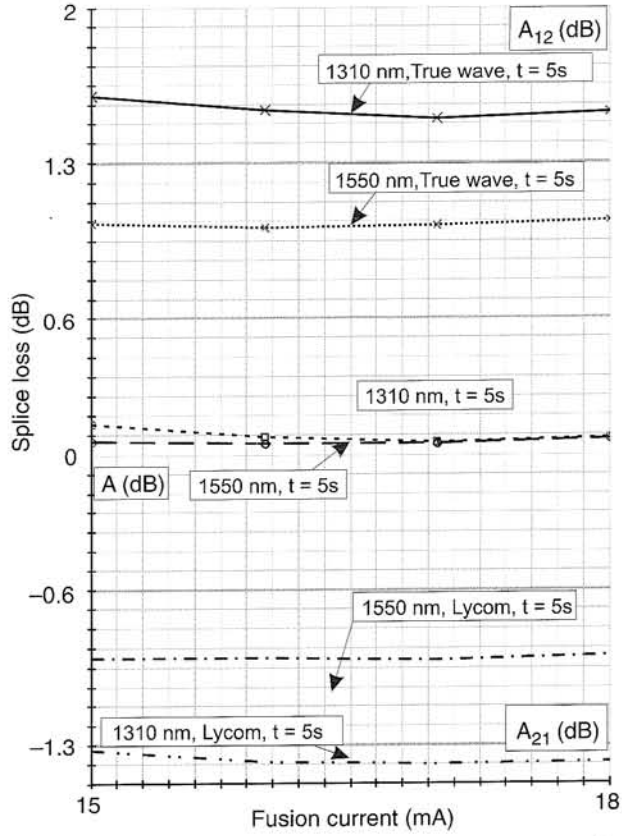

Fig. 14. Splice loss measurement results A_{12}, A_{21} and A for λ = 1310 nm, λ = 1550 nm in the fusion current function with t_2 = 5 s.

6. Anomalies in reflectometric splice loss measurements for telecommunication fibres of different types for λ = 1310 nm and λ = 1550 nm and their interpretations

Along with the increase of splicing current a signification decreases of $|A_{21}|$ and A_{12} was expected. Such an assumption resulted from the presented tests [5] concerning the transient area, i.e., faster levelling of spliced fibre mode fields during splicing due to temperature increase. During levelling of ω_1 and ω_2 according to (9) and (10) apparent values $|A_{21}|$ and A_{12} should decrease and A should, of course, decrease as well simulation of such a process has been shown in Fig. 15.

The experiment shows that up from certain splicing temperatures does not increase significantly. Therefore, for defined currents with the use of which the splicing temperature is $\approx$ 2000°C the most important is the splicing time. In the experiment we accept: $t_2 \geq 4$ s and $I_2 \geq 17$ mA.

Why, then in the one-way measurement experiment $\log(\omega_1/\omega_2) \neq \log(\omega_2/\omega_1)$ something which needs to be explained, in spite of the fact that A loss decreases, Figs. 1–5, which means that ω_2 approaches ω_1.

With comparable core diameter and numerical apertures NA of spliced fibres, splice loss is bigger for λ = 1550 nm

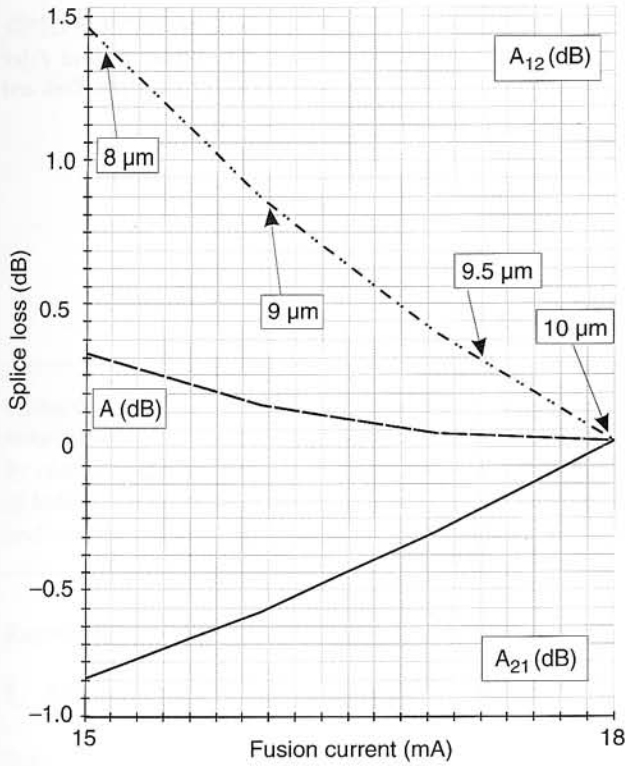

Fig. 15. Calculated loss A_{12}, A_{21}, and A on the basis of Eqs. (9)–(11). ω_2 = 10 μm (for all currents), ω_1 = 8–10 μm (for I_2 = 15–18 mA) have been assigned to fusion current.

then λ = 1310 nm. It results from the fact that the mode field for λ = 1550 nm is bigger. This means that the defect field which is the splice, is bigger for λ = 1550 nm which brings about a higher optical power loss. This phenomenon is not explicitly accounted for in Eq. (21).

Splice loss in fibres significantly differing in respect of core diameters and numerical apertures NA, on the contrary show higher values A for λ = 1310 nm than for λ = 1550 nm, Figs. 10–14. It refers especially to non-optimised splices. For optimised ones, i.e., for higher t_2 and I_2, these differences are smaller, coming down to zero, Figs. 10–14. Inverse loss dependency, which determines fusion time t_2 and fusion current I_2, on λ wavelength, for fibres significantly differing in respect at core diameters and numerical apertures. NA means, in our opinion, decrease of the effective defect area which is the splice for λ = 1550 nm, i.e., for a mode field diameter MFD bigger then in case of 1310 nm.

With the assumption of dopant diffusion within the splice, Fig. 16, for optimised splices "a bigger" it means to a high degree exclusion of cladding, and to a smaller degree exclusion of the core from the defect area which results in smaller splice loss for λ = 1550 nm, Fig. 16.

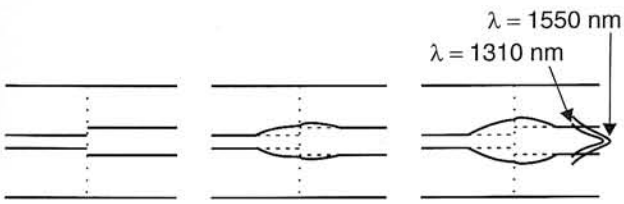

Fig. 16. Arising of transient area in the splice.

7. Conclusion

Standard splicing condition, for II basic step, of SMF one mode fibres with comparable core diameters and numerical apertures which means comparable mode field, for a fusion splicer FSU 925 RTC and FSU 975 are: t_2 = 2s, I_2 = 15–16.3 mA. According to Figs. 10–11 these conditions are not sufficient for fibres which significantly differ with NA and 2a. Then, fibre loss is A ≈ 0.12–0.6 dB. Thus obtaining splices with the loss, which is required in telecommunication ≤ 0.08 dB for II and III optical window requires splicing times $t_2 \geq 4$s and currents $I_2 \geq 17$ mA, Figs. 12–14. This result for splicing times corresponds with the results achieved during optimisation process of the intermediate area, Figs. 5–9. It ascertains the loss measurement convergence for II and III optical windows with $t_2 \geq 4$s and $I_2 \geq 17$ mA, Figs. 13–14. Finally, in order to obtain small loss for fibres, which significantly differ in respect of core diameter and numerical apertures (i.e., also in respect of mode field $MF = 2\omega = 2a/\sqrt{\ln[ka(NA)]}$) the middle, basic splicing step should be characterised by the following parameters: $t_2 \geq 4$ s and $I_2 \geq 17$ mA.

An indirect conclusion is also a statement of the fact that for non-optimised and optimised (to a smaller degree) single mode splice which significantly differ with NA and 2a the loss of these connections is smaller for λ = 1550 nm, than for λ = 1310 nm. It is an opposite result than case of splicing single mode fibres with comparable NA and 2a.

Acknowledgements

The work was financed by a grant of the State Committee for Scientific Research No 8T11 D00613.

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