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Scanning electron microscopy examination of telecommunication single mode fiber splices

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Longitudinal sections of fused splices of different telecommunication single mode fibers were prepared and examined by scanning electron microscopy (SEM). Splices were examined for diffusion of dopant elements and for the presence of an intermediate zone. Observations in the material contrast mode obtained with backscattered electrons and X-ray microanalysis with the use of an energy dispersive spectrometer were made. Material contrast provides much better imaging of fiber cores than X-ray microanalysis and it was chosen for further studies. SEM micrographs show low amount of diffusion and good coupling of cores in splices under examination. No visible intermediate zone has been found in splices of the same fibers or fibers with similar cores. In splices of fibers with different core diameters and/or different dopant distribution the transition between cores is smooth with no visible widening of cores.

Keywords: single mode fibers, fiber splices, scanning electron microscopy, backscattered electrons, material contrast.

1. Introduction

Most of the single mode fibers (SMF) consist of pure silica cladding and germanium doped silica core. Apart from germanium other materials can also be used as dopants in the core region for some special purposes, *e.g.*, fluorine in depressed cladding (DC) SMF and erbium in erbium doped fibers (EDF). Different dopant materials and different dopant concentration levels result in different refractive indexes of fibers. In general, an increase of dopant concentration in the core causes an increase of the refractive index difference between core and cladding, an increase of numerical aperture and a decrease of mode field diameter (MFD).

Connection of two single mode fibers causes optical energy loss [1]

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

where: A – splice loss [dB], ω_1, ω_2 – mode field radii of the first and the second fibers, respectively.

When fibers with the same MFD are connected the theoretical splice loss is equal to zero. MFD is given by [1]

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

where: $2a$ – core diameter, $k = 2\pi/\lambda$ (λ – wavelength), NA – numerical aperture.

In order to minimize optical signal loss in splices of fibers with different MFD, an intermediate zone with continuous change of MFD should be formed. It implies smooth transition of core diameters and dopant concentrations, and can be obtained by controlled diffusion of dopants during splicing [1], [2] (Fig. 1). The amount of diffusion

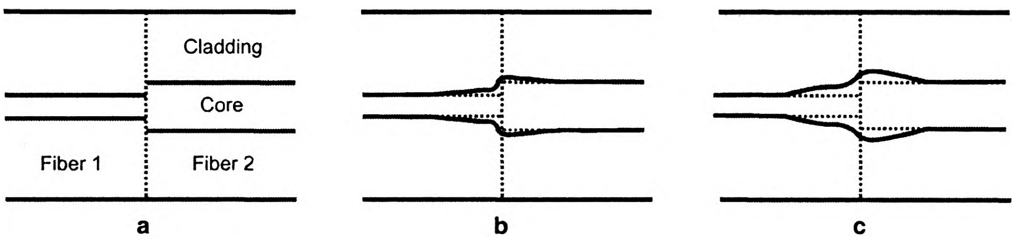

Fig. 1. Intermediate zone formation as a result of dopant diffusion during splicing. Initial condition (**a**), stages of intermediate zone formation (**b**, **c**). Fusion time increases from Fig. **b** to **c**.

depends on the temperature (fusion current in the case of an arc splicer), fusion time, dopant concentration in the core and on the material surrounding the core. Thus, obtaining an optimal intermediate zone is a function of time and fusion current [2], [3], and obviously, the type of fibers. RATUSZEK *et al.* [2], [3] developed a model of an intermediate zone formation and optimized splicing process for telecommunication single mode fibers of different types, investigated in the present work. The optimization process minimizes optical signal loss and enables obtaining optimum transition between cores. The aim of the present study is to visualize splice regions and to show the shapes of intermediate zones. Earlier observations of optimized splices with an interference-polarization microscope (PZO Bipolar PI, Poland) did not show clearly the existence of an intermediate zone. For the purpose of this study a SEM has been chosen because it has good resolution and is easily accessible. Prior to examination in the SEM, a longitudinal section of splice region has to be prepared. Two SEM techniques can be used for the imaging of sections, material contrast obtained with backscattered electrons and element distribution maps obtained with X-rays. The material contrast shows differences in the mean atomic number of the material on the specimen surface (areas with higher atomic number are lighter in micrographs). The X-ray map shows a distribution of a chosen element on the surface. The number of X-ray photons is much lower than the number of electrons, as a result X-ray images are much more noisy and they show distribution of the element if differences in its concentration are relatively high.

2. Materials and methods

Single mode telecommunication fibers with different parameters and obtained by different technologies were spliced. The types of fibers used in the work and their parameters are given in the Table. The fiber splices were made with the use of Ericsson FSU 925 RTC arc fusion splicer. The automatic program for standard SMF, supplied with the equipment, and optimized programs with higher times and fusion currents, developed by RATUSZEK *et al.* [2], [3], were used for the control of the splicing process. All splices were made in so-called "indoor" conditions (temperature 21±3 °C, relative humidity 50±20%). They have been designated as $(X\text{-}X)_Y$, where X is a number of the fiber from the Table and Y – the splicing program used (Aut – automatic, Opt – optimized). For instance, $(1\text{-}2)_{\mathrm{Aut}}$ and $(1\text{-}2)_{\mathrm{Opt}}$ designate the splices of fiber No. 1 and fiber No. 2 prepared with the use of automatic and optimized programs, respectively.

T a b l e. Types and parameters of single mode telecommunication fibers used in the experiment (DC SMF – depressed cladding SMF, DS SMF – dispersion shifted SMF, NZDF SMF – non-zero dispersion fiber SMF, OVD – outside vapor deposition, MCVD – modified chemical vapor deposition).

Fiber number		1	2	3	4	5
Type of the fiber		SMF	SMF	DC SMF	DS SMF	NZDF SMF (True Wave®)
Manufacturer		Siecor	Optical Fibres	Lycom	Lycom	Lucent Technologies
Fiber technology		OVD	OVD	MCVD	MCVD	MCVD
Core diameter [μm]		≈ 8.5	≈ 8.3	≈ 9.2	≈ 5.6	≈ 5.5
Refractive index profile						
MFD* [μm] at	λ = 1310 nm	≈ 9.3	8.8–9.6	≈ 8.8	7.0–8.5	—
	λ = 1550 nm	≈ 10.5	—	—	—	7.8–9.0
Numerical aperture		≈ 0.13	0.13–0.14	≈ 0.13	≈ 0.16	≈ 0.15

*According to definition II of Petermann

Pieces of fibers containing splices were placed on aluminum stubs, included in epoxy resin and grinded to half of their thickness. A special holder enabling precise removal of material was used. The thickness of the fiber during grinding was measured by a metallographic light microscope. When the section reached the core the process was performed very carefully and controlled in the SEM in a low vacuum mode. Next, specimens were polished with diamond pastes and alumina powders.

Splice sections were examined in the JEOL JSM5800LV scanning electron microscope. This is a standard SEM with thermionic electron gun. The microscope is equipped with a semiconductor detector for backscattered electrons (BSE) and an energy dispersive spectrometer (Oxford ISIS 300) for X-rays. The microscope was used in a standard high vacuum mode ($p \approx 10^{-2}$ Pa) and in a low vacuum mode ($p = 45$ Pa). The low vacuum mode enables insulators to be observed without conductive coating. As mentioned earlier, low vacuum mode was used to control the grinding process. Before final examinations specimens were coated with carbon layers and observed in the high vacuum mode.

3. SEM examinations of splices

Fibers consist of SiO_2 claddings and cores doped with GeO_2. Dopant concentration is relatively low and the contrast of cores in SEM micrographs is weak. Figure 2 presents images of the $(1\text{-}5)_{\mathrm{Opt}}$ splice; BSE image (Fig. 2**a**) showing material contrast and an X-ray map obtained with L_α radiation of Ge (Fig. 2**b**). Primary beam energy of 20 keV was used in order to provide enough current in an electron beam and good efficiency of the detector. The contrast in the BSE image was expanded electronically and good image of the fiber core was obtained. The X-ray image is very noisy. Its quality can

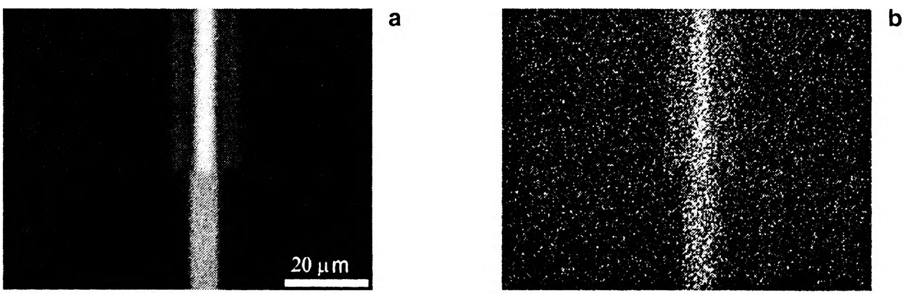

Fig. 2. Comparison of images of the $(1\text{-}5)_{\mathrm{Opt}}$ fiber splice section. Material contrast image obtained with backscattered electrons (**a**), X-ray map obtained with L_α radiation of Ge (**b**). Primary beam energy $E_0 = 20$ keV.

be improved by increasing a primary beam current or by advanced signal processing. Increasing the beam current leads to an increase of the beam diameter and worsens image resolution. Advanced signal processing procedures are not readily available. In the case of our equipment, X-ray distribution maps are not useful for investigation of diffusion in fiber splices and the material contrast mode has been chosen for further studies.

Figures 3 and 4 present images of different fiber splices in material contrast mode of the SEM. Examination of splices of the same fibers or fibers with similar core diameters does not show a visible intermediate zone. Low magnification images

(Figs. 3**a**, **b**) of splice regions and subsequent observations at higher magnifications have not enabled location of splice positions. Any widening caused by dopant diffusion was not visible. Figures 3**c**–**f** show typical images of cores in the splice zones at higher magnifications.

When fibers with different core diameters and/or dopant distribution are coupled the position of the splice is clearly seen (Fig. 4). The left column shows grayscale images of splices and the right column the same images in pseudocolors. Pseudocolor images enable better visibility of differences in dopant concentration in cores and better visibility of intermediate zones. Diameters of cores and dopant concentrations in the $(1\text{-}3)_{\mathrm{Opt}}$ splice (Fig. 4**b**) are similar and there is not visible any intermediate zone. The fiber No. 3 contains an intermediate layer between the core and the cladding but it has

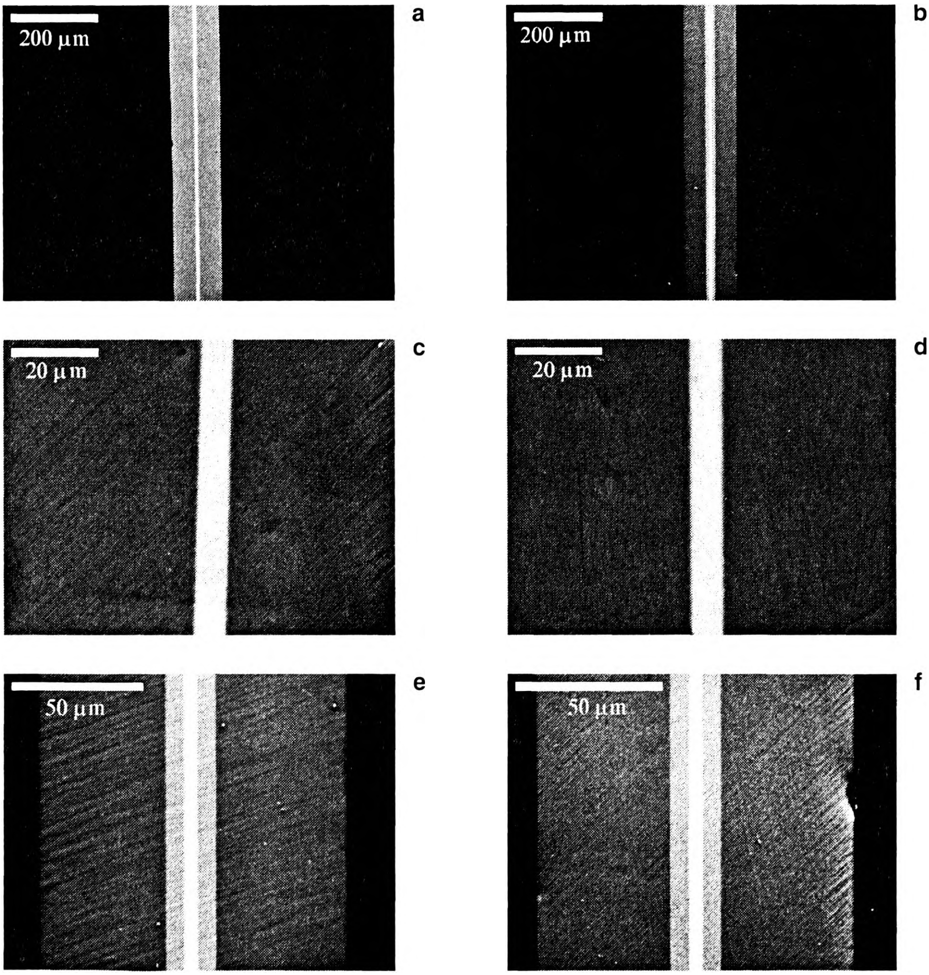

Fig. 3. Images of splices of the same fibers or fibers with similar cores. $(1\text{-}2)_{\mathrm{Opt}}$ splice (**a**), $(5\text{-}5)_{\mathrm{Aut}}$ splice (**b**), $(1\text{-}2)_{\mathrm{Aut}}$ splice (**c**), $(1\text{-}2)_{\mathrm{Opt}}$ splice (**d**), $(5\text{-}5)_{\mathrm{Aut}}$ splice (**e**), $(5\text{-}5)_{\mathrm{Opt}}$ splice (**f**). Primary beam energy $E_0 = 20$ keV.

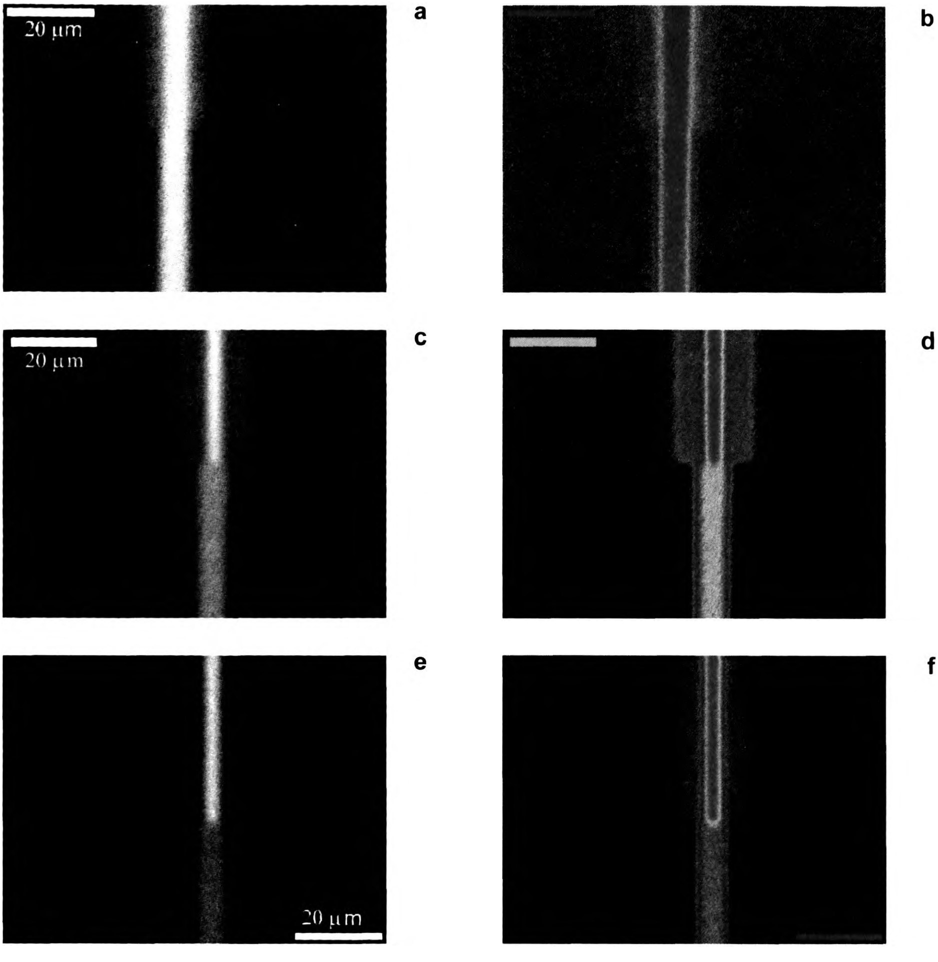

Fig. 4. Images of splices of fibers with different cores. Left column – grayscale images, right column – pseudocolor images. $(1\text{-}3)_{Opt}$ splice (**a**, **b**), $(1\text{-}4)_{Opt}$ splice (**c**, **d**) $(1\text{-}5)_{Opt}$ splice (**e**, **f**). Primary beam energy $E_0 = 20$ keV.

not been practically affected by diffusion. Fibers in $(1\text{-}4)_{Opt}$ and $(1\text{-}5)_{Opt}$ splices (Fig. 4**d**, **f**) differ in diameters of cores as well as in dopant concentration and distribution. The transient zone between cores in these splices is smooth and there is not visible any widening of the cores caused by diffusion. A small misalignment of cores in the $(1\text{-}4)_{Opt}$ splice is noticed.

4. Discussion and conclusions

Material contrast in the SEM gives good images of telecommunication fiber cores and is a useful method of examination of telecommunication fiber splices. Visibility of the intermediate zone in splices can be improved by pseudo-coloring of SEM images. The study has shown a very good coupling between the fibers examined and low amount of diffusion during fusion splicing.

Observations are affected by spatial resolution of the method that arises from the interaction of an electron beam with the specimen. The beam energy in our study was relatively high (20 keV) in order to obtain high BSE signal. Such a beam penetrates about 4.5 μm in a SiO_2 cladding and little less in a core. BSE can escape from about half of this value, though most of them penetrate much shallower into the specimen. The lateral spread of the beam is comparable with a depth spread. Moreover, the cores are not exactly sectioned in their centers and, in effect, electrons penetrate different distances in cores in different specimens. These factors worsen sharpness and change brightness of cores in micrographs.

The sharpness of core images could be improved by lowering the beam energy. Lowering the beam energy entails the use of the SEM with a brighter field-emission gun and a BSE detector efficient at low electron energies. Unfortunately, such a combination of equipment is not easily available. Quantitative estimation of the influence of beam parameters and section displacement on an appearance of images and their resolution can be done by Monte Carlo simulation of electron scattering in the specimen (work in progress).

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