# Reduction of splice loss between dissimilar fibers by tapering and fattening

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A method for reducing splice loss between dissimilar optical fibers is presented. The fibers are first spliced by using a standard fusion splicing procedure, and then the fiber with the greater core is tapered before the splice point, while the fiber with the smaller core is fattened. By using this technique we have consistently obtained splice loss values of 0.13 dB between a DS/SMF and an SMF28 fiber, and 0.09 dB between a 980HP fiber and an SMF28 fiber.

*Keywords:* Optical fibers; fusion splicing; tapering; fattening.

Presentamos un método para reducir las perdidas en empalmes entre fibras ópticas con diferentes características. Las fibras son unidas usando un procedimiento de fusión estándar, para luego reducir el diámetro de la fibra con el núcleo de mayor tamaño antes del punto de unión, mientras que la fibra con el diámetro de núcleo menor es ensanchada. Mediante el uso de esta técnica hemos obtenido de manera consistente perdidas de 0.13 dB en un empalme entre una fibra DS/SMF y una fibra SMF28, y perdidas de 0.09 dB en un empalme entre una fibra 980HP y una fibra SMF28.

*Descriptores:* Fibras ópticas; empalmado por fusión; afilado; engrosado.

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## 1. Introduction

Modern optical fiber telecommunication systems consist of sections of optical fibers that are inserted in order to perform functions such as dispersion compensation, amplification, optical signal processing, and so on. In general, these fibers differ in their optical characteristics, particularly in their geometrical dimensions and refractive index profile, which instead results in dissimilar mode field diameters that determine the splice loss when the fibers are interconnected. In this and other cases a reduction of splice loss is required in order to obtain an optimum performance of the optical fiber system. Several methods have been proposed to reduce the splice loss between dissimilar fibers, *i.e.*, thermal diffusion of the fiber core [1], tapering [2], fattening [3], and using intermediate fibers [4]. In the first case, thermal diffusion is time consuming that the fiber to be expanded needs to have some content of dopants, for instance germanium [5] or fluorine [6], so that this is not applicable to all type of fibers. On the other hand, the use of intermediate fibers requires specially designed fibers that have optical characteristics that closely match the mode field diameter of the fibers to be joined, and moreover several sections are needed. Thus only tapering and fattening can be applied to any type of optical fiber since they work to reduce or increase the mode field diameter by changing the diameter of the optical fiber core.

In this paper we combine the tapering and fattening methods for reducing the splice loss between dissimilar fibers. In contrast with the pure tapering and fattening, we do not use special machines for tapering or fattening, other than commercial fusion splicing equipment. The procedure used in this work is the following:

(1) optimization of the fusion splice parameters by using Taguchi's algorithm to obtain the lowest possible loss without tapering and fattening, and

(2) tapering of the larger core diameter fiber and

(3) fattening of the smaller fiber core diameter.

Using this procedure we obtained 0.13 dB splice loss at 1.55 $\mu$m wavelength between a dispersion-shifted fiber DS/SMF and a standard SMF28 fiber, and 0.09 dB splice loss between a single mode fiber 980HP and a standard SMF28 fiber.

## 2. Optimization of splicing parameters

The first step for obtaining a low-loss splice between dissimilar fibers is the understanding of the fusion process. Here we particularize the fusion procedure to that corresponding to a S175 FITEL fusion splicer. Considering this particular equipment, once the fiber ends have been prepared by removing the outer polymer, cleaning the glass surface, cleaving the fiber ends to a mirror surface, and properly positioning the fiber ends in the fusion splicing machine, the fusion splicing procedure consists of the following steps:

1. Arc cleaning: A low-power and low-duration electric arc evaporates any particle or dust on the fiber surface.

2. Prefusion time: During the time ranging between 200 and 260 ms an electric arc softens the fiber ends.

3. Fusion time: During this period that follows the prefusion time the electric arc is maintained while both fibers are pushed against each other overlapping by a distance known as z-push thus forming the joint of the fibers. The z-push, distance may vary between 9 and 39 $\mu$m in our particular case.

4. Additional arc: In some cases the application of an additional arc with durations in the order of 1 to 3 seconds may help to reduce splice loss by thermal diffusion of the fiber core, or by releasing induced stresses during the fusion procedure.

Taking into account the above fusion-splicing procedure and the fusion-splicing machine we are using, we found that there are four parameters that can affect the splice loss, namely, arc power, prefusion time, fusion time, and z-push distance. Following Yablon [7], we neglect the interaction between these parameters and use Taguchi's optimization method. We have used a Taguchi's orthogonal array L9, with the four parameters (arc power, prefusion time, fusion time, and z-push distance) varied between three different levels, while the quality parameter are the splice loss. At each experiment we measure the splice loss by using the two-splice method [7], where we used a single-mode diode laser with 1.53 $\mu$m central wavelength as the light source. Table I shows the orthogonal array corresponding to one set of experiments conducted to find the optimum parameters for minimizing the splice loss between a DS/SMF fiber and an SMF28 fiber. Each row in this table corresponds to one experiment or splice carried out with the parameter values indicated. Thus, at each iteration it is necessary to carry out 9 experiments or splices. The next step is the analysis of the results, which was done using the formulas and procedure described in Ref. 7. In particular we calculate the percentage of importance of each parameter by using the following formula [7]:

$$\% \text{ of importance} = \frac{SS_{p_j}}{SS_{total}} \qquad (1)$$

where $SS_{p_j}$ is the sum-of-squares resulting from parameter $p_i$, and $SS_{total}$ is the total sum-of-squares associated with each individual parameter. Once we identify the parameters with the higher importance for one set of experiments we modify the value levels of these parameters trying to select values that produce lower splice losses. Table II shows the results of the analysis corresponding to Table I. In this particular set of experiments, we observe that arc power has the higher importance, and the lowest loss is obtained when arc power is set to 86 W. Thus for the next set of experiments the arc power levels are 84, 86, and 88 W. These levels of arc power reduce the importance of this parameter, and at the same time the importance of the other parameters is increased, so that these parameters should be adjusted in the following set of experiments until we find the optimum parameters. After repeating the optimization procedure approximately 15 times for each splice, which means that we carried out more than 270 experiments or splices, we found that the optimum parameters for obtaining a splice loss ranging from 0.25 and 0.3 dB between DS/SMF and a SMF28 fiber were 71 W arc power, 1450 ms of fusion time, 15 $\mu$m of z-push distance, and 250 ms of prefusion time. On the other hand, the optimum parameters to obtain a splice loss ranging from 0.3 and 0.35 dB between a DS/SMF fiber and a 980 HP fiber were 69 W of arc power, 1350 ms of fusion time, 11 $\mu$m of z-push distance, and 240 ms of prefusion time.

## 3. Variation in splice loss with core diameter

The most important feature of a fusion splice is splice loss, and refers to the part of the optical power that is not transmitted through the splice and is radiated out of the fiber. The total loss in decibels at a fusion splice is given by the following relationship [7]:

$$\alpha_{splice} = 10 \log_{10}\left(\frac{P_{in}}{P_{trans}}\right) \qquad (2)$$

where $P_{in}$ is the total power reaching the splice and $P_{trans}$ is the total power leaving the splice.

The loss in a fusion splice can occur for the following reasons:

1) defective splicing due to misalignment or deformation at the splice and can usually be solved through the proper preparation of the fibers before being spliced, and

2) differences in the optical characteristics of the fibers, in particular, core diameter, and numerical aperture.

In our particular case, we suppose that the fibers were prepared properly before being spliced, so we just deal with the loss caused by differences in their optical characteristics of propagation. In general, if the fibers to be spliced are single-mode, the principal difference between them comes from the modal field radius, which can be calculated using the following approximate expression:

$$w \approx a_{core}\left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}\right) \qquad (3)$$

where $a_{core}$ is the fiber core radius and $V$ is the generalized frequency defined by the following relationship:

$$V = \frac{2\pi}{\lambda} a_{core} NA \qquad (4)$$

Here, $\lambda$ is the wavelength and *NA* is the numerical aperture of the fiber and is given by [8]:

$$NA = \sqrt{n_1^2 - n_2^2} \qquad (5)$$

with $n_1$ and $n_2$ being the refractive indexes in regions of the core and cladding. Thus, according to relations (2) - (4), two fibers may have a different mode field diameter, at a given wavelength, if the core diameter or numerical aperture is different. Figure 1 shows the radius variation of the modal field for a fiber SMF28 (with $a_{core}$ = 4.15 $\mu$m, *NA* = 0.13) and a fiber DS/SMF (with $a_{core}$ =3.5 $\mu$m, *NA* = 0.17).

As shown in Fig. 1, the two fibers differ in the size of the modal field radius in the entire range of wavelengths. For example, at a wavelength of 1.55 $\mu$m, the modal field radius of the fiber SMF28 is 4.88 $\mu$m, while the modal field radius of the fiber DS/SMF is 3.83 $\mu$m. This difference in the modal field radius results in loss if the two fibers are spliced. The loss by the difference in radius of the modal field is calculated by using the following formula:

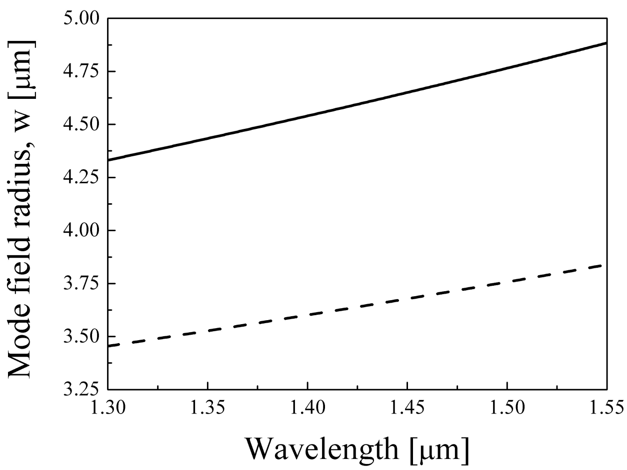


FIGURE 1. Variation of the mode field radius w with the wavelength for the fibers SMF28 (solid line) and DS/SMF (dashed line).

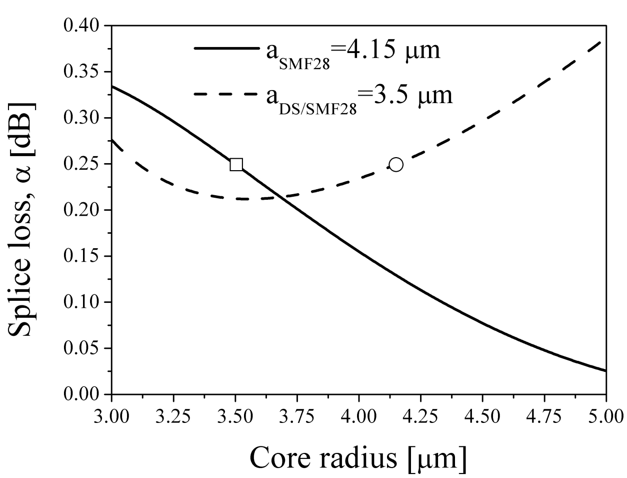


FIGURE 2. Splice loss as a function of the core radius for the case where $a_{SMF28}$ fixed and $a_{DS/SMF}$ is varying (solid line), and for the case where $a_{DS/SMF}$ is fixed and $a_{SMF28}$ is varying (dashed line).

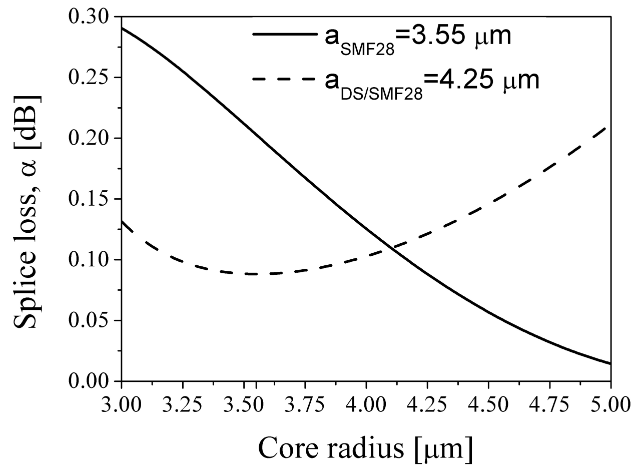


FIGURE 3. Variation in splice loss as a function of the core radius in the case where $a_{SMF28}$=3.55 $\mu$m and $a_{DS/SMF}$ is varying, and in the case where $a_{DS/SMF}$=4.25 $\mu$m and $a_{SMF28}$ is varying.

$$\alpha = -20\log_{10}\left(\frac{2w_{SMF28}w_{DS/SMF}}{w^2_{SMF28}+w^2_{DS/SMF}}\right) \qquad (6)$$

Thus, at a wavelength of 1.55 $\mu$m the loss at a splice between these two fibers would be 0.28 dB.

By examining Eq. (3) we note that the modal field diameter can be varied by varying the size of the core. Since the technique we use to reduce losses in splices between fibers of different optical characteristics is based on the change in geometrical dimensions of the fiber cores, we must consider the effect of the decrease or increase in the size of the fiber core on the level of loss at the splice. The solid line in Fig. 2 shows the variation in splice loss when the core diameter of the DS/SMF fiber is varied keeping the diameter of the SMF28 fiber fixed, and the square dot in this figure shows the original diameter of the DS/SMF fiber core. We observe that increasing the diameter of the DS/SMF fiber results in a loss reduction which can reach 0.02 dB if we increase the core diameter from 3.5 $\mu$m to 5 $\mu$m. However, for a core diameter of 5 $\mu$m the fiber will be multimode, and in this case relations (3) and (6) are not valid. Thus, we assume that, in order to have a realistic loss reduction, the core diameter of the DS/SMF fiber can be increased to a maximum of 4.25 $\mu$m (21.4% increase in core diameter) where the splice loss is 0.113 dB. On the other hand, the dashed line in Fig. 2 shows the variation in splice loss when the core diameter of the SMF28 fiber is varied keeping the core radius of the DS/SMF fiber fixed at 3.5 $\mu$m, and the circle dot corresponds to the original core diameter of the SMF28 fiber. In this case we observe that the minimum loss of 0.21 dB is obtained when the core diameter of the SMF28 fiber is reduced from 4.15 $\mu$m to 3.55 $\mu$m.

As can be observed in the solid and dashed lines of Fig. 3, if we reduce the core diameter of the SMF28 fiber from 4.15 $\mu$m to 3.55 $\mu$m, and increase the core diameter of the DS/SMF fiber from 3.5 to 4.25, 0.08dB loss is obtained. The results obtained here prove that it is possible to reduce losses in fiber splices by simply changing the dimensions of the core diameters. The values obtained in our simulations are not exact since there is some uncertainty in the real values of core diameters and numerical apertures of the fibers used in this work.

On the other hand, Fig. 3 shows how, by reducing the core radius of the fiber SMF28 of 4.15 $\mu$m to approximately 3.16 $\mu$m, the loss is reduced practically to zero. From this we may conclude that we could reduce the loss by considerably widening the fiber DS/SMF and/or tapering the fiber SMF28.

## 4. Tapering and fattening after splicing dissimilar fibers

As we have observed in the last section, changing the diameter of the spliced fibers can reduce the splice loss. Figure 4 shows the procedure for reducing de fiber diameter or tapering after the fibers are spliced. After the normal splice is completed (Fig. 4a), the electrodes are moved by $\sim$80 $\mu$m to the side where the core diameter is higher. A slight tension is applied by moving the step motors of the fusion splicer in opposite directions by 50 $\mu$m, and then the electric arc is applied (Fig. 4b), resulting in a tapered fiber section where the core diameter is reduced (Fig. 4c).

On the other hand, the process for increasing the fiber diameter or fattening the fiber is shown in Fig. 5. After the fibers are spliced (Fig. 5a), the electrodes are moved $\sim$50 $\mu$m to the side where the core diameter is smaller and a splice process is applied (Fig. 5b), which results in a fiber with an increased diameter. To enhance the fattening we changed the z-push distance parameter to 20 $\mu$m, in contrast with the original value of 11 $\mu$m, which is used to make a standard splice. The final result is the increase in the fiber core diameter.

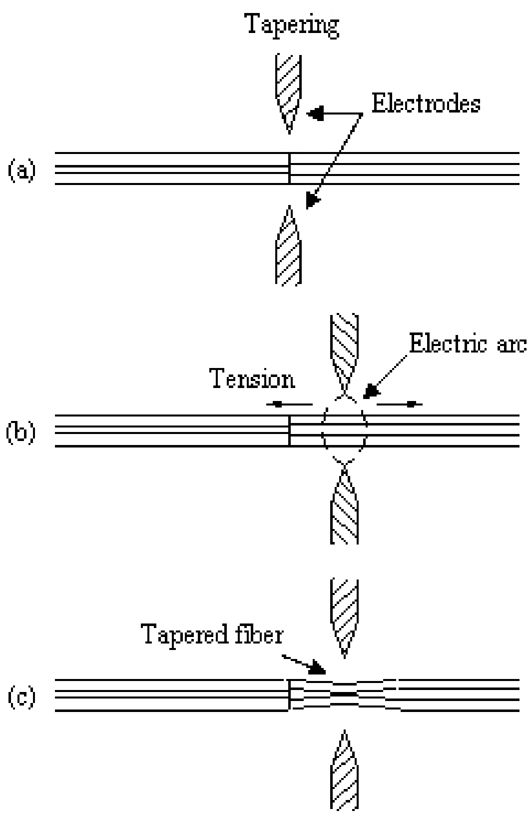


FIGURE 4. Tapering fiber process.

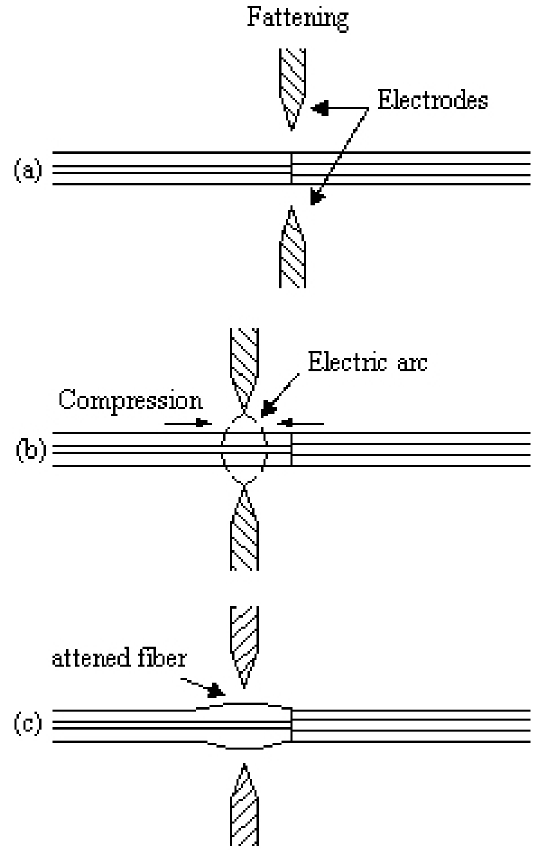


FIGURE 5. Fattening fiber process.

We used tapering and fattening to reduce the splice loss between the fiber SMF28 and the fiber 980HP. In particular, the fiber SMF28 was tapered by applying the process described above several times until we obtained a minimum loss. Then the fiber 980HP was fattened, also applying the process several times, until we obtained the minimum loss. The minimum loss point is clearly identified since further tapering or fattening beyond that point will increase the splice loss. As a final result, we obtained a minimum loss of 0.09 dB with a standard deviation of 0.015 dB. On the other hand, for the reduction of splice loss between the SMF28 fiber and the DS/SMF fiber, we only fattened the fiber DS/SMF, obtaining a minimum loss of 0.13 dB with a standard deviation of 0.014 dB. The reproducibility of the results can be increased by the use of a high quality fiber cleaver, since this is a factor that determines the loss in splices made using the same parameters of the fusion splicer. It is worth to mention that in order to identify the minimum loss point.

## 5. Conclusions

In conclusion, we have demonstrated the feasibility of reducing the splice loss between dissimilar fibers by tapering and/or fattening the fiber. After optimizing the splice parameters using Taguchi's method, we reduce the splice loss between the fibers SMF-28 and DS/SMF by fattening the fiber with the smaller diameter, *i.e.*, the fiber DS/SMF. In this case we were able to reduce the splice loss to a minimum value of 0.13 dB. On the other hand, the reduction of splice loss between the fiber SMF28 and the fiber 980HP required the reduction of the SMF28 core diameter by tapering and the increase of the core diameter of the 980HP fiber by fattening, obtaining a minimum loss of 0.09 dB. In both cases the level of losses is close to that obtained when the fibers to be spliced are identical. Further reduction is possible by a thoroughly preparation of the fiber ends before splicing, in particular a higher quality cleaver can help to reduce the splice loss by reducing the contribution from the loss induced by angular misalignment, which appears when the fiber cleave is not perfectly flat. Despite this fact, the level of losses is between the tolerated levels required in optical fiber systems, and more importantly, the method can be applied to any type of fibers, by following the procedures outlined in this work.

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