Optimization of Fusion Splice Process for High Numerical Aperture Coupler Fiber and Erbium Doped Fiber

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ABSTRACT

Fusion splicing erbium doped fiber (EDF) to other single mode fibers has become more critical as the required overall insertion loss for erbium doped fiber amplifiers (EDFA) has significantly decreased in the last few years. In this paper, we describe and discuss an approach to developing a low loss splice method for fusion splicing high numerical aperture (NA) 980/1600 wavelength-division-multiplexing (WDM) coupler fiber and EDF. The results indicate that the fiber end preparation before the fusion is especially critical for obtaining a low loss splice for the fiber pair.

Keywords: High NA 980/1600 WDM coupler fiber, EDF, Fusion Splice Loss

INTRODUCTION

In a typical erbium doped fiber amplifier (EDFA), a wavelength-division-multiplexing (WDM) fiber coupler is used as an energy and signal combiner to transmit the signal energy and deliver the optical energy from a laser diode (LD) to the erbium doped fiber (EDF), as shown in Figure 1. The transmission signal at wavelengths from 1520 nm to 1600 nm is guided through the WDM and EDF. Light coming from a 980 nm LD will be sent to the EDF to excite the erbium ions in the EDF. As depicted in the diagram, the WDM is fusion-spliced to a standard transmission fiber, an EDF, and the pigtail fiber of the LD at positions A, B and C.

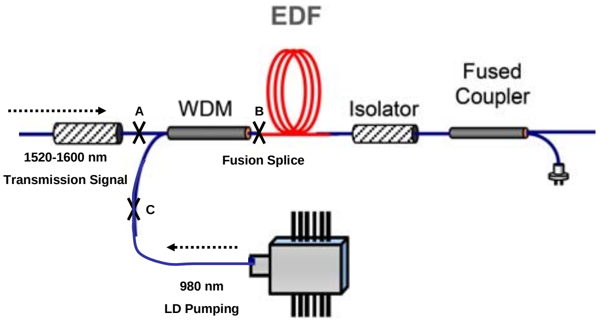

Figure 1 Configuration of EDFA

It is critical to minimize the splice loss, since any loss introduced by a fusion splice will eventually offset the optical gain obtained by EDF. In addition to this, the added insertion loss will increase the noise figure of the amplifier too.

The splice loss between an EDF and transmission fiber can be as high as 3.4 dB according to a simple calculation by Marcuse [1] due to the mismatch of their mode field diameter (MFD). Several approaches to obtain low splice loss for

EDF were reported by Singh [2], Tam [3], and Zheng [4]. Zheng introduced a real-time-control technique to monitor the splice loss change during the process and obtain a splice with lowest loss. Other authors investigated heat treatment of the EDF during the splice process or pre-splice to expand the EDF's MFD by allowing diffusion of dopant ions to the vicinity of the core to reduce the MFD mismatch. According to Tam, a 67% core size increase during fusion of 6 min at 1100°C was observed due to germanium ion diffusion [3]. Recent published papers by Veng [5] discussed that modification of EDF could lower the splice loss at 980 nm, 1310 nm, and 1550 nm to about 0.1 dB.

High NA 980/1600 WDM coupler designed to achieve low bend sensitivity for L-band EDFA applications possesses a smaller MFD of 6.75 µm at 1550 nm than the WDM fiber designed for C-band, which has an MFD of 7.8 µm at 1550 nm [6]. A typical EDF has a MFD between 6.0 and 6.7 µm at 1550 nm. The two MFDs are similar. However, when these fibers are fusion spliced together, the originally matched MFDs will become mismatched as the fibers with different glass compositions respond to the heat differently. To address this issue, the splice program requires optimization.

EXPERIMENTAL

An HP81531A lightwave multimeter with HP81531A sensor module and HP81554SM laser source module was used to deliver and measure the power at 1310 nm wavelength. An Ericsson EFC-11 cleaver and Ericsson 995FA splicer were used to prepare and splice the EDF and coupler fiber. Both pieces of Ericsson equipment were calibrated by an Ericsson distributor before the test. The system set up is shown in Figure 2. Fibers to be spliced were stripped and cleaved.

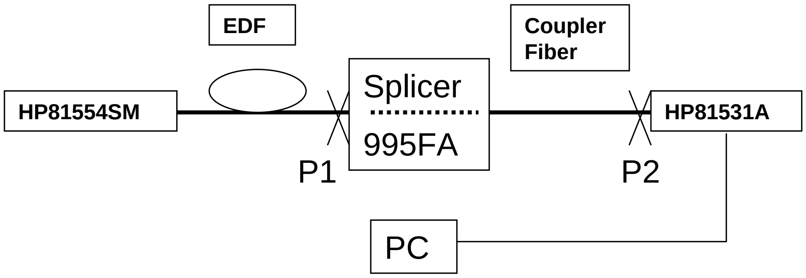

Figure 2 Splice Measurement Setup

Power P_1 is measured as the baseline before each splice. Then an integration sphere continuously records the transmitted power P_2 during the course of splice. The difference between P_1 and P_2 ($\Delta P=P_1-P_2$) as a function of fusion time is then used as a measure to determine desired condition.

A standard single mode transmission fiber and two OFS fibers, high NA coupler fiber and EDF, were used in this test. OFS fiber properties are listed in Table 1.

Table 1 Characteristics of Coupler Fiber and Er Doped Fiber Properties

	High NA Coupler Fiber	EDF
Cutoff Wavelength (nm)	930	1040
Numerical Aperture	0.21	0.18
Loss at 1550 nm	0.4 dB/km	2.05 dB/m
Mode Field Diameter at 1550 nm (μm)	6.75	6.72
Core Eccentricity (μm)	0.2	0.3
Fiber Outside Diameter (μm)	125	125
Coating Outside Diameter (μm)	250	250

In a typical fusion optimization, first test is to splice an EDF fiber to a single mode fiber. This is to establish a reference for the high NA coupler fiber. P_1 and P_2 are measured before and during the process. A standard single mode splice program is used for this test. Figure 3 displays a typical curve of transmitted power, P_2, as a function of time during the process for an EDF and single mode fiber pair. The value of P_2 at time = 0 is about 95% of P_1 when the fibers are placed sufficiently close to each other and the process is ready to start. As the fibers are driven toward each other, P_2 increases rapidly as more power is transmitted. At time = T_1, the transmitted power increases abruptly to a higher level, as the fiber ends come into contact and the air gap between them disappears. At the same time, pre-fusion heating begins. The transmitted power drops quickly as the process proceeds from T_1 to T_2, as both of the ends deform during the pre-fusion stage. At time = T_2, more current is applied to generate high heat to fuse the fibers. Under the high temperature, the MFD of the EDF increases gradually as the result of diffusion of dopant ions in the core of the EDF. This increase in MFD of the EDF reduces the mismatch in MFD with single mode transmission fiber, which has a typical MFD of 9.6 μm. Consequently, the transmitted power P_2 increases gradually. The transmitted power reaches a maximum value at time = T_3 when a minimum mismatch is achieved. The existence of such a maximum in transmitted power gives us a convenient indicator for optimizing the process. If we stop the process at time = T_3, the splice will have the lowest loss. However, if we continue to heat the splice, further increase in the MFD of the EDF can increase the MFD mismatch, resulting in a gradual decrease in transmitted power.

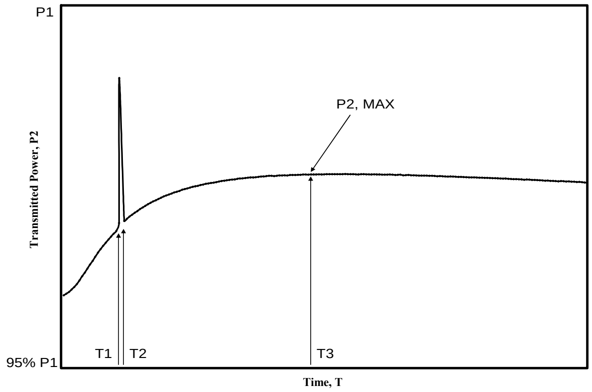

Figure 3 Typical Curve of Transmitted Power P_2 as a Function of Time

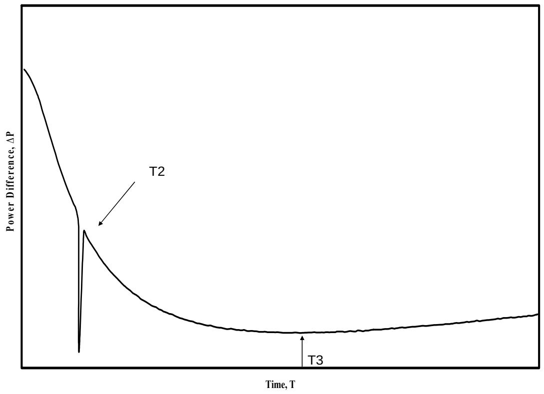

Figure 4 ΔP Curve as a Function of Time.

Since we can measure P_1 before the splice, ΔP instead of P_2 can also be used to monitor the transmitted power, as shown in Figure 4.

RESULTS AND DISCUSSION

We have described the splicing process for an EDF and SMF28 fiber pair. The process is similar for fusion splicing an EDF with a coupler fiber. However, we can expect a different behavior in transmitted power when fusion splicing an EDF to a high NA fiber since the high NA fiber has different characteristics. For instance, the fiber has an MFD close to that of the EDF. Therefore, MFD increase of the EDF could cause the MFD mismatch to increase instead of decrease.

On the other hand, the high NA fiber has higher Ge concentration in the core of the fiber and could thus cause more significant diffusion, leading to an increase in MFD. We predicted that this effect would be very limited.

To create a splice program for the EDF and high NA coupler fiber pairs, we have experimented with four different values of the fusion current II of 12 (Test 1), 13 (Test 2), 14 (Test 3), and 15 mA (Test 4) while keeping the pre-fusion current constant. For each test, six pairs of samples were tested. Typical curves of ΔP versus fusion time are plotted in Figure 5. For clarity, the fusion time in the graph begins at $t = T_2$ and the pre-fusion condition is kept the same.

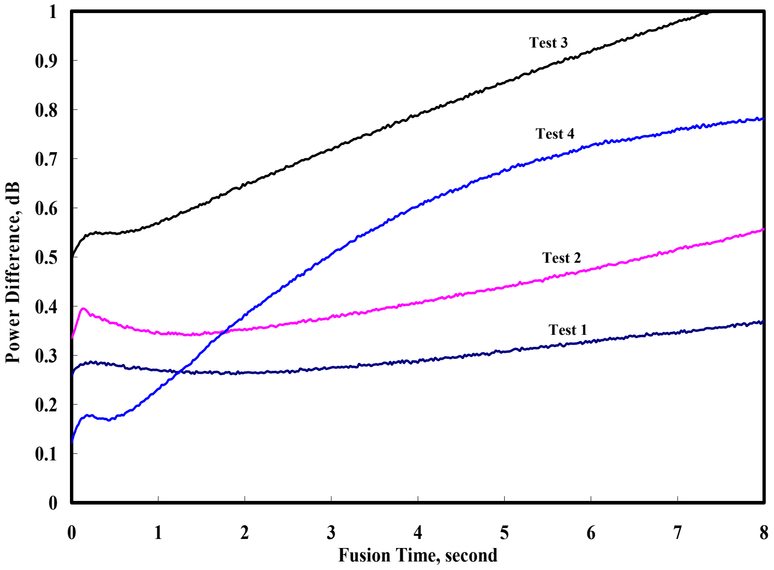

Figure 5 Typical Curves of ΔP Verses Fusion Time

It is interesting to note that the curves in Figure 5 look different from those plotted in Figure 4. This is mainly due to the fact that the EDF's MFD is so close to that of the high NA coupler fiber before fusion; therefore, the initial MFD mismatch is relatively low and the mismatch increases with heating. As we can see in Figure 5, ΔP starts low and moves up quickly as the fusion current is increased. The initial ΔP value for each test may not be important since it is mainly determined by initial fiber alignment before fusion. When lower current is used, ΔP increases with a slower rate with time. This may be readily explained by the temperature dependence of diffusion of the dopants in the cores of the two fibers. The two fibers have different diffusion characteristics and therefore the core of the fiber will respond to heat differently. The diffusion of the dopants will certainly lead to changes in fiber properties, such as MFD and NA. Since ΔP is critically dependant on the fiber MFD mismatch, the changes in fiber properties will affect splice loss. Higher fusion current may cause a fast increase in the MFD of an EDF, which is known to increase more readily when heated than the MFD of a coupler fiber because of higher dopant concentration. If we assume that all of these tests start with approximately the same initial value of ΔP, the optimized fusion time corresponding to the lowest ΔP is shown to be about 2, 1.4, 0.6, and 0.4 seconds, for Test 1, Test 2, Test 3, and Test 4, respectively. Low fusion current seems to be a good choice, with the lowest ΔP and reasonable fusion time. However, in our experience, choosing a low fusion current could cause low splice strength. In addition, we have also observed that the initial ΔP at time T_2 for all four tests is typically the lowest ΔP. This means that additional heating time will not lower the splice loss.

These observations suggest that the conventional approach of adjusting the fusion current and fusion time to achieve the lowest splice loss (low ΔP) seems ineffective for such a fiber pair. The ΔP at T_2 appears to be more critical as it seems to determine the minimum splice loss for this pair of fibers. Given the fiber types and fiber alignment, ΔP is mostly determined by the quality of the fiber, such as angle of the cleaved fibers.

In addition to fiber linear alignment, which is controlled by the splicer, there are at least two variables in characterizing the coupling efficiency before the fusion: the angles of the cleaved fibers and their relative orientation. Cleaved angles can be measured and cleaving can be repeated if the angle is determined to be too big. However, the relative rotational orientation is not controlled by the splice program. That is, even when the cleaved fiber angles are identical, the angular mismatch can cause less efficient coupling, leading to a lower P_2. To experimentally verify this, fusion splices were performed in which ΔP at time T_2 was used as a measure of coupling efficiency; and the sum of the two cleave angles, called combined angle, was recorded as the variable. Results are displayed in Figure 6. All of these tests were performed under the same pre-fusion condition.

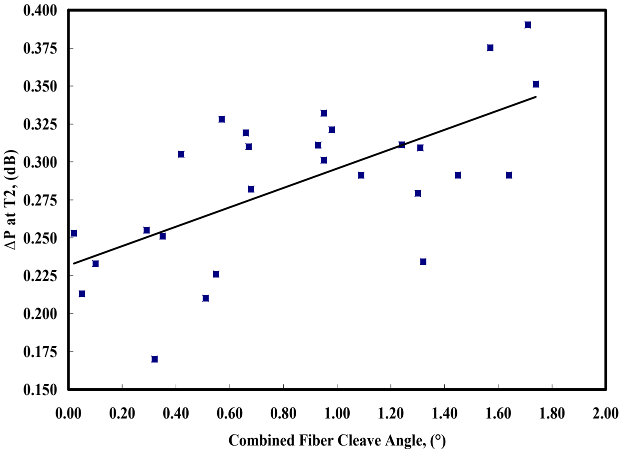

Figure 6 ΔP at time T_2 Verse Combined Cleave Angle

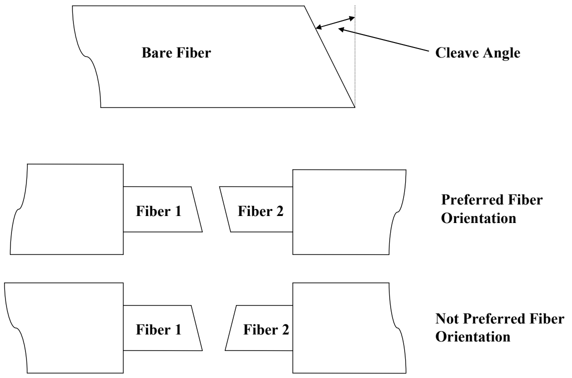

Figure 7 Cleave Angle Illustration

It is seen that ΔP at time T_2 increases with the combined angle. There is a wide range in ΔP for a fixed value of combined angle. This may be explained by the angular mis-match of the fibers. Figure 7 depicts two extreme cases of perfect match and complete mis-match. The lower limit of the range perhaps corresponds to the preferred orientation and the highest limit corresponds to the worst mis-match. The range is estimated to be 0.125 dB. There is no simple way to eliminate this variation, as the splicer usually does not allow fiber rotation and the quality of angular alignment would have to be determined when fibers are fusion spliced.

CONCLUSION

For fusion splicing a high NA coupler fiber with an EDF, we need to choose low current, for example 12 mA, to control the diffusion induced MFD mismatch in order to minimize power loss. For the same argument, the fusion time should also be minimized as long as the fibers are fully fused and the strength of the splice is ensured. The most important factor for low splice loss for this pair of fibers is the fiber end preparation, i.e. the fiber cleave angle. This determines the final splice loss while the fusion current and fusion time have limited effects. In order to achieve low loss splice for this fiber pair, we need to minimize the cleave angles and the angular mismatch of the cleaved fibers. By controlling the combined cleave angle smaller than 0.6 degree, we reduced the average six test splice loss from 0.5 dB under 12 mA fusion current to 0.2 – 0.3 dB.

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