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Fusion Splicing for a Large Mode Area Photonic Crystal Fiber with Conventional Single Mode Fiber

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Abstract: In this paper the experimentally obtained conditions for the fusion splicing with photonic crystal fibers (PCF) having large mode areas were reported. The physical mechanism of the splice loss and the microhole collapse property of photonic crystal fiber (PCF) were studied. By controlling the arc-power and the arc-time of a conventional electric arc fusion splicer (FSM-60S), the minimum loss of splicing for fusion two conventional single mode fibers (SMF-28) was (0.00dB), which has similar mode field diameter. For splicing PCF (LMA-10) with a conventional single mode fiber (SMF-28), the loss was increased due to the mode field mismatch.

Introduction

Photonic crystal fiber (PCF) is a unique type of optical fiber incorporating an array of air holes that run along its length, reminiscent of a crystal lattice, which gives to this type of fiber its name [1]. There are two main types of PCF: air-guiding which guides light via a photonic band-gap effect and index-guiding which guides light via a modified total internal reflection mechanism [1, 2].

In air-guided PCF, the core is hollow, and light is guided by the photonic band gap (PBG) effect, a mechanism that does not require a higher refractive index in the core in order to confine and guide light. The PBG guidance effect relies on coherent backscattering of light into the core. In index-guided PCFs the core area is solid and the light is confined to a central core as in conventional fibers [1].

There are many kinds of fusion splicing techniques, enabling connection between two optical fibers, such as an electric arc [3], and a CO_2 laser [4]. It is likely that electric arc fusion splicing technique has been widely applied and even better established than others, especially on the standard single mode fibers (SMFs). However, unfortunately, good fusion splicing of PCF is not easily achieved mainly due to its air hole structure that cannot be found with SMFs. Splicing PCF with a SMF is also challenging due to structural dissimilarities and modal field mismatch [5].

In this paper, we report how the optimum conditions for the fusion splicing of a conventional SMF with another SMF (SMF-to-SMF case) and also with photonic crystal fiber PCF (SMF-to-PCF case) is achieved. Evaluation of the performance was performed by measuring the splicing loss.

Challenges in splicing

During fusion process, the fiber tips are heated to soft point in the area of arc splicer and are then pressed to form a joint. In softening point, the surface tension will overcome the viscosity and cause the PCF’s cylindrical air holes to collapse, the softening points of PCFs and SMFs are different, and also their diameters. The rate of collapsing in PCFs during fusion can be calculated by using this equation [5],

$$V_{collapse} = \frac{y}{2\eta} \quad (1)$$

Where y, η are surface tension and viscosity, respectively

Depending on [3, 6], the viscosity of fused silica (PCF) sharply decreases with increasing temperature. Fused silica is a glassy form of silicon dioxide (SiO_2). In comparison to most multi-component glasses, fused silica exhibits relatively slow decrease of viscosity with temperature [7].In order to form a fusion splice, the fiber must be softened, meaning that its viscosity must be reduced to a certain value (typically about 10^5 Poise where 1 poise = 1g/cm .s=10kg/m.s) by heating it above 2000^o C [7]. For splice between single mode fibers, insertion loss (α) resulting from core offset, Mode field diameter (MFD is the characteristics of a fiber which describes the confinement of mode or light in the core part of an optical fiber) [8] difference and angular misalignment is given by equation (2), assuming a Gaussian approximation of mode fields.

$$\alpha = -10\left[\log\frac{4w_{g^1}^2\ w_{g^2}^2}{\left(w_{g^1}^2 + w_{g^2}^2\right)^2}\exp\left[-\frac{4\delta^2 + \left(\frac{2\pi}{\lambda}\right)^2 n^2 w_{g^1}^2\ w_{g^2}^2\ \sin^2\theta}{2\left(w_{g^1}^2 + w_{g^2}^2\right)}\right]\right] \quad (2)$$

where w_{g^1} and w_{g^2} are Gaussian radii of spliced fibres, δ is lateral offset between fiber cores, θ is the angular misalignment, n is refractive index of fiber material and λ the operating wavelength.

The Experimental Procedure of Splicing (SMF-28/SMF-28)

The experimental set-up is shown in Figure (1). It consists of SMF-28 to splice. Manual mode of fusion splicer was used for splicing. To accurately measure the splice loses alignment must be used.

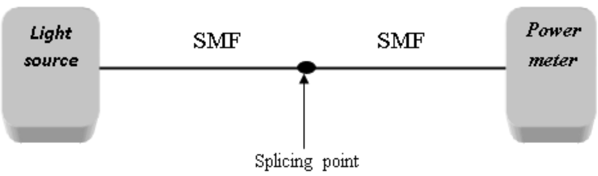


Fig.(1): Schematic of splicing (SMF-28/SMF-28).

The experiment was arranged as follows: first, the transmission power in SMF-28 was measured by using power meter (FPM-300\FLS-300\FOT-300) and light source (MW3116) with wavelength of 1550 nm and recorded as a reference measurement. Secondly, the SMF-28 was cleaved at the middle part, thirdly the two sides of the optical fiber were stripped by (JIC – 375 Tri – Hole) stripper and the protective polymer coating around optical fiber was removed. Then, the optical fiber was cleaved perpendicular to the longitudinal axis of the fiber by using Fiber Optic Cleaver (CT-30). Finally, the conventional single mode fiber SMF-28 was cleaned by alcohol and tissue.

Splice losses of (SMF-28 / SMF-28) as a function of the fusion arc time at a fixed arc power:

First the fusion splicer type (FSM-60S) was set at typical parameters; Then both ends of optical fiber (SMF-28) were placed in the splicer type (FSM-60S). Different fusion times were select for a constant value of power. The two cleaved ends were spliced for different fusion times and the transmission power in SMF-28 was measured by using a laser source with the same wavelength as mentioned earlier. The losses in SMF-28 were calculated by using equation (3) [9, 10].

$$\propto = -10\log\frac{P_{out}}{P_{in}} \quad (3)$$

where ($\propto$) the fusion splice loss of one point, (P_{out}) is the output power after fusion splice, (P_{in}) is the input power (i.e the power of the light source).

The Experimental procedure of splicing (PCF – SMF)

LMA-10 PCF of 3cm length was used in our experiment (fabricated in NKT Photonics) consisting of a solid core surrounded by six rings of air holes. As shown in figure 2 It has 10.4 µm diameter core, relative hole size (d /ʌ) of 0.46, Pith ʌ (7.14 µm), and Numerical aperture (NA) of (0.14). The diameter of the LMA-10 PCF is not similar as SMF-28 fibers but it is easy to be spliced to SMF-28 with higher stability and better repetition, compared with other larger-sized PCFs.

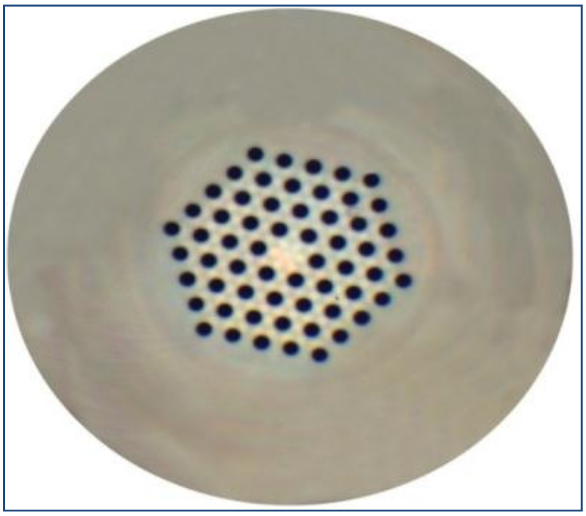


Fig. (2): Scanning electron microscope image of the cross section of the PCF (solid core) used for the experiment.

The experimental set-up used is shown in figure 3. It consists of short length of PCF (LMA-10) with length of 3 cm spliced in both sides with SMF-28 by using fusion splicer **(FSM-60S)**.

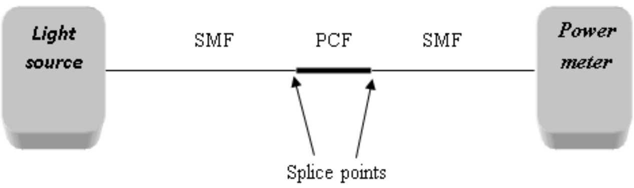


Fig .(3): Schematic of splicing (SMF-28/PCF (LMA-10)/SMF-28).

Manual mode of fusion splicer was used for splicing. Optimum parameters of the fusion splicing have been selected to splice LMA-10 (PCF) to SMF-28 with misalignment technique to accurately measure the splice losses,these typical parameters were prefusion time (180 ms), prefusion power (stdandar), gap (15 µm), and overlap (10 µm). The experiment was set as follows: first, the transmission power in SMF-28 was measured by power meter and light source with the same wavelength as mentioned earlier and recorded as a reference measurement; secondly, the SMF-28 was cleaved at the middle part. Thirdly, the two sides of the optical fiber were stripped by (JIC – 375 Tri – Hole) stripper and the protective polymer coating around optical fiber was removed. Then, the optical fiber was cleaved perpendicular to the longitudinal axis of the fiber. In our experiments Fiber Optic Cleaver (CT-30) was used. Step five was done by cleaning the conventional single mode fiber (SMF-28) by alcohol and tissue. Step six was done by stripped LMA-10 with (JIC – 375 Tri – Hole) stripper and the protective coating around optical fiber was removed. Finally Photonic crystal fiber (LMA-10) was cleaved perpendicular to the longitudinal axis of the fiber by Fiber Optic Cleaver (CT-30) and cleaned by tissue only.

Splice losses of (SM-28/PCF (LMA-10)) as a function of the fusion arc time at a fixed arc power:

The two cleaved ends of SMF-28 and PCF (LMA-10) were placed in the splicer type (FSM-60S) and spliced by selecting different fusion time with constant value of fusion power. The other side of PCF (LMA-10) and SMF-28 were placed in the splicer type (FSM-60S) and spliced by selecting the same different fusion time with constant value of fusion power. The transmission power in (SMF-PCF-SMF) were measured by using the same wavelength as mentioned earlier ,the loss of one splice point were calculated by using the equation (3),and divided the result by (2).

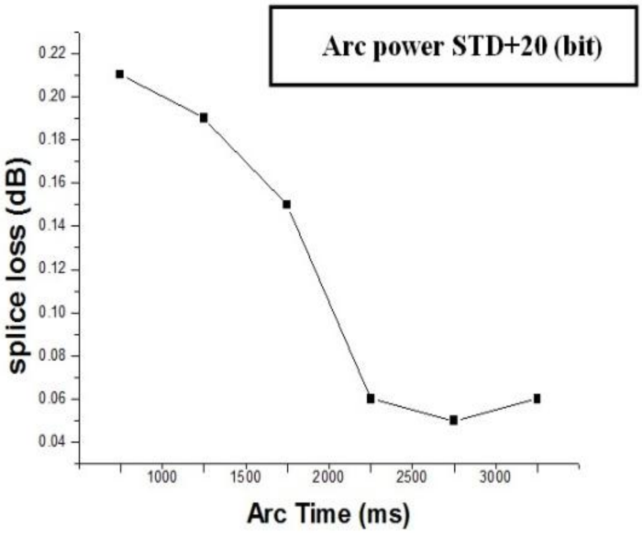
Splice losses of (SM 28/PCF (LMA-10)) as a function of the fusion arc power at fixed arc time:

The two cleaved ends of SMF and PCF were placed in the splicer machine, type (FSM-60S) and spliced by selecting different fusion power with constant value of fusion time. The other side of PCF and SMF were placed in the splicer type (FSM-60S) and spliced by selecting the same different fusion power with constant value of fusion time. The transmission power within (SMF-PCF-SMF) were measured by using the same wavelength as mentioned earlier , the losses of one splice point were calculated by using the equation (3), and dividing the result by (2).

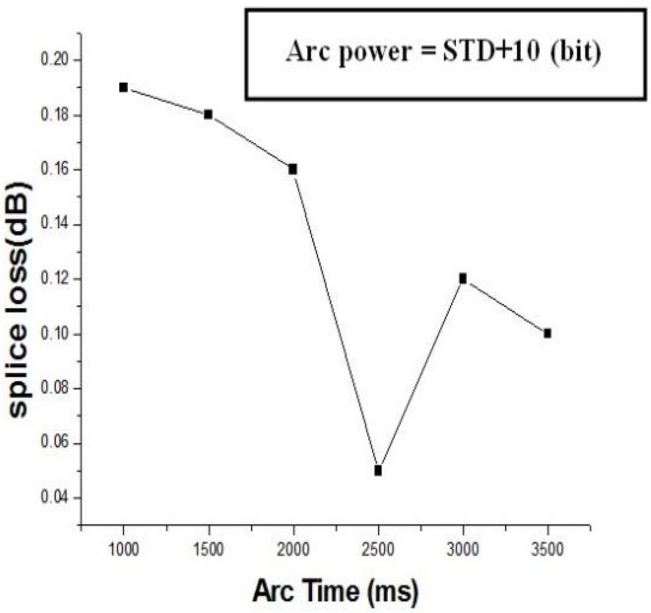
Results and Discussion:

Splice losses of SMF-28 / SMF-28

The fusion splicer (FSM-60S) was set with typical parameters; the transmission power in SMF-28 at wavelength 1550 nm was measured by power meter and recorded as a reference measurement (437.7 µw). Splice losses of (SMF-28/SMF-28) with small values, due to similar MFD. Figure (4) shows the relationships between splice loss and fusion arc time for a constant fusion arc power.



(a)



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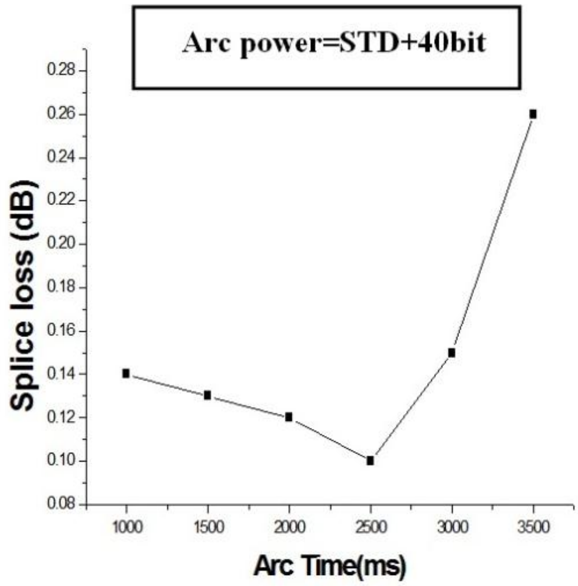

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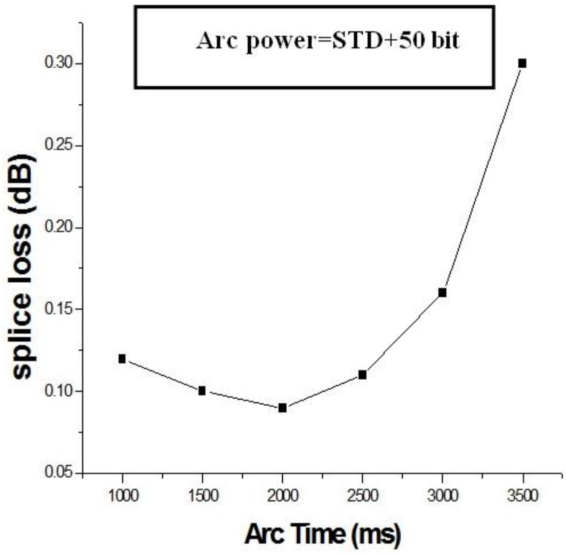

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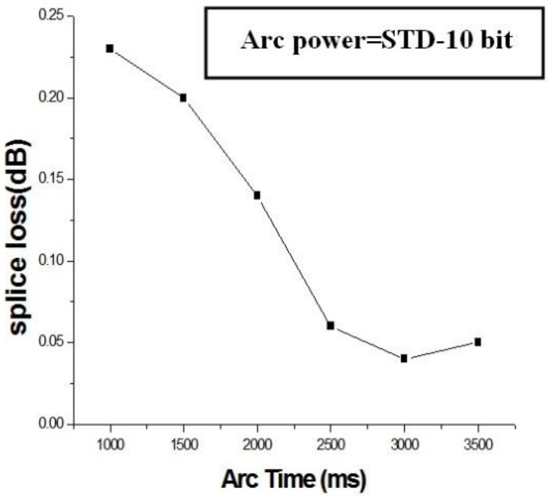

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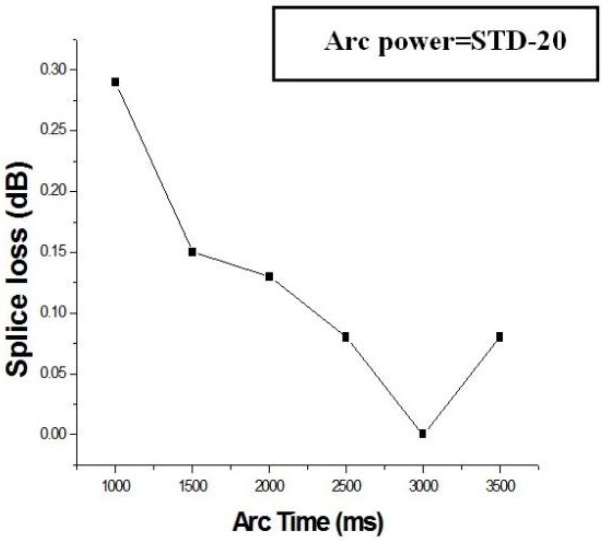
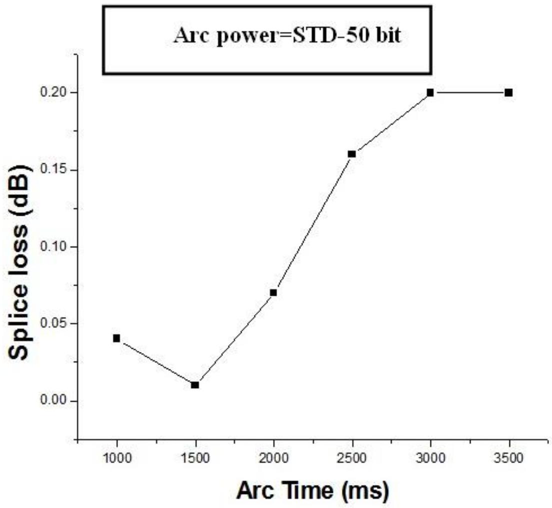
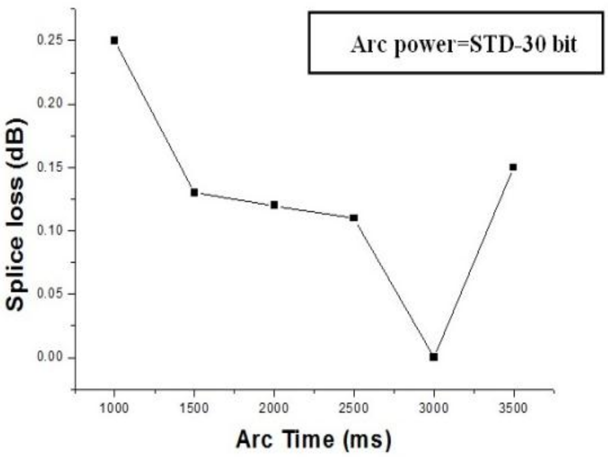


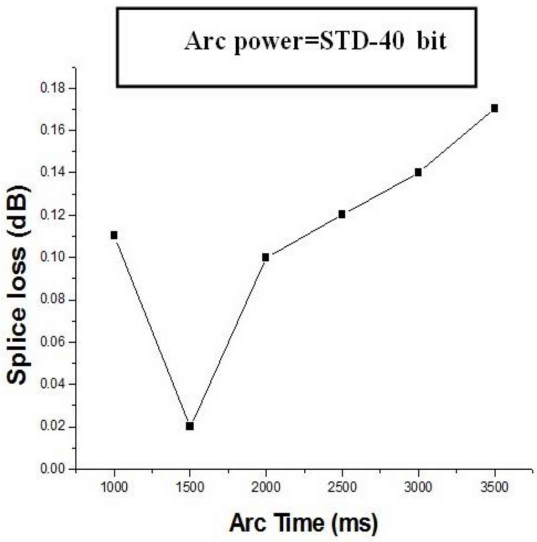
(f)



(i)



(g)



(h)

Fig. 4: Splice losses of SMF-28/SMF-28 as a function of the arc time at a fixed arc power.

The best result due to small value of splice losses (0.00 dB) when the arc power is fixed at STD-20 (bit) and STD-30 (bit) as shown in figure (4-f ,4-g) respectively and the fusion time was varied from (1000 ms to 3000 ms) with a step of (500 ms) . The best temperature at splicing joint was for (STD-20 bit and STD-30bit) with 3000 ms time. It means that the temperature of two tips of (SMF-28) fibers were above 2000^{o} c and viscosity was reduced to a certain value (typically about 10^{5} Poise), and optimizes the power match between two fibers, and hence the splicing losses were minimum to about (0.00 dB) which agree well with the theoretically estimated equation (3).

When the fusion time less than (3000 ms) at the arc power (STD-20 bit, and STD-30 bit) the splicing losses are maximize due to low temperature (below 2000^{o}c) and high viscosity (above 10^{5} Poise) which will cause power mismatching between two fibers. For fusion time higher than (3000 ms) with an arc power of (STD-20 bit, and STD-30 bit) the splicing losses are increased due to high temperature and low viscosity (Less than 10^{5} Poise) behind splicing point of SMF which causes power mismatching between the two fibers.

The image from screen of arc fusion splicer is shown in Figure (5) which represents minimum splice loss (0.00 dB) at an arc time (3000 ms) with in arc power of (STD-20 bit, and STD-30 bit). A low-loss splicing joint, was formed, this due to the spliced region of SMF-28 / SMF-28 and the region far away from the splice joint were the same.

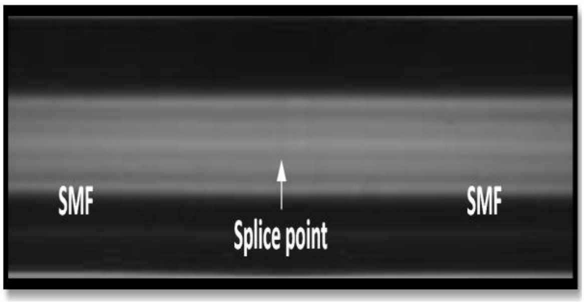


Fig. (5): Arc fusion splicer image of the fusion joint of SMF-28/SMF-28 when the splice loss is (0.00 dB).

Splice losses of SMF-28 / PCF (LMA-10) / SMF-28:

The arc fusion splicer (FSM-60S) was set with typical parameters; the transmission power in the SMF-28 at the same wavelength as mentioned earlier was measured by a power meter. The output power was set to reference measurement (437.7 μm).

The experiment was done in two ways. In the first experiment splice losses were measured as a function of the fusion time for a fixed value of the fusion power. In the other experiment splice losses were measured as a function of the fusion power for a fixed value of the fusion time. Figures (6) and (7) represent the relationships between splice loss and fusion arc time for constant value of the fusion arc power.

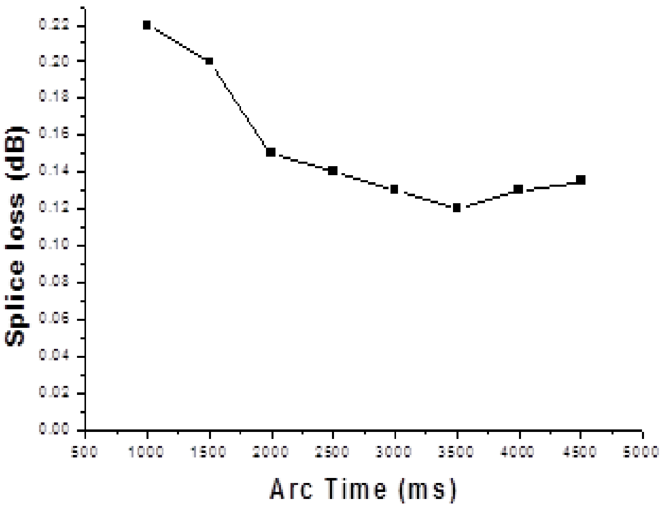


Fig. (6): Splice losses (0.12db) of SMF-PCF as a function of the arc time at the arc power STD – 10 (bit).

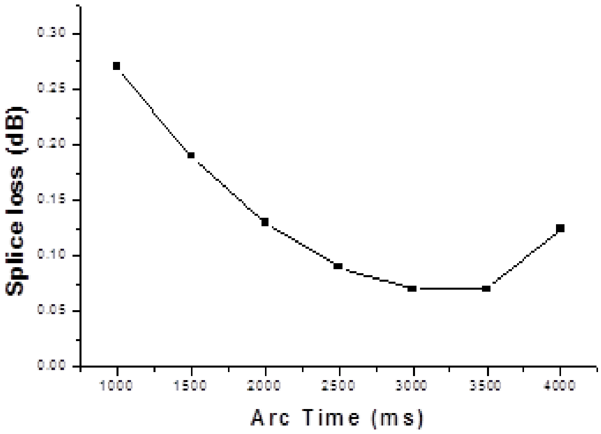


Fig. (7): Splice losses (0.07db) of SMF-PCF as a function of the arc time at the arc power STD + 10 (bit).

The MFDs in SMF-28 and LMA-10 PCF are unequal. In Figure (6) the fusion power was fixed at STD - 10(bit) and the fusion time was varied from (1000 to 4500) ms with a step of 500 ms. The smallest loss (0.12 dB) was achieved when the arc time was equal to 3500 ms at a fixed value of arc power, STD - 10 (bit) due to the increase temperature and decrease in viscosity of SMF-PCF joint. This will cause air- holes collapse of the PCF resulting in an increase of mode field in PCF and mode field matching between the two fibers. When the fusion time is less than (3500 ms) the splicing losses will increase due to the low temperature and short air- holes collapse of the PCF which will cause mode field mismatching between the two fibers. For a fusion time more than (3500 ms) the splicing losses will increase due to high temperature and long air- holes collapse of the PCF causing mode field mismatching between two fibers.

In Figure (7) the fusion power was fixed at STD + 10 (bit) and the fusion time was varied from (1000 to 4000) ms with a steps of 500 ms. The smallest splice loss (0.07 dB) was achieved when the arc time equal to 3500 ms and 3000 ms due to the increase in temperature and decrease in viscosity of SMF-PCF joint which will cause air- holes collapse of the PCF causing an increase in the mode field in PCF and mode field matching between the two fibers. When the fusion time is less than (3000 ms) the splicing losses will increase due to low temperature and short air- holes collapse of the PCF which will cause mode field mismatching between the two fibers. For fusion time more than (3500 ms) the splicing losses will increase due to high temperature and long air- holes collapse of the

PCF which will cause mode field mismatching between the two fibers.

Figure (8) shows the microscope image of splicing region of SMF-PCF from figure (7) at the largest splicing losses (0.27 dB) when the arc power is fixed at STD+10 (bit) and the arc time is 1000 ms. The MFD of PCF (LMA-10) is less than MFD of SMF-28, the air- holes collapse of the PCF is minimum and the splice loss is large (0.27 dB) due to mismatching of mode field.

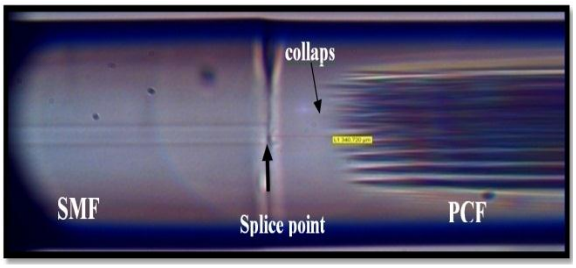


Fig. (8): Microscope image of the splice zone between PCF (LMA-10) on the right, and the SMF-28 on the left. The collapsed length is ~340.7 µm when the magnification power (65 X) at STD + 10(bit) and arc time 3500 ms.

Figure (9) shows the microscope image of splicing region of SMF-PCF from figure (7) at the smallest splicing losses (0.07 dB) when the arc power is fixed at STD+10(bit) and the arc time is (3500 or 3000) ms. When the arc time was increased to (3500 or 3000) ms the holes of the PCF collapse was increased to a certain degree that enlarges the mode field in the PCF and optimizes the mode field match between the two fibers and hence decreasing the splicing loss to (0.07dB).

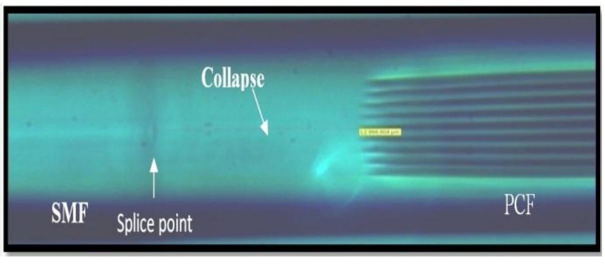


Fig. (9): Microscope image of the splice zone between PCF (LMA-10) on the right, and the SMF-28 on the left. The collapsed length is ~998.6 µm when the magnification power (65 X) at STD + 10 (bit) and arc time (3500 or 3000) ms.

Figure (10) shows the microscope image of splicing region of SMF-PCF from Figure (7) at the medal splicing losses (0.125 dB) when the arc power is fixed at STD+10 (bit) and the arc time is 4000 ms.The holes of the PCF collapse was increased to a certain degree that makes the mode field diameter in the PCF larger than mode field diameter of the SMF and hence increases the splice loss due to the mismatch of mode field.The MFDs in SMF-28 and (LMA-10) PCF are unequal. Figures (11) and (12) represent the relationship between splice loss and fusion arc power for a constant fusion arc time. In Figure (11) the fusion time was fixed at 1000 ms and the fusion power was varied.

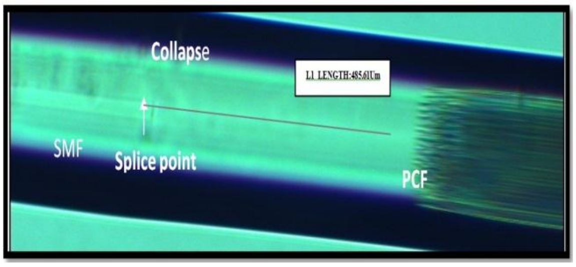


Fig. (10): Microscope image of the splice zone between PCF (LMA-10) on the right, and the SMF-28 on the left. The collapsed length is ~485.61 µm when the magnification power (20 X) at STD + 10 (bit) and arc time 4000 ms.

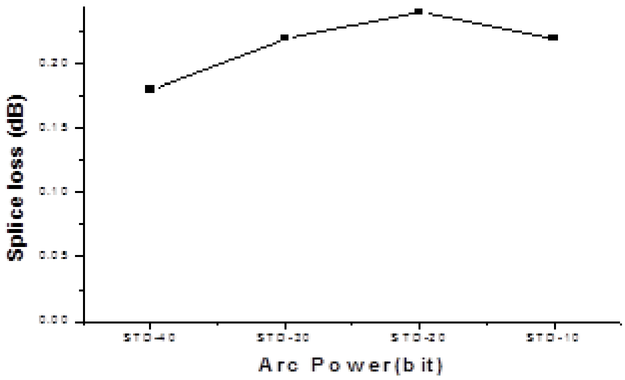


Fig. (11): Splice losses of SMF-PCF as a function of the fusion power when the fusion time is fixed at 1000 ms.

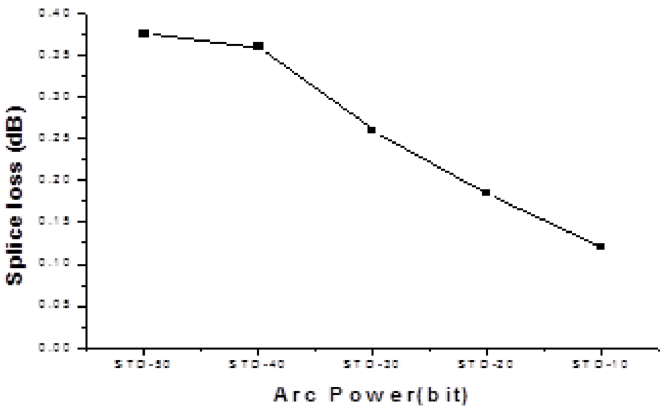


Fig. (12): Splice losses of SMF-PCF as a function of the fusion power when the fusion time is fixed at 3500 ms.

The smallest loss (0.18 dB) was obtained when the arc time was fixed at 1000 ms at arc power STD - 40(bit). The low temperature and viscosity of SMF-PCF joint which will cause air- holes collapse of the PCF to degree that enlarge the mode field in PCF and mode field matching between two fibers, when the fusion power increase the splicing losses will increase due to high temperature and long air- holes collapse of the PCF which will cause mode field mismatching between the two fibers [11, 12].

In Figure (12) the fusion time was fixed at 3500 ms and the fusion power was varied. The smallest loss (0.065 dB) was achieved when the arc power was STD-10(bit). The increase in temperature and decrease in viscosity of SMF-PCF joint will cause air- holes collapse of the PCF to degree that enlarges the mode field in PCF and mode field matching between two fibers. When the fusion power is less than STD-10(bit) the splicing losses will increase due to the low temperature and short air- holes collapse of the PCF which will cause mode field mismatching between two fibers [11,12].

Figure (13) shows the microscope image of splicing loss region of SMF-PCF from figure (12) at the largest splicing loss (0.375 dB) when the arc time is fixed at 3500 ms and the arc power is STD-50 (bit). The MFD of PCF (LMA-10) is less than MFD of SMF-2 , the air- holes collapse of the PCF is minimal and the splice loss is large (0.375 dB) due to mismatching of mode field.

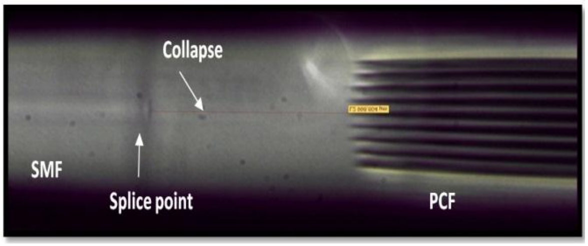


Fig. (13): Microscope image of the splice zone between PCF (LMA-10) on the right, and the SMF-28 on the left. The collapsed length is ~998.604 µm when the magnification power (65 X) at STD - 50 (bit) and arc time 3500 ms.

Figure (14) shows the microscope image of splicing loss region of SMF-PCF from figure (12) at the medal splice loss (0.26 dB) when the arc time is fixed at 3500 ms and the arc power is STD-30 (bit) ,the MFD of PCF (LMA-10) is less than MFD of SMF-28 ,the air- holes collapse of the PCF is minimal and the splice loss is large (0.26 dB) due to mismatching of mode field.

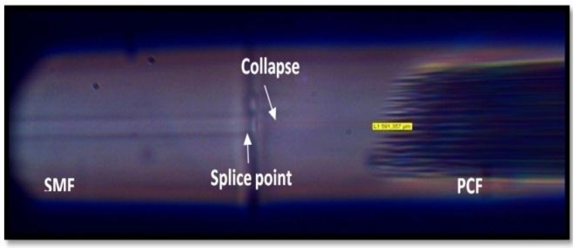


Fig. (14): Microscope image of the splice zone between PCF (LMA-10) on the right, and the SMF-28 on the left. The collapsed length is ~591.357 µm when the magnification power (65 X) at STD - 30 (bit) and arc time 3500 ms.

Figure (15) shows the microscope image of splicing loss region of SMF-PCF from figure (12) at smallest loss 0.065 dB when the arc time is fixed at 3500 ms and the arc power is STD – 10 (bit) , when the arc power increased to STD – 10 (bit) the holes of the PCF collapse was increased to a certain degree this lead to enlarges the mode field in the PCF and optimizes the mode field match between the two fibers and hence the splicing loss was minimum is equal to 0.12 dB.

Splice loss (0.065 dB) when the arc power is STD - 10 (bit) at fixed arc time 3500 ms. When the arc power increased to STD – 10 (bit) the holes of the PCF collapse was increased to a certain degree that enlarges the mode field in the PCF and optimizes the mode field match between the two fibers and hence minimizes the splicing loss to 0.065 dB.

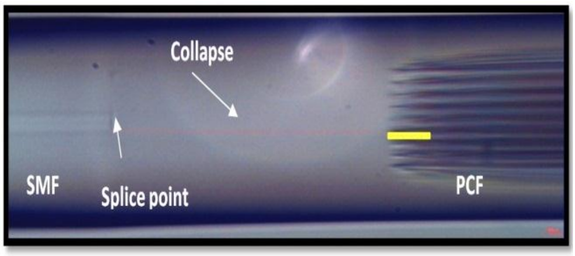


Fig. (15): Microscope image of the splice zone between PCF (LMA-10) on the right, and the SMF-28 on the left. The collapsed length is ~1426.91 µm when the magnification power (65 X) at STD - 10 (bit) and arc time 3500 ms.

Conclusions

Many conditions were investigated to splice (SMF-28) – (SMF-28) leads us to conclude that the minimum splice loss was achieved at (0.00 dB) when arc power was fixed at STD -20 (bit) and STD -30 (bit) respectively at fusion time (3000 ms). The best temperatures at splicing joint when the fusion power are (STD-20 bit and STD -30 bit) at time 3000 ms, it means that the temperature of two tips of SMF w as above 2000^{o}c and viscosity was reduced to a certain value (typically about 10^5 Poise).

Splicing SMF-28 / PCF (LMA-10) leads us to conclude that the Minimum splice loss was achieved at (0.07 dB) when arc power was fixed at STD +10 (bit) at fusion time (3000 ms and 3500 ms), due to increase temperature and decrease viscosity of SMF-PCF joint which will cause air- holes collapse of the PCF to degree that enlarge the mode field in PCF and mode field matching between two fibers. Maximum splice loss was achieved at (0.375 dB) when arc power was fixed at STD-50 (bit) at fusion time (3500 ms), due to air- holes collapse of the PCF was minimal and mismatching of mode field between two fibers.

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الربط المندمج لـ الليف البلوري الفوتوني ذو نمط مساحة كبيرة مع الليف التقليدي احادي النمط

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الخلاصة :يتناول هذا التقرير التعامل مع الحالات المكتسبة بشكل تجريبي لربط لحيم الالياف البلورية الفوتونية التي تمتلك مساحة نمط كبير .تم دراسة الالية الفيزياوية لخسارة الرابط وانهيار الثقوب الهوائية لليف البلوري الفوتوني بواسطة السيطرة على قدرة ووقت لحيم القوس لماكنه لحام القوس التقليدية (FSM-60S) ، اقل خسارة ربط لعملية لحام ليفين احاديي النمط من النوع التقليدي كانت (0.00dB) علما ان لهما نفس قطر مجال النمط . ان خسارة الربط في عملية لحام الليف البلوري الفوتوني (LMA-10) مع ليف احادي النمط تقليدي (SMF-28) تزداد بسبب اختلاف مجال النمط.