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Effects of Unstable Torch Flame for a Fused Single Mode Fiber

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Abstract: Coupled 1X2 Single Mode Fiber (SMF-28e®) is successfully fabricated using a slightly unstable torch flame at a temperature range 800-1350°C by injecting hydrogen gas flowing at pressure of 1 bar. The fiber structure and geometry are investigated for both core and cladding before and after fusion. Coupled fiber is studied using Field Emission Scanning Electron Microscopy (FESEM) and Electron Dispersive X-Ray (EDX) System. The pulling length speed, coupling time, coupling coefficient and evolution of coupling ratio from 1% until 75% are examined to study the heating effects at the coupling region. The result shows that the core and cladding geometry of fiber are reduced 80-92%. Their structures are changed which are shown by the changes in the refractive indices. These phenomena have wide applications in industrial communications and sensors such as for optical switching and tunable filtering.

Key words: Single mode fiber, flame, coupling ratio, core and cladding

INTRODUCTION

Over the past two decades, Single-Mode Fibers (SMF) have emerged as important tools for fiber optics communication. It is now the most widely used fibers, especially for long-haul communications (Senior, 1996; Khare, 2004). The main reason for this is due to the large transmission bandwidth, high quality signals transfer, the absence of modal noise, very low attenuation, compatibility with integrated optics technology and the long expected installation lifetime. Several applications SMF have been proposed and used as a coupler, such as an optical power divider, a combiner, an optical switch and a modulator. Couplers are devices that are used to combine and split optical signals (Ortega and Don, 1999). A simple 1×2 coupler consists of one input port and two output ports, as shown in Fig. 1. It is fabricated by fusing two optical fibers together and then stretching them so that a coupling region is created. Such devices allow wavelength independent over a wide spectral range. Thus an optical signal launched at input port 1 may be split into two signals that can be collected at output ports 1 and 2.

An SMF fabricated by flame is widely used for industrial purposes in communications. Beside the power can be divided and the excess loss and insertion loss are very low. However, usually the mechanism to obtain the coupled SMF is always described following at the initial input and output port, whereas the wave source transmitting to a photo detector has not been explained in more details. During fabrication, when the pre-set coupling ratio is achieved, the mechanical process comes to stop. This step is followed to heat the coupled two fibers to soften them, to stretch the fibers and to pull the length of fibers in order to reduce the fiber diameter. This processes to fabricate SMF is very crucial in obtaining the desired results (Yablon, 2005; Kashima, 1995). Therefore, this paper describes the effects of a slightly unstable torch flame towards a fused single mode fiber.

THEORETICAL WORK

The SMF-28e® with a core and cladding diameter of 8.2 and 125 μm, respectively supports only the fundamental mode (LP_{01} mode or HE_{11} mode) (Hauss, 1984). This type of fiber is designed in such away that all the higher order modes are cut off at the operating wave length. The cut off of modes is governed by normalized frequency. For a single mode fiber, the normalized frequency is over the range of $0<V<2.405$. Figure 1 depicts the fabrication process for the 1×2 SMF-28e® coupler fiber.

Consider a coupled identical single mode fiber 1×2 shown in Fig. 1 splits one source into two transmission lines turning as a Y junction.

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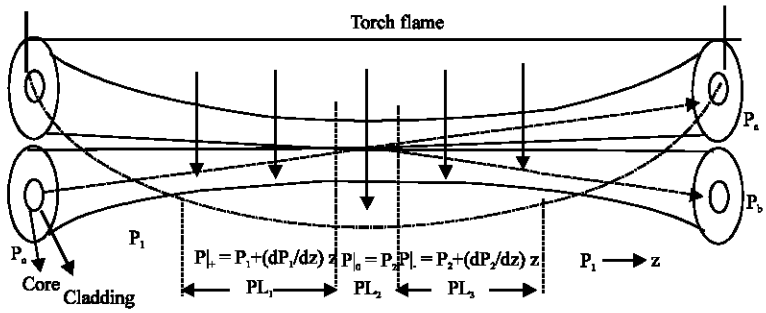

Fig. 1: Illustration of coupled fibers heated by torch flame

$$\left.\begin{aligned} P_a(z) &= P_o - P_b(z), \\ P_b(z) &= P_o\ \kappa^2/(\kappa^2+\delta^2)\sin^2[(\kappa^2+\delta^2)^{1/2}\ z] \end{aligned}\right\} \quad (1)$$

P_o is an input power of the laser diode source of λ = 1310 nm to guide a complete power transfer at a distance of $z = m\pi/\kappa$; m = 0,1,2,..., for m = 1, $z=L_c=\pi/\kappa$. L_c is the coupling length in millimeter unit. The axial length is then periodically changed by a coupling ratio (Hauss, 1984) where $P_b/(P_a+P_b)$ and $P_a/(P_a+P_b)$ are defined as coupling and transmission power, respectively. The wave propagates as a sine and cosine wave where $\kappa = \sqrt{(\delta^2+\kappa^2)}$ is the coupling coefficient and δ is the phase mismatch factor defined as $(\beta_1-\beta_2)/2$. If $\delta = 0$, then it has an equal phase velocities in both modes and $\kappa/(\kappa^2+\delta^2)$ is a fraction of the power exchanged.

The fiber coupling mechanism is analyzed using electromagnetic theory for dielectric waveguides. A laser diode (Sands, 2005) source wave (E and H) travels into a fiber as a cylindrical waveguide to both core and cladding diameter. Scalar wave (E, H) fulfills the wave equation $\nabla^2\Psi = \varepsilon_o\mu_o n^2\,[\partial^2\Psi/\partial t^2]$ with a general solution is given by

$$\Psi(r,\phi,z,t) = R(r)\,e^{il\phi}\,e^{i(\omega t-z)}$$

Since the fiber has different refractive indices n (for core n_1=1.4677 and cladding n_2 = 1.4624), Ψ can be simplified using,

$$\psi(r,\phi) = \frac{R(a)}{J_l(u)}\ J_l\left(\frac{ur}{a}\right)\cos l\phi; r < a \text{ (for core)},$$

$$\psi(r,\phi) = \frac{R(a)}{K_l(w)}K_l\left(\frac{wr}{a}\right)\cos l\phi; r > a \text{ (for cladding)},$$

Where, r is a radius of fiber, J_l and K_l are Bessel and Hankel function (Yokohama *et al*., 1982) of l order. If cos $l\phi$ =1 for SMF, the value of l is equal to zero. The electromagnetic wave brings power as a scalar approximation which can be calculated for core radius,

$$P_{core} = (\text{constant})\int_{r=0}^{a}\int_{\phi=0}^{2\pi}|\psi(r,\phi)|^2\ r dr d\phi$$

The solution of P_{core} is power in the core which can be written as

$$P_{core} = C\pi a^2\ [1-\frac{J_{l-1}(u)J_{l+1}(u)}{J_l^2(u)}] \quad (2)$$

Similarly, the power distribution in the cladding can be obtained by

$$P_{cladding} = C\pi a^2[1-\frac{K_{l-1}(w)K_{l+1}(w)}{K_l^2(w)}] \quad (3)$$

P is the power, C is a constant. Adding Eq. 2 and 3, the total power P_{total} is as follows:

$$P_{total} = P_{core} + P_{cladding} \quad (4)$$

Dividing Eq. 2 or 3 to Eq. 4, the fractional power propagating in the core is $P_{core}/P_{total} = 1-P_{cladding}$. Similarly, the fractional power for cladding is

$$P_{cladding}/P_{total} = 1-[w^2/V^2\ (1-\frac{J_l^2(u)}{J_{l-1}(u)J_{l+1}(u)})] \quad (5)$$

The symbol of V is normalized frequency, $V = (u^2+w^2)^{1/2}$, as defined $u^2 = (k^2n_1^2 - \beta_{lm}^2)\,a^2$ and $w^2 = (\beta_{lm}^2-k_2n_2^2)a^2$; $\beta_1 = kn_1$; $\beta_2 = kn_2$, where β, k are propagation constant and wave number (Jeunhomme and Dekker, 1990). The normalized propagation constant is calculated by $b_{lm} = [\beta_{lm}^2 - \beta_2^2]/[\beta_1^2 - \beta_2^2]$.

FABRICATION OF COUPLED SINGLE MODE FIBER

A coupled SMF-28e® is fabricated as shown in Fig. 2. Two fibers are twisted once to have tightly coupling when pulled by a vacuum pump. A 1mW Laser Diode (LD),

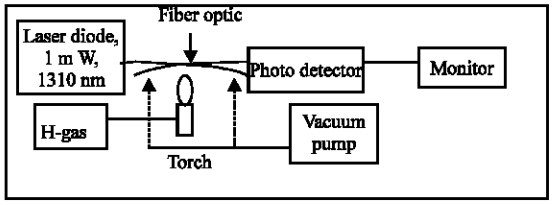

Fig. 2: The schematic of SMF coupler process

transmitting the wave along fiber 1 to 2 is detected by a photo detector at a monitor. The vacuum pump is then used to pull the fibers in micrometer size intimately between the two cores perpendicular to the direction of pulling. This pulling occurs when the flame on torch heats the twisted fibers. Total pulling of fibers to the left and right side is in the range of 7500-9500 μm with a velocity ≈100 μm/s. If the fibers reach the pre-set coupling ratio, the mechanical system will automatically stop.

A torch flame is produced by the hydrogen gas at a pressure of 1 bar over a temperature range of 800- 1350°C which is measured by using a thermocouple type K (McGee, 1998). The monitor shows the pulling length and coupling ratio over the time where the fiber 1 gives up the power to fiber 2. This operation produces the coupling ratio in the range of 1-75%. The coupling ratio cannot split the power more than 75% of coupling power from one fiber to another since the flame is unstable and result the fibers breakdown or damage.

RESULTS AND DISCUSSION

There are two measurements which have been done, temperature of torch flame and SMF-28e® structure and geometry after fusion. The SMF-28e® structure and geometry are studied by Field Emission Scanning Electron Microscopy (FESEM) and Electron Dispersive X-Ray (EDX) System and Microscope, respectively. Figure 3 shows that the highest temperature is at the centre of the torch where the fiber is heated. The temperature is slightly unstable due to the air flow and its flux velocity at the circumference. It results in the momentum of H_2 gas to form a flame into air which fluctuates and caused slight turbulence flow at the flame circumference. Since the flame is unstable, fusion is only done when the temperature is at the peak value at position y = 2 mm and y = 3 mm. At x = 1 mm temperatures vary because they are influenced by air flow rather than the hydrogen flow. However, at x = 5 mm the temperature of gas tends to be constant. Along the x position, the momentum of the gas will excite electrons from the atoms and molecules of air hence the flame readily occurs by increasing the temperatures.

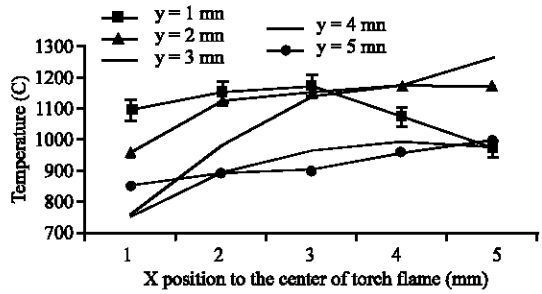

Fig. 3: Temperature of torch at pressure 1bar, horizontal (x) and vertical (y)

The initial core and cladding diameter of SMF-28e® are shown in Fig. 4a and the diameter of light radiating from core to cladding is shown in Fig. 4b. The cladding diameter is measured with a microscope magnified by a factor 20. Figure 4c, shows both core and cladding after fusion, the cores can be seen through the light diameter and are reduced from 80-92%, respectively or by a factor 3.96 and 12.5, respectively.

The light diameter radiating from core to cladding can be seen in Fig. 5. Since the light has some modes and the refractive indices of core and cladding change then the light can radiate to the cladding. The core diameter can be comparable as shown in Fig. 6. The coupling ratio cannot determine that the cladding diameter must be constant even though the LP_{01} diameter position is achieved. The reduction in the refractive index of the Y junction fibers leads to a pre-set value of the coupling ratio even though the distance between the two cores is very small as compared to the radius of the two claddings. Therefore, LD wave can travel to both the core and cladding. In Fig. 5 at x>50 of coupling ratio the diameter of cladding tends to increase from 18 μm, it is heated much longer time and a larger pulling length then fiber 1 has to supply more than 50% power to fiber 2.

The core after fusion is reduced from 80-92% over a period of 35-45 sec in order to achieve complete coupling ratio. The core diameter also fluctuates because the flame heating the fibers are unstable and the refractive index changes. In this condition, the laser wave can transmit and split at the closest range of core separation. A half pulling length of fiber coupler increases significantly over coupling ratio as depicted in Fig. 7. The fibers become soften and will achieve a certain diameter size. The power travels longer in fiber 1 as compared to fiber 2. The wave travels along the one fiber is less than the critical beam propagation with angle 4°52'. The core power is nearly 83% corresponding to 8.3×10^{-4}W and cladding is 17% corresponding to 1.7×10^{-4}W. The power propagation at core and cladding, respectively is

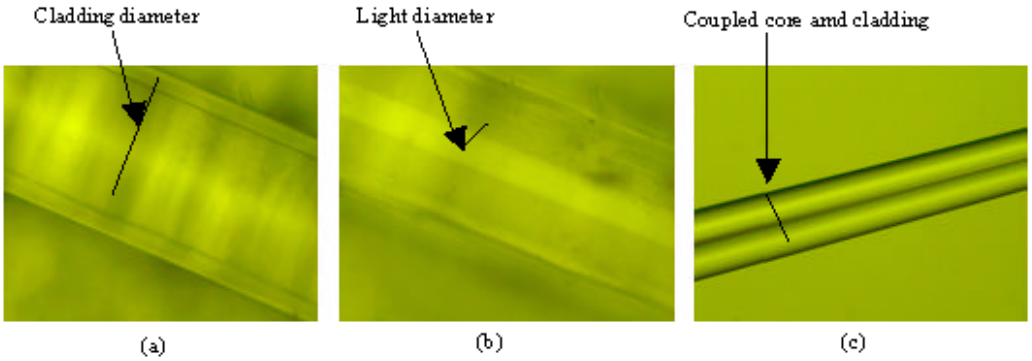

Fig. 4: The cladding and light diameter in SMF-28e®

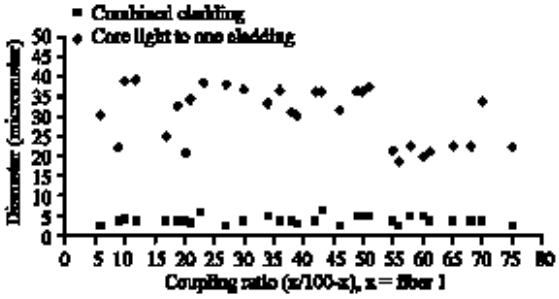

Fig. 5: The diameter of light and two coupled claddings

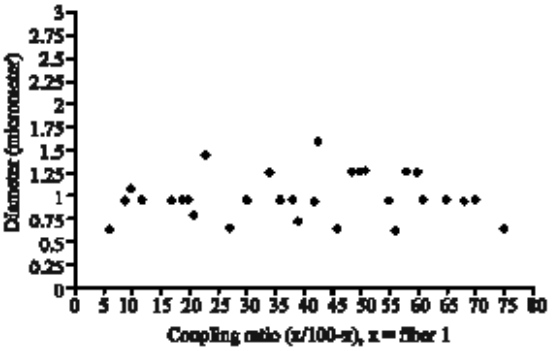

Fig. 6: Core diameter after fusion

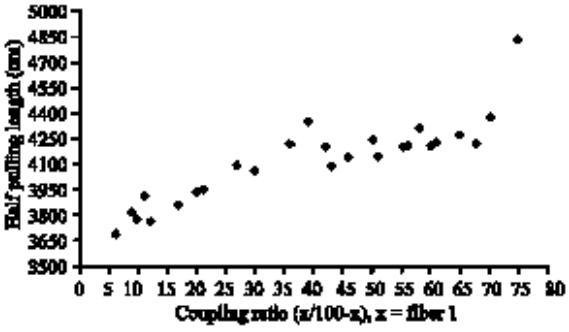

Fig. 7: Pulling length of two fibers

calculated by Bessel and Hankel function. At boundary of core and cladding, waves are affected by refractive index changes (Pone *et al*., 2004; Yariv and Yeh, 2003; Sharma *et al*., 1990) there is a displacement that the function is not completely continuous due to refraction.

Figure 8 and 9 show the changes at the surface and cross section structure of fibers on the cladding and core. This may be attributed the power radiating out of the cladding. Figure 8a and b shows the fiber after fusion and before fusion, respectively. The structure element of core and cladding is different. The core still consists of the germanium element and most of cladding structure consists of silica dioxide. However, after fusion both core and cladding are still separated and as illustrated in Fig. 8c. There is a peak on the curve that does not show the gold element. The FESEM is only able to detect the fiber if it is coated by the gold during preparation.

Due to the fundamental mode, the electric field wave is higher at the core radius than cladding radius. In addition, waves traveling to cladding cannot be neglected although the power in cladding radius is weak at a slightly higher modes; only about 13% of the power during fusion is able to reach certain radius of the coupled fiber. This allows the power to travel to another section of fiber. In this region, the speed at which the fiber diameter changes is much faster than the change of the refractive index. The speed of the pulling length is about 100 μm s^{-1} when the changes of the refractive index are in the range of 20-40 μm (LP_{01} region). Due to this there is a minimum power required to split into another fiber. In addition, the higher the coupling ratio suggests that more power propagates to another fiber. Therefore, the power decay change is inversely proportional to coupling ratio.

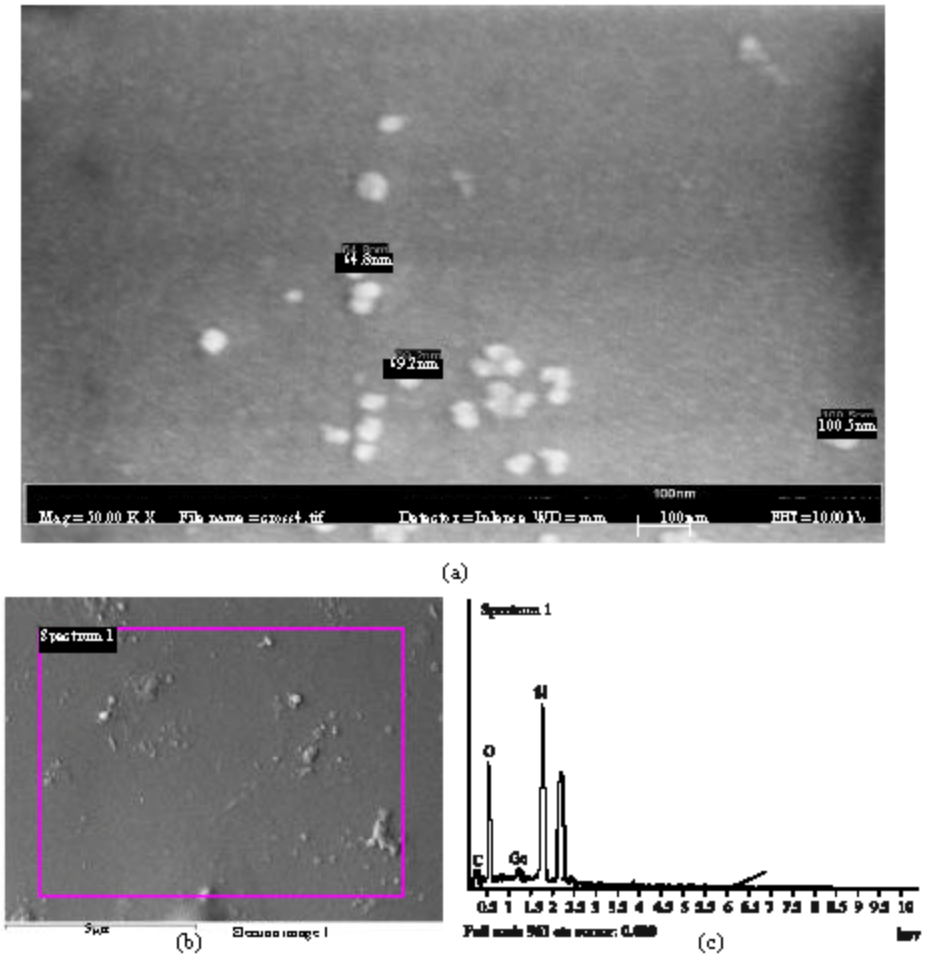

Fig. 8: Characterization of coupled SMF-28e® after fusion by FESEM and EDX, (a) Characterization of coupled SMF-28e® after fusion by FESEM, (b) The surface of fiber before fusion, (c) The cross section of fiber elements after fusion

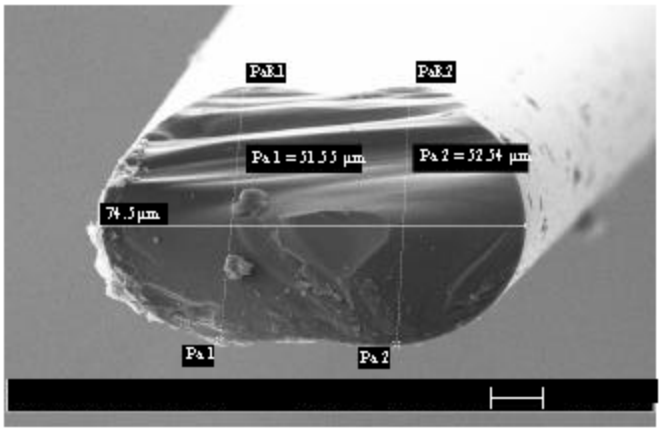

Fig. 9: Two coupled SMF-28e® after fusion at coupling region (nearest distance to the coupling length)

CONCLUSION

The coupling ratio can still be obtained even by a slightly unstable torch flame. This was coupled and fused by two identical single mode fiber, where the core and cladding radius are reduced from 80-92% in order to achieve a certain radius for both core and cladding and also a separation between cores at the LP_{01} region. This would allow the power to transmit from one fiber to another fiber during fusion. The effect of torch flame in this study is mainly producing uneven diameter of the cores and claddings after fusion to achieve a complete coupling ratio in the range of 1% until 75%. As such the power transmission is slightly affected. After fusion the two cores still exist even though the temperature nearly reaches 1400 C. Refractive indices changes lead to geometrical and structural variation of the fibers. This however does not affect the overall performance of the SMF28e® coupler.

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