Second generation of low-cost fused tapered (LFT) splitters based on POF technology

Mohammad Syuhaimi Ab-Rahman*, Mohd Hazwan Harun, Hadi Guna and Kasmiran Jumari
Broadband, Computer & Network Security Lab, Department of Electrical, Electronic and Systems Engineering, University kebangsaan Malaysia (UKM), (National University of Malaysia), 43600 Bangi, Selangor, Malaysia

Received 03 November 2010; revised 03 May 2011; accepted 05 May 2011

This study presents second generation low-cost fused tapered (LFT) 1 × 3 splitter (G2) as novel, low-cost and low-loss splitting device made from PMMA-based polymer optical fiber (POF). G2 (short taper, 0.5 - 2.0 cm) was fabricated by reformulated handwork fusion method using candle and metal tube. A new process, twisting-effect removal, is added to refine ripple surface in fused input fiber. LED fiber source (wavelength 650) was injected into input fiber while optical power in output fibers was measured by optical power meter. Insertion loss (7 dB) and excess loss (0.53 dB) for G2 are extremely low. G2 are homogenous splitters since their splitting ratio are very close to 33:33:33% with ± 5% of tolerance.

Keywords: POF, PMMA, Fused, Polymer optical fiber, Splitter

Introduction

Polymer optical fibers (POFs) provide significant cost advantages over silica fiber in areas from raw material cost to processing and to connection costs, large diameter core from 1 mm, high coupling efficiency with light emitting diode (LED) (emitting area 300 µm²), electromagnetic interference (EMI) immunity, no grounding necessary, resistance to heat, narrow bending radius and use of low-cost and eco-friendly visible light as data transmission window for POFs. POFs replace copper-wire and fiber glass in short-haul communication. Many sorts of POF splitters, fabricated using different methods, are very useful in providing optical signal combining or splitting solution for tree or star optical data network. Commercial POF splitters though perform with excellent power-splitting efficiency but are costly. This study introduces a low-cost fused tapered (LFT) splitter as novel, low-cost and low-loss splitting device.

Experimental Section

Low-Cost Fused Tapered (LFT) Splitter

LFT 1 × N splitter is a passive device that ended by N number of ports (MP), where N is greater than one while other side is ended by single port (P). In principle, bidirectional LFT splitter performs two operational functions; either as wavelength combiner/multiplexer (in MP-P direction) or as splitter (in P-MP direction). Fused tapered fiber (FTF) is featured in splitter input port, in which multiple fibers are liquified and merged as a single fiber, so that optical data can be coupled to other ports. By means of fusion, twisting and pulling procedures, all fibers combine each other and are tapered, as radius of fibers collection is reduced from 1.8 mm to 1 mm.

First Generation LFT Splitters (G1)

G1 were fabricated by simple handwork fusion technique, giving low cost device. In G1, fused tapered section was fabricated to be tightly-twisted, stretched and tapered with 6 cm of length while diameter of fiber collection decreases to ~ 1 mm (Fig. 1a). In order to suit these specification, splitters were fabricated with handwork fusion method, which is practiced with utilization of simple tools (candle and metal tube) rather than oxyhydrogen burner-equipped fusion machine. Handwork fusion method include three main processes (fiber bundle configuration, tightly-twisted spiral fiber fabrication and fiber tapering process). In new method, fusion technique is altered and a new process is added to refine twisting-effects in FTF. Though G1 is cost-effective device, splitter is not a low-loss device as excess
loss (EL) exceeds higher than 10 dB. Besides, structure of FTF is perishable. Main factor of high loss in G1 is fiber imperfections, which cause light scattering in fibers where some rays leak to atmosphere through core-cladding interface.

Second Generation LFT Splitters (G2)

This study introduces G2 as a novel optical device to provide cost-effective and low-loss splitting solution for small-world communication system. Taper length is reduced to short dimension (< 6 cm), diameter of fiber collection remain decreases to ~ 1 mm and FTF is fabricated by highly-fused plane surface without twisting-effects (Fig. 1b). Plane surface in FTF implies that each fiber is melted, highly-fused and combines each other perfectly so that wavelength of interest can pass through coupling region (FTF) and coupled to other output port with low loss and excellent power-splitting ratio (~0.33). Short taper design is intended to decrease intensity of light scattering in fused tapered section. In order to satisfy all requirements in design specifications for G2, devices fabricated through reformulated handwork fusion technique using candle and metal tube. Twisting-effect removal process is demonstrated in present fusion method to enhance coupling characteristic in FTF, whereby ripple surface with twisting-effects in FTF is refined. By mean of twisting-effect removal, all fibers are liquified, combines each other and are highly-fused.

Multimode step-indexed POF having a polymethyl methacrylate (PMMA) core (diam, 1 mm) was used as material fabrication for G2. PMMA’s intrinsic absorption loss is mainly contributed by carbon–hydrogen stretching vibration in PMMA core\textsuperscript{12}. In addition, polyvinyl chloride (PVC) is another material that was used as jacket for insulating POF ports.

Fabrication Method

In fabrication method, maximum temperature required for melting POFs is 85°C\textsuperscript{3,11}. Fused fiber bundle is base construction of fused splitter. In this study, handwork fusion technique was used as fabrication method for novel G2 because technique is easy-to-fabricate, less time-consuming and results in low production cost. Proposed fusion technique is reformulated in order to fabricate FTF with minimal imperfections. By means of suppression of structural fiber imperfections in FTFs, excess loss of G2 are expected to be minimal. In present fusion method, controllable parameters are distance between candle flame metal tube, heating period, twisting and pulling strength. In G1, heated fiber length is 7 cm (length of metal tube). In reformulated method, however, length is reduced to 5 cm in order to minimize imperfection area. In order to develop G2 by alternative and improvised fusion method, fabrication method includes four processes as follows:

i) Fiber Bundle Configuration

In order to configure fiber bundle, a fiber bundle consisting of \( N \) core unjacketed polymer fibers \((N = 3)\) inserted into metal tube and is placed in symmetrical coordination (Fig. 2a).

ii) Fabrication of Spiral Fiber Process

Fiber bundle is twisted with maximum strength, pulled with little strength, exposed to heat of candle flame repeatedly and continuously untill several fiber turns formed to produce twisted spiral fiber with 5 cm length in the center of fiber bundle (Fig. 2b).

iii) Twisting-effect Removal Process

After obtaining twisted spiral fiber in the center of fiber bundle, while fiber bundle covered with metal tube and exposed to candle flame, fiber bundle is pulled and twisted with moderate strength. When fibers reach melting point, fiber bundle is pulled with little more
strength and twisted in clockwise and counter-clockwise in both sides, then twisted in opposite direction in both sides, repeatedly and continuously until ripple surface in center of fiber is flatten to form plane surface without twisting-effects (Fig. 2c).

iv) Fiber Tapering Process

While indirect heating process continued, fiber bundle is pulled and twisted with moderate strength. When fibers reach melting point, fiber bundle is pulled stronger without twisting fiber until diameter of fiber collection decrease to ~ 1 mm (Fig. 2d). Centre of tapered region is cut by hot knife and final structure of fused splitter is obtained from half of fused tapered bundle. Each fiber port (output and input) is insulated PVC jacket.

Power-splitting Characterization

Experimental measurement was carried out to characterize power-splitting performance for G2 of LFT 1 × N splitters. In order to determine optical parameters [insertion loss (IL), excess loss (EL), splitting ratio (SR) and crosstalk] for each G2 1 × 3 splitter, optical power P (W) was measured for each port, in which port I defined as input fiber (fused tapered region) whereas port A, B and C are as output fiber.

In characterization of 1 × N splitter, LED fiber source AF-OS417MD with 650 nm wavelength (red light) and optical meter AF-OM110A were used for optical power measurement. While LED source injected into input fiber, an observation was made for illuminated light in output fibers, then optical power measured by optical meter. If there is no illumination in each output port, splitter is considerably failed to perform splitting operation. IL (dB) for each individual output port is given as

$$IL_{port} (dB) = 10 \log \left( \frac{P_{output}}{P_i} \right)$$

EL (dB) is determined for each splitter since it implies total power loss in splitter. If EL is < 3 dB, splitter is considered as low-loss device. EL is given as

$$EL (dB) = 10 \log \left( \frac{P_{out}}{P_i} \right)$$

$$P_{out} = P_A + P_B + P_C$$

In this study, SR, which determine capacity of optical power carried in each output fiber of splitter, is given priority. SR is mainly effected by cross-section of FTF. For 1 × 3 splitters, reasonable SR is 33% in each output port. In other words, one-third of power input is coupled to three output ports. In each output fiber, SR is given as

$$SR (%) = \frac{P_A}{P_{out}} \times 100\%$$

For measurement purpose, while LED source injected into either output fiber, optical power in two other output measured by optical meter. Cross-talk (dB) in a splitter is given as

$$Cr (dB) = 10 \log \left( \frac{P_A + P_C}{P_A} \right)$$
To distinguish power-splitting performance, G1, G2 and commercial splitters were compared in term of IL, EL, SR and crosstalk.

**Results and Discussion**

LFT splitter has low optical loss (< 3 dB) in the range of taper length of 1.5 - 3.0 cm (Fig. 3). FTF has good coupling characteristic in the range of 1.5 - 2.3 cm since coupling ratio of each output fiber reach ~ 0.33 within this range (Fig. 4). Minimum reasonable length (~1.5 cm) is required for inserting fused input fiber into a small channel (diam, 1 mm) in DNP connector. Therefore, reasonable length dimension (1.5 - 2.3 cm) was selected of FTF that decrease to 1 mm diameter. Through progressed fusion technique, FTF was successfully fabricated, diameter of fiber bundle decreased to ~1 mm, taper length reduced to 0.5 - 2.0 cm and plane surface featured in FTF with refined twisting-effects. Both splitter with taper length 0.5 cm and 1.2 cm were not acceptable as minimum length was limited to ~1.5 cm for inserting fused input fiber into a small channel (diam, 1 mm) in DNP connector. G1 features long taper exceeding 6 cm and ripple surface due to twisting-effects, implying weak coupling characteristic in fused input fiber. G2 has minimal structural fiber imperfection in their fused tapered region, as 1.7 cm maximum length of fiber afflicted with structural imperfection. Plane surface without twisting-effects in fused tapered region indicates better fusion quality and this results in high survivability of FTF. In G2, twisting-effects was successfully refined with twisting-effect removal process as plane surface featured in FTF. In final structure of G2 (Fig. 5), input and output fiber ports were covered with PVC jacket and ended with DNP connector (Ø 1 mm diam channel).

Before power measurement was carried out, both generations of LFT splitter were injected with LED fiber source with 650 wavelength through fused input fiber and observation was made on light illumination in each output fiber. Each output port in G2 emits high-intensity red light, whereas each output port of G1 emits red light with low power intensity except in one output fiber among them. Thus G2 has good coupling characteristic as light were able to be coupled to each port with low optical leak. High-intensity illumination in each port reflects to coupling characteristic of FTF since short taper region and plane surface (with refined twisting-effects) implies all fibers are highly fused and has minimal imperfection. For G1, all fibers were weakly coupled in fused tapered region as only one output fiber illuminated with high-intensity light.

It was realized that highest temperatures to which a polymer material may be exposed outdoors (~80°C) do
not supply sufficient thermal energy (290 kJ/mol to 375 kJ/mol) to cause bond rupture of polymer chains\textsuperscript{3,11}. In this study, heating temperature is the most crucial controllable parameter. However, since present fusion method use candle as burner, heating temperature is controlled by controlling distance between candle flame and metal tube, which is exposed very closely to candle flame to heat fiber bundle with maximum temperature. In other case, metal tube is kept distance off candle flame to reduce heating temperature. Under such circumstances, polymer fibers reach melting point within 12 s of heating period. In fiber fusion fabrication, oxidation is concerned as an important phenomenon that takes place in thermally induced polymer fusion process with participation of oxygen\textsuperscript{11}. In removal of twisting-effects process, once fiber reaches melting point, fiber is heated continuously for 6 s, then twisting-effect can be effectively refined when fibers are stretched outward. Twisting procedure that explained fabrication method is essential to remove twisting-effects in fibers.

**Insertion Loss (IL)**

On IL in port A, B and D, for G1, G2 and commercial fused splitters (Fig. 6), G2 performed optical splitting operation with low IL (4 - 17 dB) in each output port. In contrast, IL for G1 is terribly higher (10 - 20 dB), whereas for commercial splitter, IL is within 0.2 - 7.0 dB. Performance of commercial splitters was indeed better than G1 and G2. G2 of fused tapered splitter is closely on par with commercial splitter since tolerance considered small and insignificant. G2.5 is most excellent device since average IL in each output port is < 5 dB. Among output of G2.3 splitter, IL in port C is extremely high (16.42 dB). From present observations, high IL in port C is mainly due to macro-fracture at cross-section of fused input fiber, caused by improper cutting at the center of tapered region in fused bundle.

**Excess Loss (EL)**

Looking into results on EL for G1, G2 and commercial splitter (Fig. 7), EL of G1 ranges from 7.89 - 18.88 dB, whereas for G2, maximum and minimum loss is 5.88 dB and 0.77 dB, respectively. On the other hand, EL of commercial splitter vary between 0.88 - 1.39 dB. Thus G2 that feature minimal structural imperfections are better than G1. G2 (G2.1, G2.4 and G2.5) considered as low loss device since their EL are < 3 dB. Overall, commercial splitters are better than G2 however performance of G2.5 splitter is on par with commercial splitters since EL is < 0.99 dB.
Splitting Ratio (SR)

In this study, SR measured for determining coupling characteristic of FTF in input fiber, in which each POF fused and combined by mean of liquefaction. For a homogenous $1 \times 3$ splitter, reasonable SR is 33:33:33%. For G2 (except G2.1 and G2.3), homogeneity of SR did reach 33:33:33% exactly since SR deflect from 33% level with ± 5 % of tolerance (Fig. 8). SR of each commercial splitter is 1:50:49%, 15:39:46% and 4:47:49%. Thus homogeneity of SR for G2 is better than that of commercial. G2 (G2.1 and G2.3) were considered as inhomogenous splitter since their SR were 48:27:25% and
25:26:49%, respectively. It was suspected that for G2.1, inhomogeneous SR was effected by defection in core as a small red-light spot was observed, whereas for G2.3 splitters, it is due to crack in cross-section of fused input fiber caused by improper cutting.

Crosstalk

On crosstalk in G1, G2 and commercial splitter (Fig. 9), maximum and minimum crosstalk in G2 of handwork-fused splitters is 18.73 dB and 24.25 dB, respectively. In contrast to G2, optical crosstalk for G1 ranges from 28.34 to 33.53 dB, whereas crosstalk in commercial splitters varies from 19.08 to 20.18 dB. For G2, optical power coupled to other output port with higher crosstalk compared to G1. On an average, crosstalk in G2 is lower than commercial splitter since average crosstalk in G2 and commercial splitters is 21.7 dB and 19.75 dB, respectively. Overall, performance of G2 is better than G1 since overall loss from input to output ports in G2 is extremely low.

In this study, extrinsic loss is considered as major factor of optical loss in LFT splitter since structural fiber imperfection featured in fused tapered region. Several imperfections (change in fiber diameter, twisting-effects and polymer degradation) were concerned due to liquefaction. Overall, performance of G2 is better than G1 as FTF was restructured to have minimal imperfections in order to suppress power loss in splitter. Minor optical loss was effected by LED projection during measurement in power-splitting characterization. Projecting LED fiber source to fiber input in misaligned arrangement cause some optical ray leak to atmosphere through interface between LED and fiber input. Carbonic dust also cause minor optical loss, which effect power loss in splitter due to light absorption.

Conclusions

Handwork fusion is an alternative and realiable fabrication method to produce low-loss and low-cost splitter for a small-volume production. G2 was successfully fabricated by reformulated and progressed handwork fusion method with an additional process. Through experimental optimization of taper length (1.5 - 2.3 cm) for FTF design was selected for reasonable taper length since low EL (< 3 dB) exhibited in this range. G2 was effectively fabricated with minimal structural imperfection and no twisting-effects in fused tapered section. Multimode SI-POF with 1 mm PMMA core was used as base material for the fabrication of novel LFT splitter. Overall performance of G2 is better than G1 since insertion loss and EL is extremely low (7 dB and 0.53 dB respectively). On the other hand, G2 are homogenous splitters since their SR are very close to 33:33:33% with ± 5% of tolerance. G2 are also potential in competing other commercial splitter as this device has several valueable advantages (very low in cost, better homogeneity in SR, low IL and EL). Excellent power-splitting performance of G2 is mainly effected by its fused tapered structure.
having minimal imperfection. G2 is recommended for automotive, in-house, WDM and sensors network.

Acknowledgments
Research was conducted in Broadband, Computer & Network Security Laboratory, Universiti Kebangsaan Malaysia. Project is supported by Ministry of Science, Technology and Environment, Govt of Malaysia, 01-01-02-SF0493 and Research University Grant fund UKM-AP-ICT-17-2009.

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