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Fabrication of Polymer Optical Fiber Splitter Using Lapping Technique

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Abstract

This work involves in designing and developing a POF-based directional coupler/splitter using lapping technique and geometrical blocks. Two fiber strands were first tapered at the middle and they were attached to the geometrical blocks and lapped together. Design parameters that are used to develop this coupler/splitter are core diameter, D_c, etching length, L_e, bending radius, R_c, coupling length, L_c and pressure, F_c. All the parameters were taken into account during characterization and analysis of the designed coupler in order to find the most optimum prototype coupler/splitter. Characterizations are done by experimental set-up to test the efficiency, splitting ratio, coupling ratio, excess loss and insertion loss for all the couplers/splitters. Through the characterization process and analysis, the optimized coupler with high splitting ratio and low excess loss were identified. Throughout the experimental process, some of the fibers were improved and renewed in order to realize the design and development of the coupler using this technique. The device can also be utilized as an optical tap and the applications of the device are not only limited in in-house network but also in automotive applications. By using a platform, several splitting ratio can be obtained by integrating different core-cladding thickness and bending radius in order to get the desired splitting ratio and excess loss.

Keywords: polymer optical fiber, splitter, low-cost, lapping technique, green technology, short-haul communication system, geometrical blocks

1. Introduction

1.1. POFs for main medium in short-distance transmission

Polymer optical fibers (POFs) have many advantages compared to other communication medium such as glass fibers, copper cables and wireless communication system. Although glass fibers show high performance in terms of speed, higher bandwidth and minimal loss, POFs in the other hand, offer easy and cost-efficient processing and flexibility, whilst glass optical fibers are very brittle, expensive and the cost of installing overall system is very expensive [1]. Therefore due to the complication of installation using glass optical fibers, where the fibers is easily broken and very sensitive, POFs are more handy and easy to install.

For short-haul distance application, POFs show lower attenuation and data transmission works perfectly within distance less than 1 km. Thus, POFs are more suitable as for medium transmission for home-networking, optical data buses for automotive applications or industrial automation sector. Transmission method of using POFs have emerged as a highly-potential candidate for cost-effective and future-proof solution [2]. Glass optical fibers have replaced copper for telephone networks and backbone wiring for buildings, however, still unable to be used in short distance applications due to its cost.

Polymer optical fibers are widely known around 1960s after glass optical fiber was introduced as an effective transmission medium for optical communication. Over the decades, the performance of POFs have shown improvement in terms of transmission capability from having large attenuation as large as 300–20 dB/km and 3 dB/km for passive device such as optical splitter at visible wavelength [3]. Characteristics that give advantages for POFs include low insertion loss, low production cost, having thermal and mechanical stability and highly potential for mass production reliability. Although the loss of POFs is generally higher than silica or glass fiber, POFs are mostly used in intra office communication system where the distance requirement is only up to a few hundred meters where the losses are low and cost-effective. It provides cost-effective solutions to short distance applications such as local area networks (LAN) and high speed internet access and in vehicles [4].

Multimode POFs particularly is chosen as the fiber technology that is largely employed in short-distance communication applications such as in LANs and interconnects. It is also driven by the needs of higher bit rates and lower cost as cost is one of the important drives in short distance communications.

1.2. DIY kit

Although for short-haul communication system, POFs show lower attenuation and cost-effective compared to glass optical fibers, however, there are lack of industry attention received due to less of industry marketing and education of the end user on how to utilize POFs in the system. The lack of information for the end-users on how to install POF-based devices and components lead to the limitation of POF utilization among the customers or end-users. Although huge companies of automobile and medical equipment companies have already

utilizes POFs, however, the lack of education of the end-users on the technique to install and implement the POFs in home-networking causes the industry to pay less attention on building POFs "do-it-yourself" components and devices [5, 6].

1.3. Green technology

About 3% of the world-wide energy is consumed by the information and communications technology (ICT) which contributes to the carbon dioxide (CO_2) emissions [7]. Telecommunication applications can have a direct impact on lowering greenhouse gas emissions and power consumption. Technical approaches of achieving green communication includes energy-efficient network architecture and protocol and energy-efficient wireless transmission techniques [7]. A green technology coupler/splitter is presented based on polymer optical fiber. The splitter has been fabricated by using harmless chemical solvent to etch the fiber and by using various radii of geometrical blocks as the platforms that are made of acrylic and aluminum.

Wavelength from eco-friendly light emitting diode (LED) is utilized to transmit signal. The red LED (650 nm) is capable to download and upload data through Ethernet cable or video signal. LED source used in the system is a solar powered product of semiconductor diode. Compared to incandescent light, light produced by LED is a cool light. The lifetime of LED surpass incandescent which has at most 50,000 hours. Compared to laser, LED is much safer source and little effort is needed to maintain and conduct the source.

The technique used to fabricate this device includes etching using harmless chemical solvent, acetone and also side-polishing. Both the techniques used are environmentally safe and easy to conduct. Acetone is a safe chemical solvent where studies suggest that acetone has low acute and low toxicity if being ingested or inhaled. It is not regarded as carcinogen, a mutagenic chemical or cause chronic neurotoxicity effects. It is mostly used in cosmetic products, processed food and other household products. Acetone has been rated as "generally recognized as safe" (GRAS) substance [8].

1.4. POF couplers

Polymer optical fiber coupler or splitter is a passive device that is built to perform functions required by optical communications such as isolator, circulator and attenuator [9]. Coupler or splitter is important device in the development of optical networks such as in transportations, local area network and for short-distance or in-house applications, in industrial automation or for sensor applications.

Optical couplers are used to combine two or more optical signal inputs from different paths into one output while splitters act oppositely. A particular message encoded as optical signal that needs to be delivered to several outputs at the same time can utilize 1 × N splitter so that the optical signal can be sent to different routes of optical fibers connected to intended end-users or destinations [10]. The requirements for POF couplers are having small excess loss and insertion loss, various power splitting ratios, easy to develop, can be mass produced and having low cost.

Common types of optical splitter are directional, distributive and wavelength-dependent. The mechanism involves can be characterized as diffusion type, area-splitting type and beam-splitting type. Evanescent wave coupling or radiative coupling is part of diffusion couplers. In evanescent wave coupling, two or more fibers are placed sufficiently closed to one another [11]. It is crucial to place the fibers in parallel over a finite distance known as coupling length so that the evanescent field from the primary fiber builds up a propagation field in the secondary fiber to provide two outputs.

A traditional silica optical coupler in one work is formed by placing the two polished-cladding fibers closely together making the light couple from the direct branch to the coupling branch by evanescent field as shown in **Figure 1**. By changing the polishing depth or tapering depth, the contact area and angle, certain modes can be selected and bandwidth can be enhanced in network systems [12]. When the light is transmitted to the coupler, some light will leak out to the branch and be transmitted as stable transmission mode due to the changed of waveguide structure by polishing. Some of the modes were selected by changing the angle of the contact areas of both fiber [12].

1.5. Existing technique of POF splitters/couplers

One of the advantages of polymer optical fibers as compared to other cable types is the simple connector fittings. Copper cables for high data transfer rates mostly require the connection of twisted pairs that must be individually shielded. At frequencies of several 100 MHz, however, cutting open the shielding over a distance of 1 cm results in a noticeable drop in quality of the connection. Glass fibers in the other hand, have a core diameter between 10 and 200 μm. Precise guides are required and glass fibers cannot simply be cut. The face must either be precisely cut by craving with diamond blade or the face must be polished after the cutting. Other advantages for POF is due to its material where the surface of plastics can be smoothed by both cutting and simple polishing and thermal smoothing of the surface is also possible for PMMA.

One of the existing couplers that have been fabricated is done by [7] where the team had demonstrated for the first time that the POF devices can be fabricated by hand using fused
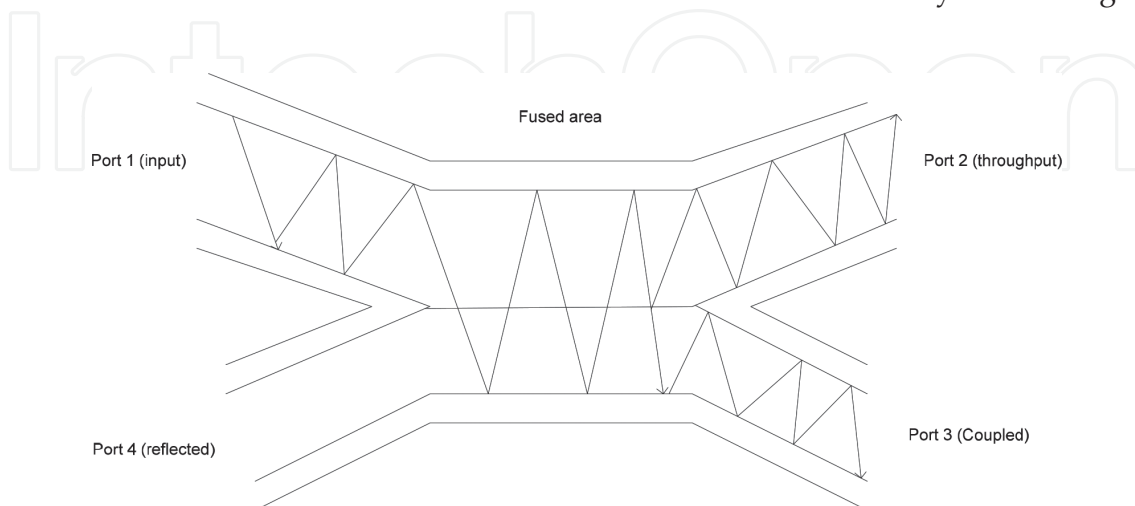
Figure 1. Lapping fibers.

technique. The temperature, stress and splitting technique are the most important parameters to fabricate low loss device. With some modification the device can be used for the extended function such as demultiplexer which is fabricated from uniformity optical splitter [7].

Other techniques include cutting and gluing where in this technique, POF is cut at certain angle using hot knife and glue is applied to attach the two segments of POF. Thermal deformation is a technique where two POF ends are shaped into semicircular form by thermoplastic deformation using hot plate flattening technique. Molding in the other hand is a technique where POF is assembled by a polymer waveguide. Lithography method is used to fabricate the mold [3].

1.6. Etching technique

There are several ways of technique to develop a coupler/splitter. In some cases, tapering is done unto the fibers in the process of developing the coupler. One of the tapering techniques is using chemical etching [4, 5]. Tapering offers unique optical properties that have application to couplers and sensors. The change of diameter can redistribute the modes within the core or remove selected modes. The penetration depth of the evanescent field and proportion of power within this field increases in the tapered section. The change in diameter is used for coupling fibers or interface fibers to devices [13]. This technique has been used by [13] where the cladding of the fiber is thinned using hydrofluoric acid where cladding layer of four micron thick is removed. A technique for removing the cladding of polymethylmethacrylate (PMMA) polymer optical fiber using chemical solvent is used to create etched tapers of a certain length in the middle part of the fiber [14]. PMMA POF is a thermoplastic with softening temperature of 75–80°C. Heat drawing sometimes done unto POF for tapering, however, polymer is not so compatible with drawing due to the latent stress within the structure from production and different physical properties of core and cladding [13]. Thus, etching is by far one of the best methods. The process is simple, low cost and requires no sophisticated equipment and is a safe process since it involves a harmless chemical solvent which is acetone.

PMMA is dissolved using organic solvents such as acetone and methyl isobutyl ketone (MIBK) in order to remove the polymer in concentric layers as required. The method requires no tension to be applied on fiber under etching process so as to prevent brittle stress fracture from occurring and break the fiber. Isopropyl alcohol is used to neutralize the solvent and leave the exposed core clean and grease-free. Once the region has been washed, it will return to PMMA physical and chemical properties.

By tapering the multimode optical fiber cladding, higher modes of the fiber are removed while some other modes are redistributed. As the tapered section is developed, the evanescent field and proportion of total power within this field increases in the affected region. This technique is conventionally applied to glass fibers, however, POF has becoming widely used in optical communication systems and this method can be as a potential towards fabricating a practical coupler using this technique.

The etching process of POF gives an optically smooth surface of similar quality to the original POF due to the polymer quality of POF. If the tapered region is cleanse and washed appropriately the core material section will remain its original properties of PMMA.

1.7. Polishing technique

Side-polishing is one of tapering technique that can be done unto fibers other than etching and fusing. It has been used by other researchers [12, 15, 16] in order to develop couplers/splitter. In this process, single strand multimode fiber is polished at the outer cladding layer for several micrometers. Then the polished fiber is lapped to the other fiber in a bent surface and aided by a thin film of UV curing adhesive is used between them as mode stripping. When the launched port is injected with light source, the mode coupling will occur between the lapped region and split the light accordingly. The strength of the evanescent light coupling is tuned in the range of 0–50% by translating the fibers in or out of alignment of each other [17]. The insertion loss of using this technique is below 5 dB. Polishing technique is considered as one of the simple method to fabricate a directional coupler over the years.

1.8. Macro-bending loss by radiation

Attenuation is a loss of optical power as light travels along the fiber as a result of loss mechanisms such as absorption, scattering and bending. One of the important concepts applied in this research is loss due to macro-bending. Macro-bends are bending that has relatively large radius of curvature compared to the fiber diameter. The loss is high when the bending is smaller. Any dielectric waveguide will radiate if it is bent [18]. Radiation loss occurs in the cladding even when the propagating ray is greater than critical angle. If radius of bending is smaller and wavelength of transmitted light is longer, the macrobending loss or power loss is due to the radiation [19]. Below a critical radius optical fiber bending, macrobending loss is significant. When light facing total internal reflection an electromagnetic disturbance which is known as evanescent wave penetrate the reflecting interface. The amplitudes of evanescent wave decay exponentially when it gets further than the reflecting interface because it cannot propagate in medium of lower refractive index. Non-uniformity in the reflecting interface may cause the evanescent wave to convert into propagating wave. In bending loss, evanescent fields extend to the cladding but decay exponentially with radial distance.

All rays in bent fiber are leaky where at some reflections they lose power by either refraction or tunneling. By stripping the cladding layers, bent fiber will escape from the fiber and the cladding will behave as if it were infinite. The power losses in bent step-index multimode fibers can depend on the cladding thickness. Decreasing the bend radius and increasing fiber core will increase the bending losses. As bend radius begins to decrease, more refracting rays are produced and more power is transferred to the cladding.

Low losses can be obtained in bends that have small radii of the where width of the channel is decreased and the refractive index contrast is increased. Bend losses of multimode channels are independent of wavelength. At some point from the center of the bend, the portion of the field in the cladding would have to exceed the speed of light and be radiated, thus reduce the power in the guided mode [20].

In this research, light that escapes from the bending is utilize to develop an optical coupler or splitter by varying the bending radius in order to obtain certain splitting ratio using mechanical platform of circular blocks and elliptical blocks [21].

1.9. New approach of using lapping technique

Directional coupler is a passive device where power exchanges between two waveguides that is placed in proximity to each other. When a certain power is launched into a waveguide, some of the power is transferred to an adjacent guide due to coupling. The power exchange depends on the interaction length and coupling strength along with other parameters. When two guides are parallel to each other, coupling coefficient is constant and the power launched into one guide will alternate back and forth between the two guides as long as they are close [22].

Complete power transfer occurs when phase velocities are perfectly synchronized and the interaction length is half the coupling length [16]. In [16], they developed a coupler with variable spacing where by gradually increasing the separation between the two guides where all or some of desired power may be transferred from one guide to the other in strong interaction region. By controlling the separation between the channels, the coupler can be realized as switch, splitter and power divider [23].

This research focuses on developing user-friendly and inexpensive splitters with various splitting ratio and low excess loss using POF splitter kit consists of circular blocks and elliptical blocks of varied radii and several pairs of splitters. This technique of splitter development has the advantage of low-cost installation, environmental-friendly with considerable low losses. The proposed fabrication of the coupler/splitter consists of two parallel fibers in contact with each other along a certain coupling length or know as lapping technique [24].

The technique used in this experiment is lapping technique where two similar length fibers are tapered in the middle region using harmless chemical solvent for particular time and the tapered regions of certain diameter, D_c and etched length, L_e are lapped to each other. The taper introduces variations in the effective refractive index of a waveguide and a change in coupling coefficient [16]. Chemical solvent, acetone is used to taper the fiber and stripped off the cladding layer. The thickness of cladding layer that is being stripped off depends on the duration of the etching process. The time duration for etching process in this research range from 30 to 120 minutes. The longer the duration process, the smaller the fiber cores obtained. At this diameter, the cladding layers have been fully etched and leave only the bare core. The aim of this process is to strip off the cladding layers so that when the bare cores are lapped to each other and bent, the rays that propagate in the first fiber can transfer to the second fiber. However, for some fibers the etching process strips off the whole cladding layer including the region that will not be lapped to the other fiber core, this situation will lead the unnecessary losses during splitting/coupling. Thus, the geometrical blocks that the fibers are attached to are customized using acrylic material that has similar refractive index so that it replaces the cladding layers that has been etched.

To stimulate the energy transfers between the primary fiber that has been injected with light source to the secondary fiber, macro-bending effect is a parameter used where the fibers are bent accordingly to the customized geometrical blocks of several bending radii, R_c. It is known that when an optical fiber is bent it radiates power to the surrounding medium. The radiation power in the fiber depends on radius of curvature and the difference between refractive indices of core and cladding. The size of bending radius of the blocks either circular or elliptical

gives the coupling length, L_c, of the contact region of the lapping cores. Coupling length is important in order to obtain high splitting ratio and coupling efficiency.

Two forces, F_c are exerted upon blocks that hold the lapped splitter together, i.e., normal force and given force. The aim is to characterize the splitter when the fiber cores touches each other without external force and recorded as normal force and with external force or namely given force. Force is exerted upon the blocks and fibers in order to minimize the gap that exists between the two lapped fibers in order to observe and characterize the energy transfer of the splitter when different bending radii are formed along with particular core-cladding thickness at certain coupling length. The force exerted upon the fiber also has small impact on the coupling length between the two fibers.

The pair of fibers will be attached to different circular and ellipse-shaped blocks that consist of different bending radii, R_c. The tapering and bending contributes to the effective index of higher-order modes that approach cladding and when the tapering section is constant, the modes become cut-off and radiate which contributes to the loss.

The aim of varying the bending radii, R_c is to characterize and analyze the macro-bending effect on the splitter having varied diameter, D_c, varied etching length, L_e, coupling length, L_c with different load force, F_c. The aim of the design is to obtain optimum bending radius that gives the optimum splitting ratio and low excess loss.

Analytical work is considered where the parameters of core thickness, D_c, coupling length, L_c and distance between the two fibers, d, are taken into account in order to obtain the coupling efficiency between the two fibers. The bent fiber using circular and elliptical blocks encourages the modes to radiate out of the tapered section. The amount of power transfer is calculated using Coupled Mode Theory. The coupling length between the two fibers also affects the coupling efficiency [24].

1.9.1. Taper

Taper changes the fiber diameter or thickness which allows redistribution of the modes in the core or eliminates the modes. The penetration depth of the evanescent field and proportion of power within this field increases in the tapered section. The modified core-cladding thickness is used for coupling fibers or interface fibers to devices [13]. In [17] in their research stated that they polished the fiber for several micrometers and lapped the fibers together and when source is inserted, mode will couple between the lapping regions and split the light accordingly. By adjusting the alignment between the two lapping fibers, the strength of the evanescent light coupling can be tuned. However, [17] do not apply mechanical technique of circular and elliptical blocks to vary the splitting ratios, rather the alignment is varied. In [13] in the other hand manipulate the thickness of cladding in order to obtain desired results. In [25] states that at the end of the tapering section of the first fiber, the rays propagate in the cladding will be recaptured by the core. If the tapering section of parallel fibers is small, the coupling ratio is high. However, if the radius of the tapered section is too small, the coupling efficiency will decrease dramatically due to the lost rays while passing through the down taper.

For some tapered fibers in this research, whole surfaces were etched around the fiber creating extra taper regions that allows unnecessary losses of the splitter. Thus, circular and elliptical blocks were made of acrylic and when the fibers are placed in the groove, the non-lapping surfaces are surrounded by acrylic material. This material is aimed to reduce the losses of the splitter due to tapering of the fiber cladding.

1.9.2. Bending and radiation

Generally, loss is high when the bending is smaller. Radiation loss occurs in the cladding even when the propagating ray is greater than critical angle. If light facing total internal reflection, an electromagnetic disturbance occurs which is known as evanescent wave where it penetrate the reflecting interface. Non-uniformity in the reflecting interface may cause the evanescent wave to convert into propagating wave where in bending loss, evanescent fields extend to the cladding but decay exponentially with radial distance [26].

The loss in bent step-index multimode fibers not only depends on bending but also on the cladding thickness [11]. When a refracting ray hits a core-cladding interface, two rays are created where one ray is refracting at the cladding interface while the other ray is tunneling at inner core interface. At cladding interface, some rays will be reflected back and some will be refracted with considerable power content [27]. By decreasing the bend radius and increasing fiber core, losses will increase. As bend radius begins to decrease, more refracting rays are produced and more power is transferred to the cladding [28].

Some rays in the incident radiation are not bounded by core of the fiber rather the rays that propagate through the core-cladding interface and get into the cladding region. Due to the finite radius of curvature at the cladding surface, some of the rays will be reflected back into the cladding and propagates while some will radiate. The rays that propagate in the cladding are known as the cladding modes and coupling can occur with the higher-order modes of the core resulting in loss of the core power. According to [27], the refracting rays lost most part of their energy at the beginning of the bent section and then the rate of loss will be slower whilst the remaining losses afterwards are due to weakly leaky rays which are known as whispery gallery rays of tunneling rays.

Therefore, this research integrate the concept of taper, lapping and bending the splitter in order to increase or limiting the splitting or coupling of rays between the two lapping fibers in order to gain certain splitting ratios.

1.9.3. Coupling length

The coupling efficiency describes the total power of coupling between the two fibers depending on the distance, fiber core thickness and length of the contact region. In [14] stated that cross type coupler is not able to achieve high coupling efficiency due to its short coupling length. Coupling length must be long in order to achieve high coupling efficiency such as parallel type coupler. For short coupling length, coupling is dominant only for higher order modes. In cross type coupler, the radiation loss is increased by increasing the pressure since the coupling length is quite short in order to gain optimum result. In [14] shows that as the

coupling length is longer, the coupling efficiency will be stabilized. However, high coupling efficiency is achieved at coupling length between 6 to 10 mm and from 18 to 22 mm.

1.9.4. Distance of cores

In [29] agrees that the distance between the two fibers affects the coupling efficiency among other considered parameters. Although coupling length is important, however, the optimum efficiency of coupling not only depends on the optimum length but also on the distance between the two cores. In [29] shows that when the gap is zero between the lapping cores, high coupling efficiency is achieved, however, when gap exists or distance over the two cores is 1.01, the coupling efficiency drops to less than 30%. When the gap or distance over the two cores is further increased to 1.05, the efficiency drops to less than 5%. The distance between the two fibers affects the coupling efficiency strongly.

According to [25] states that when the ray of light propagates along the tapered section of the lapping fiber, the angle of incidence on the core surface decreases with each reflection and the high-order modes may have cutoff points in the down-taper section and therefore will leak out the core. If the cladding modes encounter the air-cladding interface at incident angles smaller that the critical angle, the modes will radiate away from the fiber at the air-cladding interface. However, if the claddings of the two lapping fibers are closed enough over appropriate length, the light in the cladding of the fiber will be transferred to the second fiber.

Therefore, load is accounted in this research in order to minimize if not eliminate the gap between the two lapping cores. The difference of characterization is compared when normal force is exerted and external force is exerted.

1.10. Fiber preparation development

Apart from the platform design, the development of the coupler/splitter also comprises of three sets of fibers tapered by etching method and side polishing. The first set of fibers were prepared by fully etching using harmless chemical solvent, acetone. During the etching process, the tapered length of each fiber was set to be 25 mm long and the duration of each pair of the fiber strands was varied from 30 to 120 minutes. For second set of fibers using fully etching method, the etching length of tapered length of the fibers were varied for each pair between 4 and 25 mm long and the duration of etching also was set to 60 minutes. The third set of fiber pairs were tapered using side polishing method and side etching where only one side of the fiber strand was polished and etched to clean the rugged surfaces. The tapered length of the fiber pair of each coupler/splitter is also varied from 4 to 25 mm long and the duration of etching is about 60 minutes. The effect of etching duration leads to the different diameter of core-cladding of the fiber pairs. The longer the etching process, the smaller the core thickness diameter. **Figure 2(a)–(c)** show the surface of the fibers before etching process, **Figure 2(a)** and post etching fiber, **Figure 2(b)**.
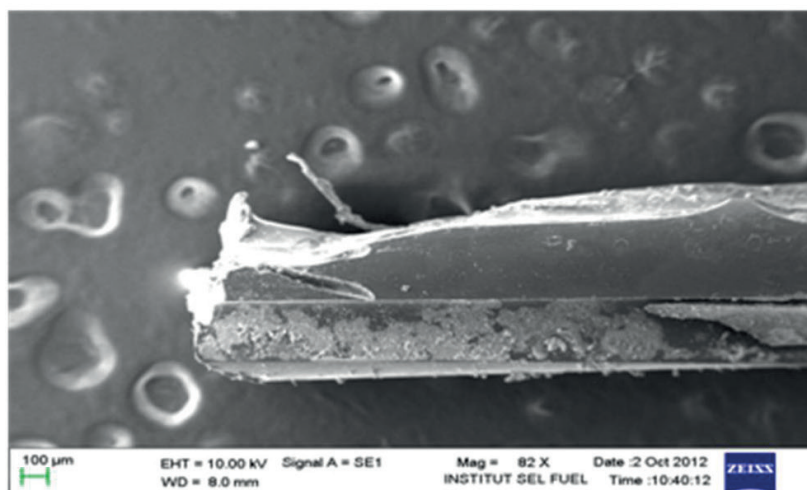
This shows that the physical property of the fiber strand is sustained when the fiber is tapered using chemical solvent. However, when the fiber is etched while it is in bending state, brittleness occurs and leads the fiber to break apart. **Figure 2(c)** shows the physical state of the fiber
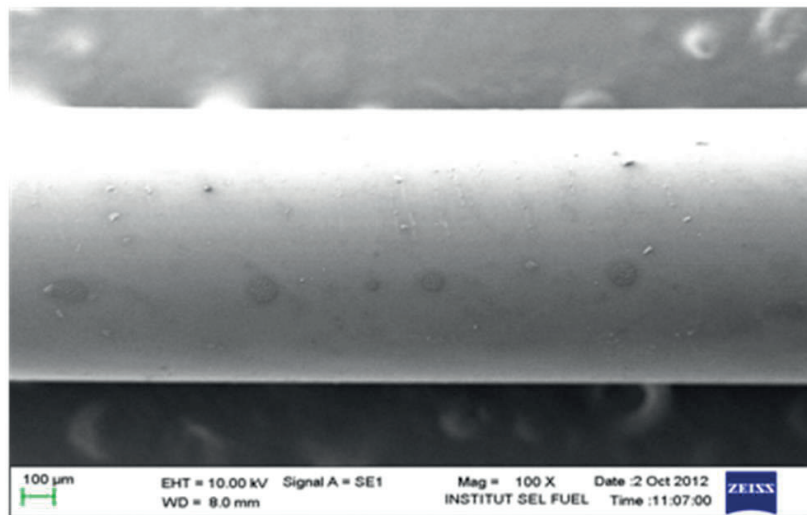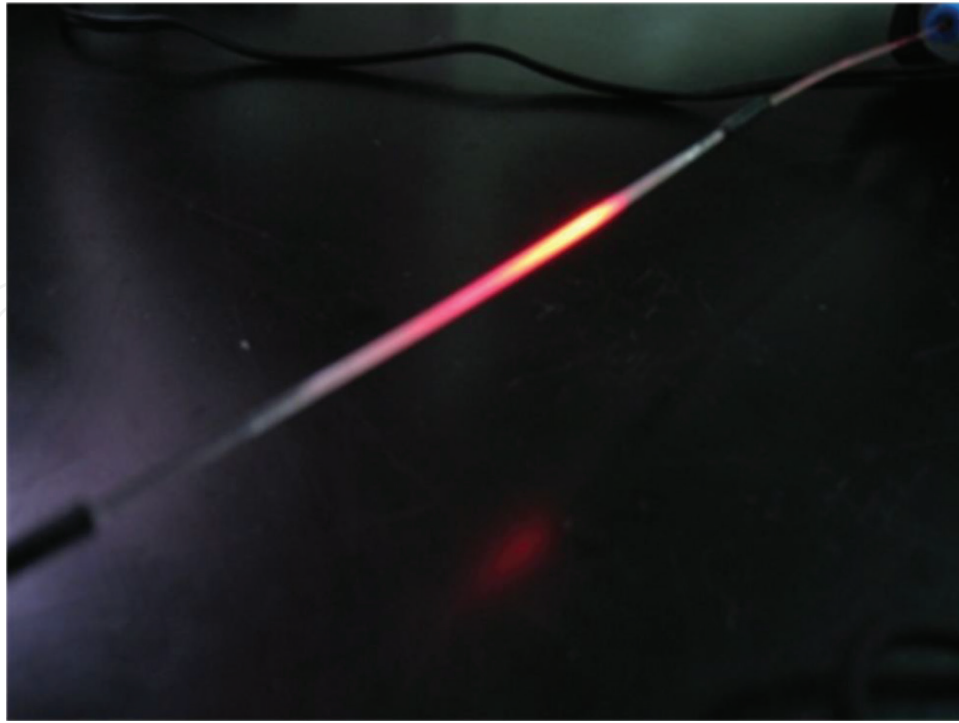
(a)
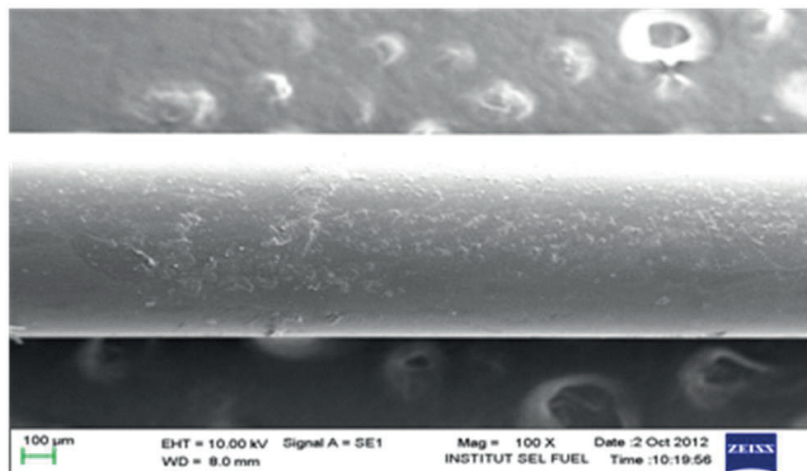
(b)

(c)

Figure 2. Physical surface of the (a) pre-etch (b) post-etch fiber and (c) fiber breaks due to brittleness.

Figure 3. The light transmitted over the etched fiber.

when brittleness causes the fiber to break. **Figure 3** shows the light signal transmitted over the etched fiber and it shows that the light spread out at the etched region only and due to this behavior, insertion loss increases and output power decreases.

1.11. Platform development

The coupler/splitter platform is one of the important parts of developing this directional coupler using lapping technique and geometrical blocks. The platform of the coupler is customized using acrylic material. The platform of the fiber coupler/splitter is consisted of mainly circular/elliptical blocks of various radii, made of acrylic material that has similar refractive index as the cladding of the fiber.

1.11.1. Circular

The first phase of platform development involves the development of circular blocks made of acrylic material as shown in **Figure 4**. The circular block functions to hold the etched fibers while the fibers will be bent accordingly to the bending radius of the circular blocks. A groove of 1 mm is carved along the edge of the blocks in order to place and hold the fibers as shown in **Figure 5**. The tapered area of the fiber is facing outward of the groove and will be lapped to the other tapered surface so that coupling or splitting between the two fibers can occur. The etched area or surface that is not facing or lapping to the other fiber is covered by the groove of the blocks that are made from acrylic. Acrylic material has similar refractive index as the cladding layer, n = 1.402. Therefore, the unlapping surface of the etched area is covered

by similar cladding layer refractive index. Thus, when the propagating modes are traveling along the etched fiber, some of the modes will be transferred to the other lapped fiber while some the modes that radiated out of the unlapping area is bounded by similarly refractive index of cladding, that is the groove of the block. Therefore, this will decrease the loss. The pivot is designed to hold the etched fibers that are placed at the groove so that they do not move and the tapered surfaces are lapped to each other. The screws of the pivots are used to loosen and tighten the pivot accordingly so when other block of bending radius is placed, the fiber can be bent according to the bending radius of the circular blocks.
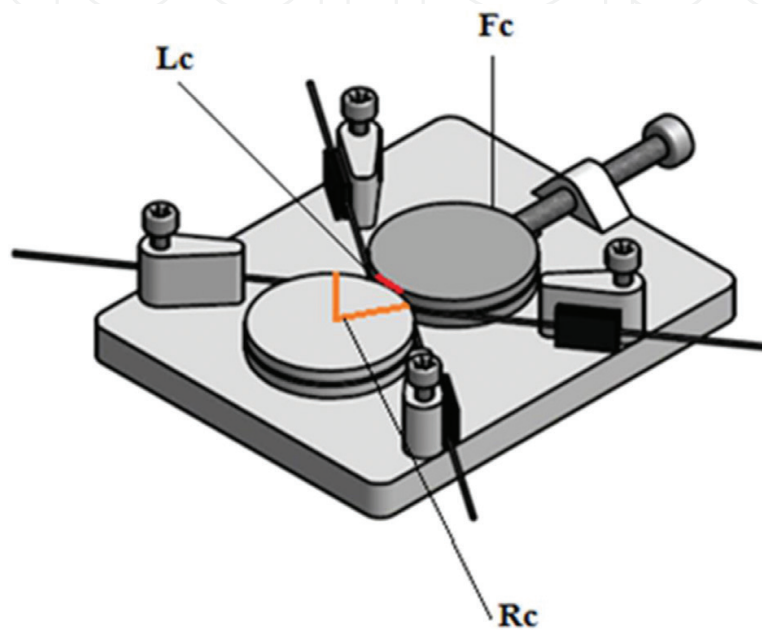
**Figure 4.** Circular blocks platform and fibers lapped.
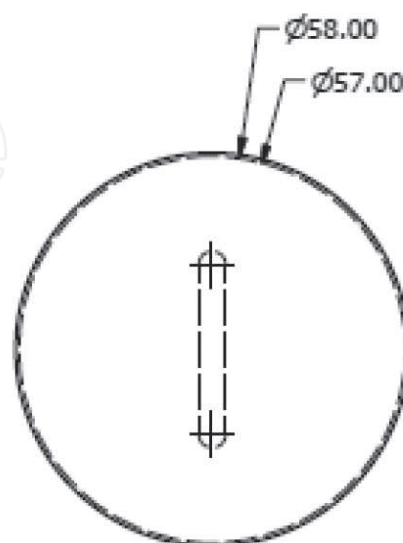
Figure 5. The bottom view of a circular block with groove showing at the round edge of the block.
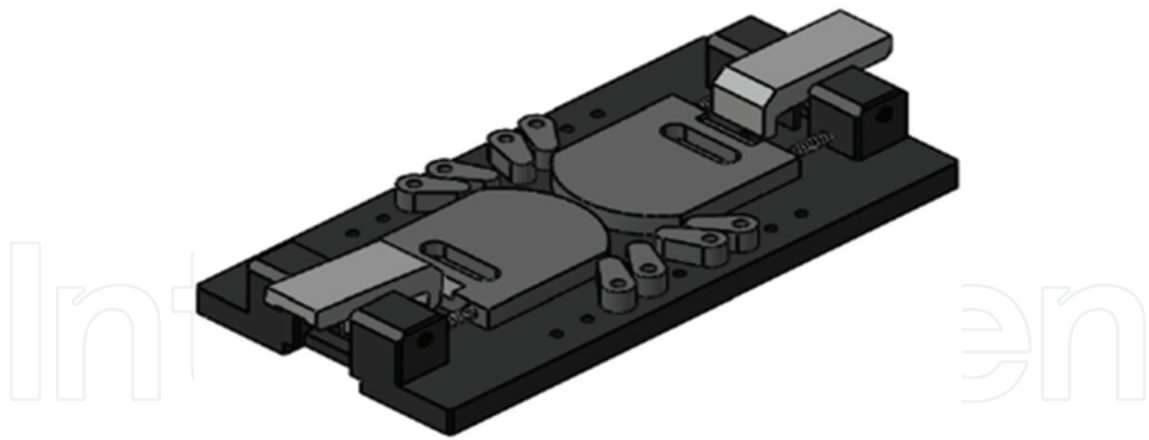
1.11.2. Elliptical

Elliptical blocks shape are designed apart from circular blocks as another geometrical shape in order to study the effect of different bending radius, R_c, and coupling length, L_c, between the two lapped fibers. Apart from circular blocks having bending radius or curve that is more critical than elliptical shape, circular blocks are used to mainly study the effect of bending radius when the fibers of the coupler are bent at certain bending radii. Elliptical shapes in the other hand, when fibers are attached to the elliptical blocks and bent, the bending radii are less curvier than that of circular blocks, however, the curves of ellipse shape blocks are more flatter thus the coupling length between the two lapped fibers are longer than that of circular blocks. Bending does play part in order to stimulate the transfer of modes from the first fiber to the second one, however, another parameter that also play an important part is coupling length, L_c. The bending radius of elliptical shapes range from 10 to 29 mm. The bigger the bending radius of the elliptical shapes, the longer the lapping region between the two lapping cores. **Figure 6** shows the dimensions of the elliptical platform together with the force gauge embedded in the design. The experiment platform is big as to characterize and analyze which bending radius range is the most optimum to be used and developed as an efficient optical coupler/splitter using lapping technique.

1.11.3. Semi-elliptical

The third phase of the development is using semi-elliptical shaped blocks and platform with spring embedded as shown in **Figure 7**. The semi-elliptical shaped blocks have bending radius of 30, 40 and 50 mm. No force gauge is used on this platform because the force is exerted unto the blocks and fibers by the spring embedded in the platform.
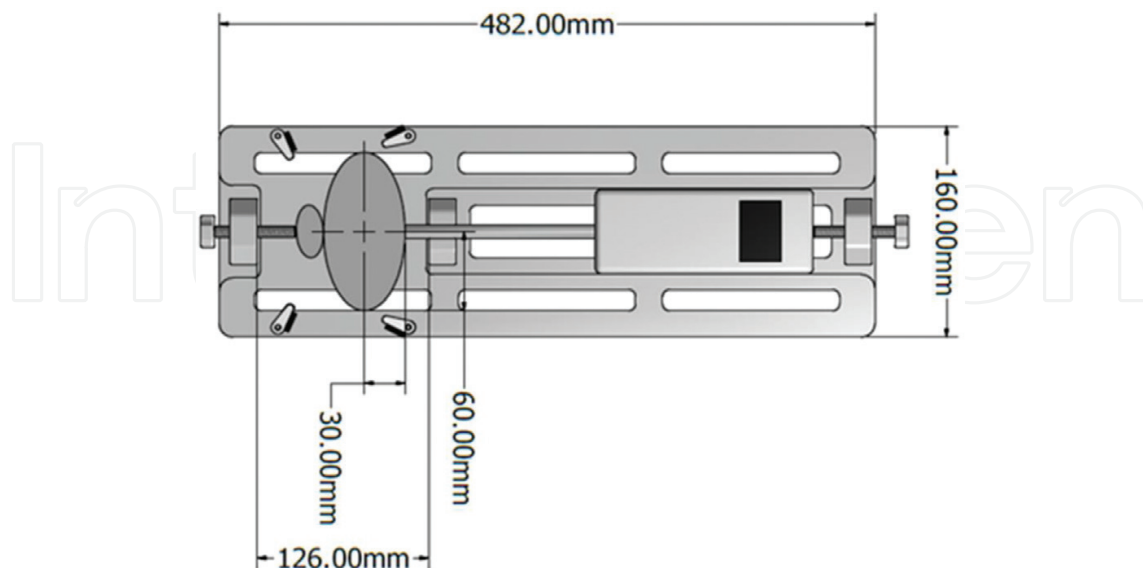
Figure 6. Elliptical blocks platform design measurement with ellipse-shaped blocks.

Figure 7. Coupler/splitter experimental platform using semi-elliptical blocks and embedded spring.

1.12. Coupling efficiency by integration of CMT and Hertz's law

The amount of power transfer is relatively in accordance to the coupling length. Thus, in this study, two very important theories are applied where the force exerted on the fiber through geometrical blocks relates to elliptical point contacts of Hertz's Law [30] and the amount of force put upon the fibers determines the radius of contact area or coupling length which brings to Couple Mode Theory. The propagation of modes between the two fibers is studied analytically and coupling efficiencies are obtained by varying the load force, coupling lengths and the distances between the two fibers.

To obtain an efficient coupling ratio or splitting ratio, the coupling length between the two lapped fibers must be long in order to obtain an adequate level of coupling efficiency. In this research, two similarly fibers were tapered at the middle region with particular diameter of core-cladding. They are attached to the circular blocks/elliptical blocks of certain bending radius that determines the bending angle of the lapped fibers that helps the transfer of energy from primary fiber to the secondary fiber. The performance of the splitter/coupler is analyzed through the relationship of the distance between the two fiber waveguides and the load put upon the blocks and fibers which gives effect in the coupling length. For the multimode step index fiber, a group of modes exist as according to parameters assigned by the optical wave-guides. Between reflections of each of the propagation rays, each ray travels in straight line and Snell's Law determines the reflection on the interface [31].

Coupling efficiency is calculated by first specifying the coupling length, L_c, which in this design is assumed to be directly relative to radius of contact area, c, of Hertz's ellipsoid. Coupling efficiency is done by integrating the coupling coefficient and coupling length.

$$\eta = \frac{P_{A \to B}}{P_{in}} \leqq \frac{1}{N} \int_0^1 \sin\left(\frac{(2^{1/4}\,\Delta^{1/4})\,L_c}{\sqrt{\pi k\,n_0}\,D_c^{\,3/2}}\,t\,(1-t)^{1/4}\right)^2 dt \tag{1}$$

$$\eta = \left(\int_0^1 \sin\left(C_{coef} \cdot L_c\right)^2 dt\right) \tag{2}$$

Here the relationship between CMT and Hertz's can be focused on coupling length or twice the radius of contact area of the elliptical point contacts of two spheres.

$$\eta = \int_0^1 \sin\left[\left(\frac{1}{\sqrt{\pi}}\frac{\sqrt{NA(n0, n1)}}{\sqrt{k(\lambda)\cdot(D_c)}\cdot(n0)}\right)\left(\frac{(t)\cdot(1-t)^{1/4}}{D_c}\right)(2)\left(\sqrt[3]{\frac{3\cdot F\cdot (Re)}{4\cdot E}}\right)\left[(F1)\left(\frac{R1}{R2}\right)\right]\right]^2 dt \qquad (3)$$

This expression will be used to vary the distance between the two fibers having different load F_c and the coupling efficiency of the splitter can be determined accordingly.

1.13. Performance

During characterization of the couplers/splitters, the experimental set-up is first prepared as shown in **Figure 8**. Geometrical blocks of different radii are placed on the platform with pair of tapered cladding secured in the groove of the circular/elliptical blocks. At each of the ports of splitter/coupler except at the input port, power meter is set to take readings of the output power. Red LED of $\lambda = 650$ nm is injected through input port and normal force of $F_n = 0.3$ lbF is exerted upon the middle region of the coupler/splitter through the geometrical blocks as shown in **Figure 8**. Normal force is the reading at which the two cores of the fibers touch each other without any external force. Output power is taken accordingly at each port. Then, given force or external pressure is exerted upon the blocks and fibers, namely $F_c = 3.0$ lbF. This external pressure is presumed to minimize the air gap that existed between the two lapped cores.

The experiment was repeated twice as in the first test, normal force is exerted upon the blocks and the fiber cores and in the second test, external force is exerted upon the blocks and the fiber cores. Based on the data collected, efficiency of each coupler/splitter can be measured. The efficiency of a coupler/splitter, σ can be defined as power ratio of overall output, ΣP_o against the power input, P_1. The mathematical equation that refers to the coupler/splitter efficiency is:

$$\Sigma P_o = P_2 + P_3 + P_4 \qquad (4)$$

$$\sigma\ (\%) = \frac{\Sigma P_o}{P_1} \times 100\% \qquad (5)$$
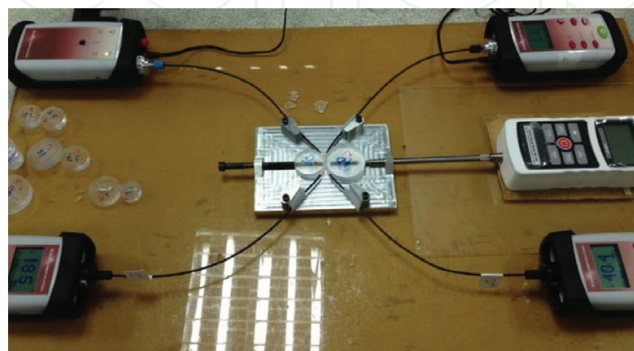
Figure 8. Experimental set-up platform with force gauge.

P_2, P_3 and P_4 are the output power of the light signal that propagates out of the throughput port, P_2, coupled port, P_3 and reflected port, P_4, while P_1 is the input port of the injected light signal.

The objective of this work which is to apply theories of CMT and Hertz's Law in studying the effect on coupling efficiency by manipulating the cores and coupling lengths between the fibers are analyzed and the optimum efficiency obtained shows that when the two fiber cores are closed to each other, the efficiency lies between 40% and 70% depending on the coupling length and distance is zero. When force exertion is small, the coupling length decreases thus coupling efficiency decreases to less than 50%. It decreases when the force, F_c is less and the coupling length, L_c is shorter. The efficiency decreases as the distance, d, between the two fiber cores is bigger. The optimum range of efficiency achieved based on coupling length, L_c, depends on the fiber core size, D_c. The diameter of the cores affects the efficiency where optimum efficiency is achieved at shorter coupling length range when the core diameter is smaller. This study gives an insight of the optimum distance and fiber core size of the lapping fibers used in the experiment.

Experimental results show the splitters having different splitting ratios as high as 80% to as low as 1%. Each of the splitter has different bending radius, R_c and different tapered length, L_e. Macro-bending effect shows that different bending radius of circular and elliptical blocks allow different bending angle for each splitter. Small angle of bending leads to radiation of rays that propagate along the bent section. The radiation is enhanced by the tapered regions at the bent section where some of the cladding layers are etched to allow coupling between the lapping sections. Different core-cladding thickness may influence the amount of rays coupling into second fiber. Large bending radius in the other hand slows the radiation rate, however, helps the splitting and coupling by lengthen the lapping region or coupling length. Diameters of 0.88 mm of splitters show optimum splitting ratios such as 80%, 70% and 60%. However the losses are high due to the surfaces of the tapered fibers that were etched wholly around the surfaces. The non-lapping section may contribute to the losses. Diameters of 0.77 mm in the other hand give splitting ratios between 20% and 50% with considerable losses. All bending platform of circular, elliptical and semi-elliptical blocks contribute to these range of splitting ratios. Side-polished and side-etched splitters and fully etched splitters with varied etched length are mostly used with the platforms to obtain optimum results. Long tapered region as given by fully etched fibers with constant etched length shows very low splitting ratios with considerable high losses. However, shortest tapered region does not give the most optimum results. Therefore, depending on each parameter, particular tapered length, diameter and bending have to be considered into the design to obtain desired optimum results.

1.14. Maintenance and reproducibility

Another important attributes that represents a coupler include its flexibility, maintenance and reproducibility. The device is flexible since the fiber pair and blocks can be exchanged in order to get desired splitting ratio. Even though the blocks needs to be exchanged for obtaining desired splitting ratio, the blocks and fibers are ready to be fitted into platform and they are highly durable. Since the splitter is custom-made, the splitter can be reproduced by handling

each process of fabrication meticulously to the etching rate, polishing rate and bending size in order to achieve uniform and persistent results.

1.15. Installations and performance

Installations and performances are very important attribute to any coupler or splitter developed. Although a coupler is a small component in a system, it does play an important role throughout the whole performance. Although the coupler/splitter developed has considerable higher loss than the ones in the market line, the ability of the coupler to achieve several splitting ratio has high potential where improvements and expandability of the device can be done in order for the device to compete in the market line.

The device developed is easy to install using prepared platform and mix matched fiber pair and blocks where varied splitting ratio can be obtained using one platform. Although targeted loss is considerably higher than marketed splitter, however, the device is applicable for signal transmittance and applications. The device developed is green technology-based since the production process is using eco-friendly material, harmless solvent, moreover, LED source is used which is very safe for consumers.

1.16. Research future Prospect

The limitation of "DIY" kit can be overcome by this design. Since the design of this splitter gives several solution of splitting ratios, users that demand different value of splitting ratios can utilize the splitters. Although the prototype design for users are yet to be finalized, however, based on the results shown, the platform shows good performance and can be realized as DIY kit. Apart from that, the since the cost of POF is low and materials and tools needed to build the platform are inexpensive and does not involve high-end expensive machine, this device has low-cost production and very economic. The material used to develop this device such as POF, harmless chemical solvent, acrylic and aluminum are safe and green technology based.

1.17. Summary

New technique of developing an optical coupler using POF and mechanical platform using lapping technique is discussed and analyzed in this chapter. Three different categories of splitters are prepared where the first category of splitters has constant etching length of 25 mm and the diameter of the tapered section is varied. The second category is splitters that have been etched with different length between 4 and 25 mm but having constant diameters of 0.88 mm. The third category is splitters that have been polished and etched at one side of the fibers only having different etching length between 4 and 25 mm and constant diameter of 0.77 mm. Three different platforms are also built. The first platform having small angle of circular blocks, the second platform having larger angle of elliptical blocks and the third platform having intermediate angle between small and large angle of semi-elliptical blocks with spring embedded. Varied angles represented by the bending radii of the blocks are chosen and designed in order to study the bending effect of the splitter. Different bending radius with combination of fiber diameter and coupling length leads different coupling behavior between the two lapping regions and therefore provides different splitting ratios.

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