Chapter

Polymer Optical Fiber Splitter Using Tapered Techniques for Green Technology

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Abstract

Polymer Optical Fiber is opted as the most suitable medium for short haul communication system since it has lower cost and low loss for limited distance of transmission compared to glass fiber. This topic aims to show an alternative, green-technology based, economic and user-oriented communication passive device specifically a directional coupler by lapping tapered-fibers technique. This developed device is using designed geometrical blocks with integration of tapering effect, D_c, macro-bending, R_c, force exertion unto the coupling region, F_c, and etching lengths of the cores, L_e to gain different splitting ratios, i.e., 50:50 and 90:10 experimentally by using the designed geometrical blocks with varied bending radii that affects the radiation of evanescent wave and to relate the integration of Couple Mode Theory and Hertz's Law to obtain optimum coupling efficiency. The development may be an option to current device that are less user-friendly and fragile. This device is developed as a green technology-based device as an option for higher speed communication devices since the materials using in the development is safe, harmless, and inexpensive.

Keywords: polymer optical fiber, acrylic blocks, directional coupler, splitter, geometrical blocks, low-cost, short-haul communication

1. Introduction

This work is conducted to develop an optical fiber passive device based on polymer optical fiber, specifically a splitter or also can be known as a coupler. This device is developed as an effective green-technology based device yet providing an economic solution for home-networking fiber to the home system. The splitter is mainly developed for short-haul communication system where the splitter is developed using polymer optical fiber that has been tapered using harmless organic compound chemical solvent which is acetone. Other method of tapering used in this research is by using side polish where only one side of the diameter of the fiber strands is being tapered. The platform of the device is built using acrylic material having customization of dimensions of the prototype design. Geometrical shapes of circular blocks and ellipse blocks were developed with various bending radii where the tapered fibers are attached to the groove of the blocks and brought closed together. Parameters that involve in this research includes bending radius, R_c, diameter of fiber cores, D_c, coupling length, L_c, and force exertion, F_c.

The coupler/splitter developed in this research includes the preparation of the fibers by etching, side polishing, and building the splitter platform which includes the geometrical blocks with various radii of the macro-bending. The purpose of etching is to eliminate the cladding layers in order to allow the propagation of the modes to travel into the other fibers. However, other factor that could help the transfer of modes from one fiber to the other is macro-bending of the fiber. Evanescent field allows the modes in the fiber to propagate in the cladding. When the fiber bends, losses happen due to the evanescent field that would have to travel faster in order to keep up with the core field. At certain bending, i.e., beyond critical bending, the modes tend to radiate away. In consequence of tapering the multimode optical fiber cladding, higher modes of the fiber are removed while some modes are redistributed.

Other contributing factors that encourage the transfer is the force exertion unto the blocks and fibers attached to the blocks. Some pressure is exerted upon the fibers in order to eliminate any macro-gap that exists between the two parallel fibers. Therefore, when the two fibers are lapped together, the transfer of modes between the two fibers can prevent any leaks of modes that radiates away due to the evanescent field when bending. Length of the parallel coupling also contributes to the effectiveness of mode coupling since when the coupling length is short, only small number of modes get transferred. Coupling length is varied with several bending radii and diameter of the cores to find the optimum performance parameters based on the characterization.

In applying analytical modelling method to characterize and analyze the device, two important theories are used, that are Coupled Mode Theory and Hertz's Law. A simplified couple mode theory between two parallel, lapping multimode step-index fibers are studied where parameters in control which is radius of contact area or coupling length are induced or related by the amount of force or pressure exerted upon the lapping fibers that are attached to geometrical blocks with various radii. The radiation of the propagation modes is induced by the bending of the fiber accordingly to the radius of the geometrical blocks. Depending on the coupling length of the parallel fibers lapped together, the power transfer between them varies in accordance to the length. However, due to physically lapping fibers without any fusion between them, force or pressure is an important aspect in this study so that to eliminate or at least reduce the number of losses of the power transfer due to macro gap. Two important theories are applied which are Hertz's Law and Couple Mode Theory that relates to analytical study of force exertion and radius of contact area.

Polymer optical fibers (POF) show great advantage compared to glass fibers in short-haul communications links due to its flexibility and less expensive, although they are not used for very long distances because of their relatively high attenuation. These characteristics are an advantage for fiber-to-the-home networking having high speed communication. An example would be Internet access within home or within an office [1].

There are several methods that can be used to develop optical fiber coupler/splitter. However, this work aimed to develop optical splitter/coupler that is green-based, safe to use, low cost, economic, easy to install and has multiple solutions for important performance parameters required by users. The optical fiber pairs and the combination of blocks allow the designed platform to produce several performance parameters with minimum loss. Therefore, the device developed can also be a do-it-yourself device since it is customer friendly. The technique used in the process of development is harmless and requires detailed measurement, thus, producing an effective yet low cost POF splitter/coupler that can be used widely by the users.

2. Polymer optical fiber (POF) as lead medium in short distance transmission

Commercially available POF for data communications are polymethilmethacrylate (PMMA) POF core material as shown in **Figure 1**. For visible light of 650 nm, the IR-absorption is 95.9 dB/km, the Rayleigh scattering is 10.3 dB/km and total loss of 106.2 dB/km with no UV-absorption [2]. PMMA POF used in this study is manufactured by Mitsubishi Rayon (Japan). PMMA is produced from ethylene, hydrocyanic acid, and methyl alcohol. It is resistant to water, lyes, diluted acids, petrol, mineral oil and turpentine oil. PMMA tensile strength is approximately 8 kN/cm^2. The refractive index of the core is 1.492 and the cladding is 1.402. The transition temperature lies between +95 $°C$ and 125 $°C$. At room temperature and 50% humidity, the material can absorb up to 1.5% water that can affect the attenuation. The applications include light transmission for signs, illumination, sensors, couplers, nuclear radiation detectors and medical applications.

Polymer optical fiber was introduced in 1960s after glass optical fiber was introduced shortly as a transmission medium for optical communications. Over the years, the transmission capability of POF is improved from having a large attenuation as large as 300 dB/km to 20 dB/km at 650 nm wavelength [3]. POF technology has advantage characteristics such as low insertion loss, low-cost production, thermal stability, mechanical stability, and mass production reliability [3]. Although POFs have higher loss than silica fibers or glass fibers, POFs are never used in long distance communication systems but are being used in intra office communication systems where one requires only a few hundred meters of the fiber. POFs are providing low-cost solutions to short distance applications such as local area networks (LAN), high speed internet access and in vehicles [4].

POF offer the advantages of being lightweight, flexible and easy to handle. Other advantage includes having large fiber cross-section which makes it easier to positioned fiber end at the transmitter or receiver compared to GOF that needs an expensive precision component to center the fiber. PMMA POF has 1 mm diameter

Figure 1.
PMMA polymer optical fiber with diameter 1 mm.

which makes it easy to handle and flexible compared to GOF where the fiber is quite easy to break. PMMA POF is also easy to cut, grind, polish or melt. It also has high flex resistance where the cost used is low even under intense loading conditions that encountered in mechanical engineering applications. Other than that, the easy connecterization of the end faces can be performed cost effectively even after assembling in the field [5].

In respect of electromagnetic compatibility, electrical isolation, immunity to eavesdropping and risk of explosion in hazardous areas, polymer optical fiber and glass fiber have the advantages compared to copper since the photons as the carrier of information in optical fiber have no electrical charge like the electrons which carry the information in copper conductors. In terms of external and mechanical properties, small bending radius and high flexibility are advantages that make POF an attractive choice compared to GOF. The low weight of optical fibers compared with copper is an advantage in most applications.

3. Existing techniques of POF splitter

Couplers work by combining two or more optical signals and combined them into one signal being modulated and propagates through one single fiber whilst splitter in the other hand, separates the signals at the end of the fiber and send the particular signals to their particular destinations [6].

There are three kinds of optical couplers which are directional, distributive, and wavelength-dependent couplers. The mechanism involves in these couplers can be categorized as diffusion type, area-splitting type, and beam-splitting type. Diffusion couplers involve either evanescent wave coupling or radiative coupling. Two fibers are place in proximity [7] and the length of the parallel lapping cores are measured which is known as coupling length. Once they the gap is reduced, radiation of light or known as evanescent wave coupling will initiate thus power transfer will happen. In radiative coupling, bent fibers are coupled to each other by the radiated field. These works well with multimode fibers. Such example is twisted-pair coupler of fused biconical taper coupler. In the fused section, the fiber cores are still separated from each other but the core modes are converted to cladding modes, therefore, partly coupling optical power from one fiber to the other [8]. Example of distributive couplers would be star coupler and example of beam splitter couplers are monitors coupler. This work mainly focuses on directional coupler that has mechanism of diffusion type. Mode selection in multimode fibers has been done by employing offset-launch techniques and mode scramblers by bending the fiber to leak the high order modes and utilized them [9].

Lapping technique is chosen due to the simplicity of the design. Since the development focus on customized and low-cost device, lapping technique could easily be implemented. Other technique such as fused coupler has widely been used and the technique is hardly modified for new approach and new research contributions. Butt coupling and core-facet coupling technique in the other hand has alignment problems and to obtain optimum output will require high-end tools. Y-coupling in the other hand could only produce one output only although the performance is excellent. Other techniques are also discussed in **Table 1** [3, 5].

The demands of couplers include low loss, easy to handle, reproducible coupling behavior, lower manufacturing costs, small dimensions, having thermal and mechanical stability, having low mode dependence and have good isolation between the inputs [5]. Common designations of couplers include 1 × 2, 2 × 2, 1 × N

Type	Technique of fabrication	Advantages	Disadvantages	Loss
Y-coupler	The output fibers are ground where end faces completely cover each other	Has excellent performance as 50:50 power splitters/couplers	• Costly grinding • Difficult alignment • Losses are caused by the surface of the coupled-in not being fully utilized.	EL: 2.7 dB IL: 5.5 dB CR: 1.08 dB Dir: 16.8 dB
Side polishing	Two POF segment are bonded and polished until the core-cladding interface appears.	• The polished depth can be controlled to achieve desired split ratio. • Jacketed POF can be used. • High precision coupling adjustment is possible		NA
Chemical etching	Chemical solvents i.e. acetone, chloroform, methyl isobutyl ketone are used to taper the fiber		• Jacket must be removed • Not easy to control the solution concentration	NA
Reflective body	Device used to split the light is a cylindrical polymer rod.			IL: 4.3 dB

Table 1.
The types of couplers/splitter, the advantages and the disadvantages.

and N × N coupler. Types of couplers/splitters include butt coupler, core fusion coupler, bend coupler and core facet coupler [5].

For coupling to happen using lapping tapered-fibers technique, the two waveguides must be very close so that there is modal overlap, and the coupling coefficient is not zero. The wave is mainly confined within the core thus it is not possible to have wave coupling between fibers by just putting together two fibers side by side. Therefore, a core in one fiber must be very close to the core of another fiber or the propagating wave must extend far outside the core. One of the simple methods is to melt and fused the fiber together. By fusing and tapering the core together, this causes the dimension of the fiber core to be very small, thus the V number (mode number) is small.

Therefore, the propagating waves in the fiber extend far outside the core and coupling occurs according to coupling theory. By properly controlling the dimension of the fiber in the coupling region, a desired ratio of power coupling can be obtained [10]. If the two fibers are identical in the coupling region, both propagating waves will couple or split the same ratio of power from one fiber to another as shown in **Figure 2**.

Most of the existing 1 × 2 splitters only provide one or two fixed splitting ratios. Lapping technique provides the potential of producing multiple splitting ratios by adjusting the coupling length between the two lapping fibers and bending at certain angle. Due to this flexibility of adjusting the coupling length this work is focused on using lapping technique to develop this splitter. In order to produce multiple splitting ratios by bending and tapering, new platform is required to bend the fibers at certain angle and coupling length so that different coupling or splitting behavior

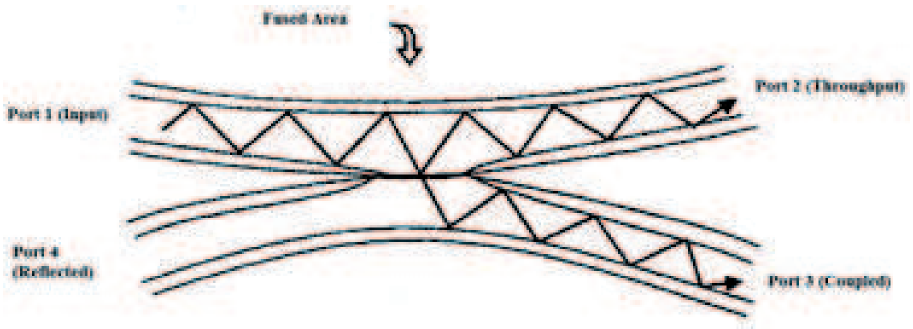

Figure 2.
Lapped fiber coupler with particular lapping length and radiated modes.

or rays will give different splitting ratios. Apart from lapping the fiber at particular length and diameter, certain amount of force is exerted upon the splitter in order to minimize the macro-gap between the fibers. Since parameter of force is also included, study of coupling efficiency between the two lapping curved surfaces with certain amount of load is based on Coupled Mode Theory (CMT) and Hertz's Law. No studies have been done in analyzing the coupling efficiency between the two lapping fibers based on the integration of CMT and Hertz's Law. The coupling efficiency is analyzed when distance, coupling length and fiber diameter is varied.

Ab-Rahman et al. has shown the fabrication of POF coupler/splitter using fusion technique where two POF are melted together and fused to developed N × N coupler/splitter [11]. The modifed coupler/splitter can be extended into demultiplexer. A novel fused POF splitter fabricated by fusion technique is an effective transmission media to split and recombine a number of different wavelengths which represents different signals. The demultiplexer device using different thin film having different colors to filter wavelength and optical splitter that provide optimal results when applied to the data transmission systems [12]. Although fused technique is easy, however, novel approach to develop the splitter is difficult to find. Thus, lapping technique using geometrical blocks are used to develop a directional coupler/splitter.

4. Fabrication using etching technique

There are some methods already done by researchers in order to fabricate coupler/splitters such as fusion between two or more fibers. One of the effective methods is tapering. Tapering can be done for example by technique of stretching fiber whilst it is heated under flame [13], and the other method is by chemical etching. The chemical used, acetone, is safe and harmless and it is effective to remove the cladding layer in certain time. Although tapering may change the physical fiber structure of the fiber itself, however, optical properties mostly remain the same. Due to the core being eliminated, the modes contained in the fiber will be radiated. The radiation of modes may be applied to this study that utilizes couple mode theory.

4.1 Cladding removal by organic solvent

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. Research done by Merchant et al. [13] shows that by using pure acetone without any dilution in water can be used to efficiently remove the cladding layer of PMMA POF. 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. The fiber should be supported in a curve and de-stressed fiber is supported in a straight line.

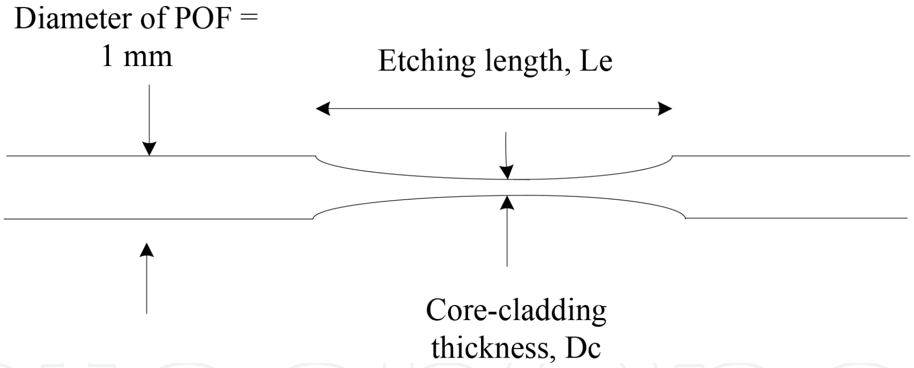

Figure 3.
The waist of the etched region is tapered.

Two to four drops of acetone are applied unto lint-free tissue and it is rotated along the region. The exposed core can be detected as the fiber is decreased in surface friction. 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. Another alternative method is by immersing the fiber into solution containing suitable mixture of organic solvent and water. Even when the solvent is diluted with 20% of distilled water, the brittle property of the fiber during the etching process remain. The fiber region that immerses in the solvent will be uniformly etched producing a linear waist region.

By tapering the multimode optical fiber cladding, higher modes of the fiber are removed while some other modes are redistributed when light source is propagating along the fiber. As the tapered section is developed, the evanescent field and proportion of total power within this field increases in the affected region.

Tapering the fiber can reduce the diameter as shown in **Figure 3** which can filter high-order modes in the fiber and create an effective reduction in numerical aperture which can be an advantage for optical sensor. POF tapers require no alignment and have constant attenuation of low-order modes. The modal redistribution length of POF is a few hundred meters and so the effect of tapers is local to that distance [13].

4.2 Polishing technique

Polishing technique is one of the methods [14–16] to reduce or eliminate the cladding so that the modes that propagate along the fiber may be radiated out due to evanescent wave theorem. Due to polishing effect, which is rough surfaces of the polished fiber, that may lead to increase in losses, therefore, some treatment has to be done. UV curing adhesive having similar refractive index may be used to bridge the gap between the polished fiber in order to reduce the losses. The efficiency of

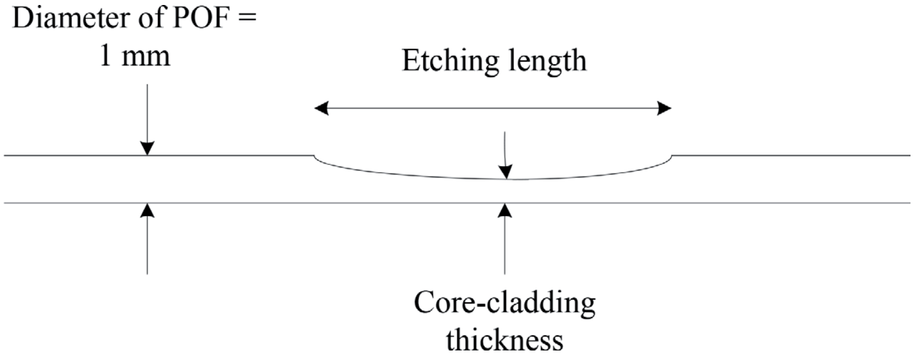

Figure 4.
Side-polished of a fiber.

the coupling light ranging up to 50% and the insertion loss is less than 5 dB [17]. Although it was simple, the limitation occurs when polishing leaves a rugged surface of the fiber. Thus, in this study, the polished surface is done by side etching the surface as shown in **Figure 4** in order to minimize the losses of surface.

5. Macro bending loss by radiation

Losses in optical fiber can be traced back by absorption, scattering or bending. Although losses are not a preferred performance parameter, however, it can be utilized into something useful such as coupling of modes of the bent dielectric waveguide [18]. One of the concepts applies is loss due to macro-bending of tapered bent fiber. The smaller the bending radius, the higher the losses will be [19].

At certain bending radius, which is known as critical radius, the loss is very high where total internal reflection an electromagnetic disturbance which is known as evanescent wave penetrate the reflecting interface. The rate of the propagating evanescent wave will reduce when reflection interface is no longer exists because it cannot propagate in the medium of lower refractive index.

When a light ray hits core-cladding interface, one of the rays will be refracted at the cladding interface and either the ray will be reflected back or refracted with some amount of power [20] while the other ray will propagate at inner core interface. More losses may be observed if bending starts to get smaller in radius where more rays will be refracted so thus the amount of power transferred at the cladding.

Refraction can also cause leaks of rays at the core-cladding interface. Electromagnetic tunnelling at the core-cladding interface is due to the cross section of the curvature. However, the leakage occurring at the tunnelling modes are slower as compared to refracting modes [8]. Some number of rays are not bounded by the core which results in propagating in the cladding region. This is known as the cladding modes and coupling can occur with the higher-order modes of the core resulting in loss of the core power.

There are few benefits of bending losses which are based on either the increase in the attenuation or on making use of the light which escapes from the optic fiber. One of the examples of making use the attenuation experienced by the fiber as it bends is fiber optic pressure sensor where a particular length of bare fiber is placed between two rugged pieces of rubber while the fiber is placed in straight line. A light detector is placed on the end side. When a step pressures the rubber, bends is created, and light intensity is detected, and the alarm went off. On the other hand, an active fiber detector uses light that escapes from the bent fiber. A fiber is placed between jaws of tool and when the fiber is stepped on and pressure exerted upon it, a sharp bend is created by the jaw and some light escapes and detected by the photocell and switch on a warning light [21].

6. Analytical concepts

Simple analytical analysis is studied to analyze the developed coupler using two important concepts which are Coupled Mode Theory and Hertz's Law. Simple coupled mode theory derived by Ogawa [22] analyzes the coupling theory between two parallel multimode step-index fibers and obtaining the coupling efficiency. Hertz's law in the other hand deals with contact mechanics where when load existed between two surfaces that relates to elliptical point contacts and the amount of force on the fibers determines the coupling length of the two fibers.

6.1 Coupled mode theory

Optical directional couplers can be described by coupling length and coupling coefficient as described in Coupled Mode Theory (CMT). The study of CMT has been done among researchers; however, the study of multimode is quite complicated compared to fiber having one or few modes [23]. Thus, this study focuses mainly on two multimode parallel fiber cores using simplified Coupled Mode Theory to find the coupling coefficient and coupling efficiency derived by Ogawa [22]. 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 [24].

A multimode coupler or tap coupler is an important component in any short distance communication system. In multimode fiber, it is not easy to evaluate the coupling process between hundreds of modes. Ogawa [22] derived a simplified expression for coupling efficiency between two identical, parallel, step-index multimode fibers which can expand to all modes with a condition that the two fibers are touching each other. Ogawa [22] agrees that the distance between the two fibers affects the coupling efficiency among other considered parameters.

The higher the modes launched at the input of the fiber, the higher the coupling efficiency will be. Higher order modes leakage may result in higher coupling in short lengths [25].

The simplified coupling coefficient given by Ogawa [22] describes that when distance over both radii of core or distance, *d* is given by D_c, the coupling coefficient becomes as in Eq. (1):

$$C_{\mathrm{coeff}} = \frac{2^{1/4} \cdot (n_{co} - n_{cl})^{1/4}}{\sqrt{\pi \cdot k \cdot n_{co}} \cdot a^{3/2}} \left(\frac{i}{N}\right)\left(1 - \frac{i}{N}\right)^{1/4} \tag{1}$$

Where a = radius of core

$k = \dfrac{2\pi}{\lambda.}$

n_{co} = refractive index of core

n_{cl} = refractive index of cladding

d = distance between the two fibers

$i = \dfrac{4}{5} \cdot N$

N = number of modes in step-index multimode fiber

Coupling coefficient reaches maximum when i = 4/5 (N) based on the field interaction between evanescent field of first fiber and second fiber. Higher order modes have stronger field in cladding relative to the field in the core. Ogawa works shows that coupling occurs only between the higher-order modes as the gap increases.

6.2 Hertz's law of elliptical point contacts

Elliptical contact area forms when two 3-dimensional bodies, each with orthogonal radii of curvature come into contact [26]. When force, F is applied between two curved surfaces, compression happens at the beginning of the contact and theoretically a flat surface is formed between them. The area is tangential to the surfaces of the two contacts and it is perpendicular to the line of action of load, F [27].

The radius of the contact area is given by Eq. (2):

$$a = \sqrt[3]{\frac{3 \cdot F \cdot \left(\frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right)}{4 \cdot \left(\frac{1}{R_1} + \frac{1}{R_2} \right)}} \tag{2}$$

where E_1 and E_2 are the moduli of elasticity for contact 1 and 2 and v_1 and v_2 are the Poisson's ratios.

The depth of indentation 'd' is related to the maximum contact pressure by Eq. (3):

$$d = \frac{a^2}{R} = \sqrt[3]{\frac{9 \cdot F^2}{16 \cdot R \cdot E^2}} \tag{3}$$

where R is the effective radius defined as shown in Eq. (4):

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \tag{4}$$

where R_1 and R_2 are the radius of each body respectively.

The size of the circular contact increases weakly with increasing load P and relative radius but decreases weakly with increasing contact modulus. The maximum pressure is 1.5 time the mean pressure and occurs at the center of the contact area [27].

7. New approach using lapping technique

Directional coupler is a passive device where modes exchange between two waveguides that is placed closed to each other. Due to radiation and phenomenon of evanescent wave, some of the power will be transferred to an adjacent guide due to coupling. The factors that contributed to the power or modes exchange between the two parallel fibers are the force exertion and the length of lapping fibers. 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 [28].

Lapping technique is the method used in the study where two tapered fibers with certain thicknesses, D_c are placed in proximity at certain length, L_e to each other. Due to the elimination of cladding around the core area, the effective refractive index of the waveguide is varied and coupling coefficient also change [16].

Acetone is a harmless chemical solvent that is used to etch or taper the cladding layer at certain thickness or diameter. The duration of the etching process took around 30 minutes to 120 minutes. Depending on the time of the etching process, the diameter of the tapered fiber will vary. If the cladding layer is decreased, the transfer or power between the lapping fiber will occur. In some cases, the tapering not only causes the cladding layer to be stripped off entirely, but also affect the region where the lapping does not take place which in the other hand resulting to extra losses of the coupler/splitter. Therefore, a platform is developed where mechanical blocks with certain radii will be used together with the tapered fibers having similar refractive index of the fiber that will replace the refractive index of the etched cladding layer.

The varied bending radii, R_c will result to different macro-bending effect, thus, the power transfer between the fiber will also vary accordingly. Coupling length and pressure applied unto the region of the lapping tapered fibers are important in order to obtain high splitting ratio and coupling efficiency.

7.1 Design development

The preparation of the fibers includes preparing the fiber strands of 300 mm long, etching process and side polishing process. Basically, each of the fiber strands was prepared using Mitsubishi Eska Polymethil Methacrylic (PMMA) step-index polymer optical fiber.

The process of etching process is done on polymer optical fiber which has diameter core of ø = 980 μm and diameter cladding of ø = 20 μm thick as shown in **Figure 5**. Chemical solvent that is acetone is used in this study in order to remove cladding layer. Etching process as shown in the figure takes between 30 minutes to 120 minutes to stripped off the cladding layer as intended. Due to the effectiveness of the solvent to impair and remove the cladding layer as reported by the research done by Merchant et al., [29], pure 100% acetone is used in the experiment without any additional liquid or solvent involved or modification the concentration of the solvent.

Figure 6 shows the light transmitting over an etched area between the two blue marks shows faded red light along the area. This fiber has been properly etched and contains the transmitting light with low leakage. Some of the modes are radiated out due to the cladding layers are etched over some duration of time. Therefore, as can be seen in the figure, at the etched region, LED light of wavelength 665 nm are radiated out. The etched fibers are used to develop directional couplers by using geometrical blocks. Etched fibers or denoted as coupler A is fixed unto the circular blocks and they are lapped together. Wavelength of red LED, 665 nm with input power of 16.0 μW is used as the light source. In **Figure 7**, a schematic of bent fibers lapping at certain length with tapered cladding can be seen. Light source having 665 nm wavelength is used to send signal in port a, and the power output are measured at the end of port b, c, and d. The measurements are taken at the end of the

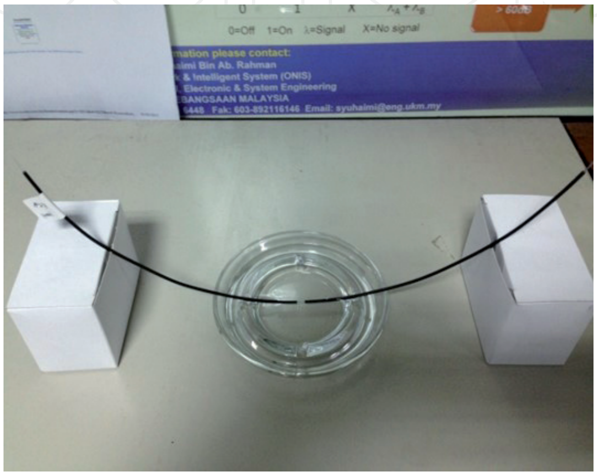

Figure 5.
Etching done by stress-free bending.

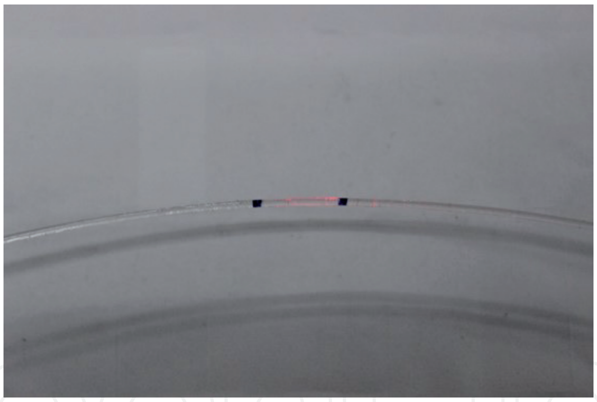

Figure 6.
Light transmission in properly etched fiber.

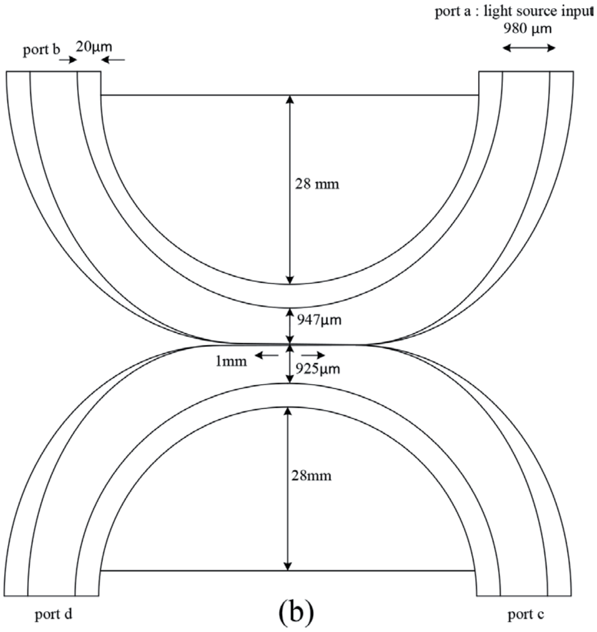

Figure 7.
Schematic of coupler using fibers that were etched.

three output ports in order to analyze the losses due to tapered cladding and force exertion between the two lapping fibers.

7.2 Directional coupler/splitter

There are many efforts done by researchers on developing an optical directional coupler using various techniques as discussed previously. In this work, new technique of developing 1 × 2 optical coupler is fabricated using mechanical techniques where geometrical blocks namely circular blocks of several radii, elliptical blocks of several radii with external forces exerted upon the blocks and fibers and semi-elliptical blocks with spring embedded are used where a pair of etched fibers is placed between them and bent as according to the bending radius of the blocks. Then at input port, P_1, a red LED signal of wavelength 650 nm is injected through the input arm and power meter is placed at the throughput port, P_2, coupled port, P_3 and reflected port, P_4 where the signal strength or output power is obtained and recorded for each output arms. The data recorded are then characterized and analyzed for each pair of coupler/splitter using each pair of blocks with particular bending radius. Characterization such as splitting ratio, insertion loss and excess loss are plotted for each coupler/splitter.

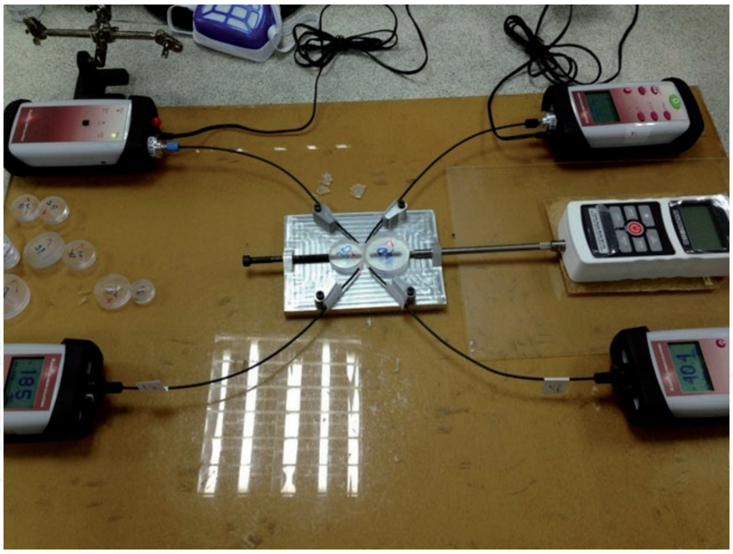

Figure 8.
Circular blocks platform with a pair of tapered fibers bent according to the bending radius of the blocks and input of 650 nm is inserted into one of the input and the output power is recorded.

Figure 8 shows the setup of circular blocks where the fibers length are around 30 cm using Mitsubishi Rayon Eska POF. The end of each fiber is connected with power meter of type AF OM 210A.

Table 2 shows the optimum splitter at each circular blocks pair. Splitter of coupling diameter, D_c of 0.92 mm–0.90 mm and 0.85 mm–0.75 mm give the optimum value of splitting ratios, SR for most of the circular blocks. Insertion loss, IL and excess loss, EL can be referred in the table accordingly. The reason might be due to the thickness of the core-cladding layers of each splitter that allow some of the light rays to propagate along the tapered length and when the fiber is bent accordingly and lapped to the tapered region of second fiber, the rays is coupled in the second fiber. Due to the fully etched region around the fibers that is not lapped to other waveguide and the extra tapered length, high losses are observed.

Although splitter of D_c of 0.92 mm–0.90 mm shows the most optimum SR_c for circular blocks, however, the excess losses are also the highest followed by D_c of 0.92 mm- 0.94 mm and the lowest excess loss (EL) is given by splitter of D_c of 0.95 mm- 0.95 mm as in **Figure 9**. Since most of the rays were transferred by the

Rc (mm)	Dc (mm)	SRc (%)	EL (dB)	IL (dB)
25–25	0.92–0.90	2.41	6.00	22.00
30–40	0.85–0.75	2.00	3.00	20.00
35–27	0.85–0.75	2.30	3.00	19.60
30–20	0.92–0.90	2.60	6.00	22.00
52–40	0.85–0.75	1.00	3.50	23.00
28–26	0.85–0.90	1.30	2.70	21.00
28–22	0.85–0.75	2.50	3.50	19.60
28–23	0.85–0.75	1.70	3.80	21.00
38–34	0.85–0.90	1.00	2.80	22.00
38–37	0.85–0.75	1.80	3.80	21.00

Table 2.
Splitters with optimum SR, EL and IL for each bending radius.

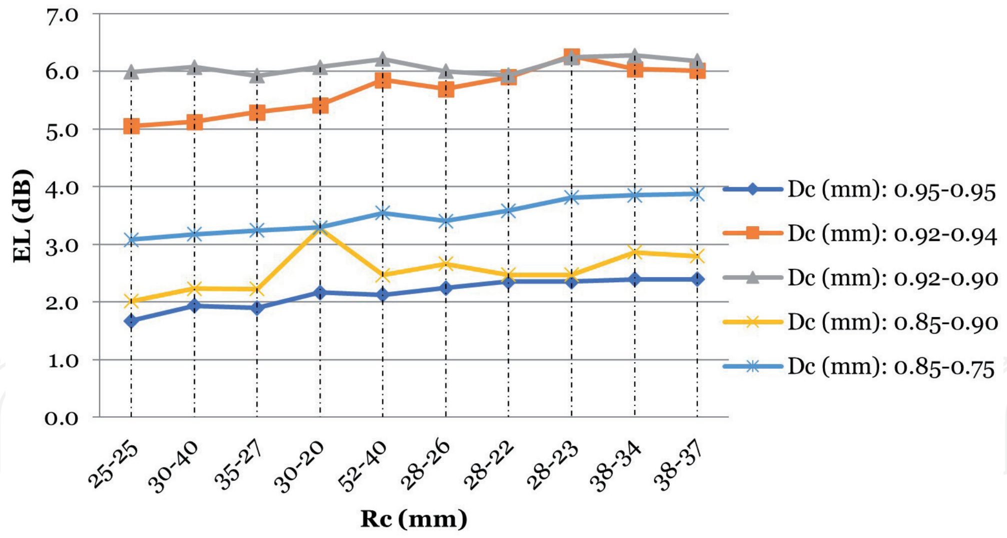

Figure 9.
Excess losses for each coupler/splitter of different core-cladding Thickness, D_c, for each circular blocks of different bending radii, R_c.

first fiber to the second fiber for D_c of 0.92 mm –0.90 mm, due to the unlapped region of the tapered section, many of the rays radiated out by small bending of circular blocks and the small coupling length between the two lapped regions contributed to the losses. However, for splitter of D_c of 0.95 mm- 0.95 mm, since the cladding layers conserved many of the rays from being radiated out of the fibers, the excess losses are lower for all the bending radii of the circular blocks.

At throughput port as shown in **Figure 10**, splitters of D_c of 0.92 mm- 0.94 mm and D_c of 0.92 mm –0.90 mm show the highest losses due to the radiation of the first fiber to the second fiber whilst D_c of 0.95 mm- 0.95 mm shows the lowest insertion loss at throughput port since the cladding layers that existed in the fibers prevent the rays from being transferred or radiated out from the first fiber.

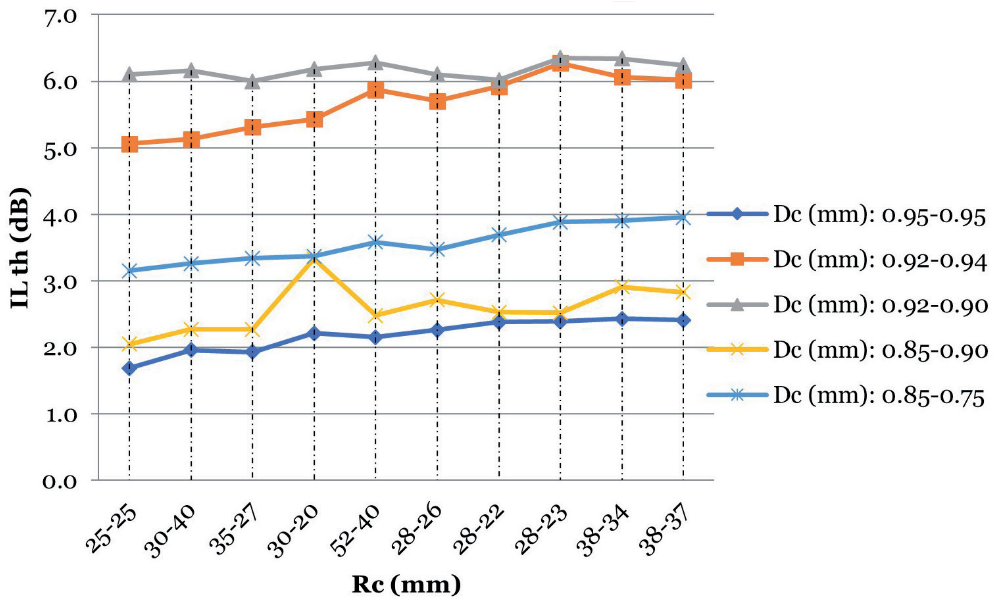

Figure 10.
Insertion losses at throughput port for each coupler/splitter of different core-cladding thickness, D_c, for each circular blocks of different bending radii, R_c.

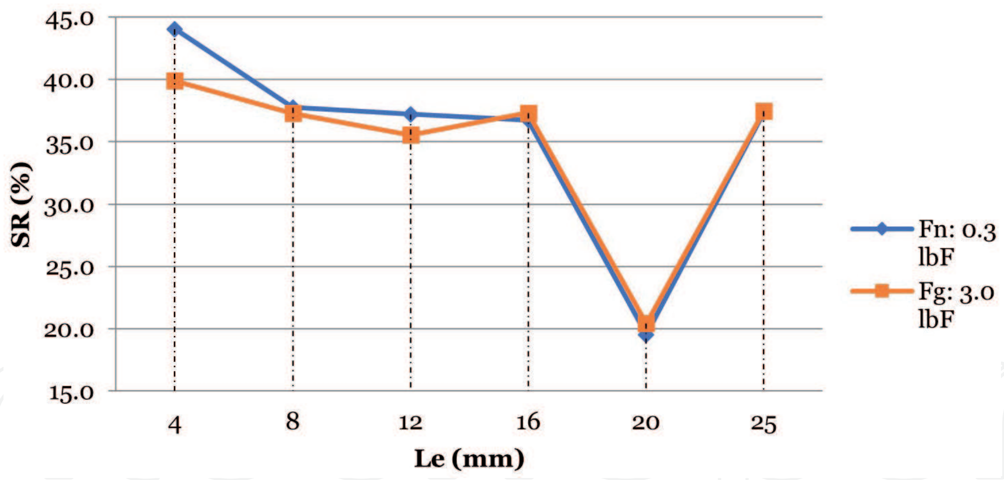

Figure 11.
Average splitting ratio for normal and external load unto splitter of varied etching length fiber splitters using varied combination of circular blocks.

7.3 Load exertion

Figure 11 shows the average splitting ratios when external load is exerted upon the splitters fitted into circular blocks. Splitting ratios show a slight decreased when external load is exerted upon the splitters of etching length, L_e of 4 mm, 8 mm, 12 mm. However, splitting ratios increase when load is exerted upon longer tapered length of L_e of 16 mm, 20 mm and 25 mm. Splitting ratios of L_e of 4 mm decreases from 44% to 40%, for L_e of 8 mm, SR decreases from 38% to 37% and for L_e of 12 mm, SR decreases from 37% to 36%. Splitting ratios for all other splitters increase about 1% when external force is exerted.

8. Comparison of efficiency between experimental and analytical values at particular coupling length

The coupling efficiency from experimental values are calculated by

$$\eta = \frac{P_o}{P_i} \times 100 \tag{5}$$

The efficiency of coupling length, L_c of 3 mm, 5 mm and 8 mm are 21.69%, 29.3% and 28.7% respectively is compared to analytical values simulated in MathCAD using Eq. (5) as shown in **Figure 12**.

Analytically, the result shows the coupling efficiency of core radius of 0.75 mm at coupling length extends from 0 mm to 20 mm. The distance, d, between the two cores is assumed 1 μm. Coupling efficiency from the graph at specific L_c, namely 3 mm, 5 mm and 8 mm is found to be 29%, 52% and 70% respectively.

It is observed that the pattern of the coupling efficiency of experimental values and analytical values is similar as shown in **Figure 13**, however, analytically the ideal simulated wave shows higher percentage of efficiency compared to the values of the efficiency of the experiment. The average difference of efficiency between analytical and experimental values is between 7% to 22%. The differences between the values are due to several factors. Due to the varied bending angle, R_c, of the fibers attached to the semi-elliptical blocks, the radiation of rays from the input fiber to the second

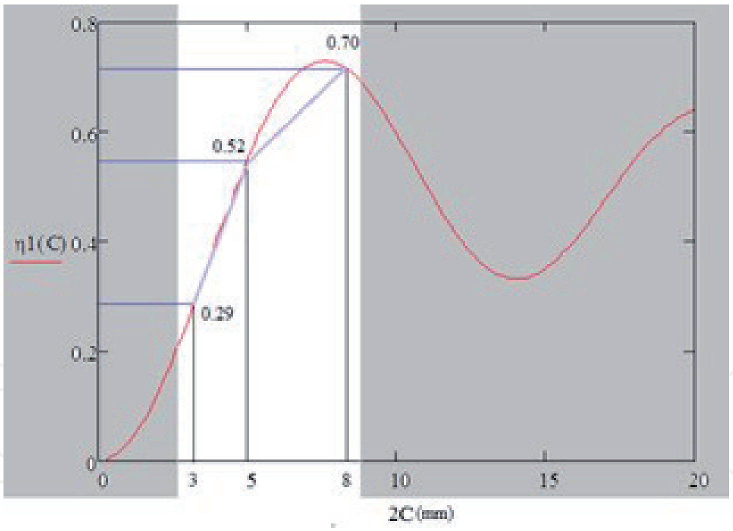

Figure 12.
Efficiency values at coupling Length.

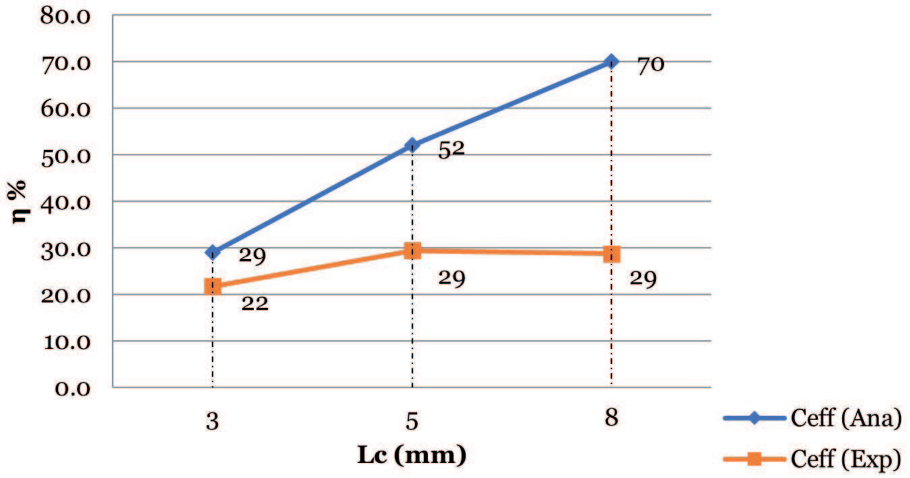

Figure 13.
Similar pattern of efficiency is observed for both analytical and experimental values at specified coupling length.

fiber varies accordingly. At 30 mm bending radius, the smaller bend stimulates the rays to radiate out more extensively, however, the losses are high due to tapered length that is longer than 3 mm which reduces the efficiency. At 40 mm, since the coupling length is longer which is 5 mm, the efficiency is higher. However, at 50 mm bending radius, although the coupling length is longer, however, the bending angle is larger which hinders the stimulation of rays to radiate out that causes the efficiency to reduce again. The etching or tapered length also causes the efficiency of the experiment to reduce since the extra tapered length could contribute the radiation of rays at the non-lapping region. High efficiency is found at simulated graph since the condition of the coupling is ideal where the condition of coupling in experiment accounts several factors that lowers the efficiency such as the tapered length of the cores, bending angle, insertion losses and connection of the fibers to the power meters.

9. Conclusion

New technique of developing an optical coupler using POF and mechanical platform using lapping technique is discussed and analyzed. The device fabricated is flexible since the splitter does not only give one particular splitting ratio desired, but it can be customized using different blocks of bending radius and several pair of fibers with different core-cladding thickness. The different pair of fibers can be matched with different pair of blocks in order to obtain particular splitting ratio for different applications. The implementation is simple where the blocks need to be placed on the platform where spring-like component will force the blocks to hold the fiber pairs close in proximity. Analysis of efficiency between experimental values of splitters and values obtained by simulated analytical values are compared where similar pattern of efficiency behavior is observed for the splitters which shows that the splitter is good to be used.

The effect of different angle of fiber bending integrates with different taper length and core diameter with force exertion is studied and analyzed in this study. Optimum results of splitting ratios is obtained by having bending radius between 30 mm to 50 mm, taper length between 4 mm to 20 mm, core thickness between 0.88 mm to 0.77 mm, coupling length between 4 mm to 10 mm and 18 mm to 22 mm and pressure not less than 3.0 lbF. The variation of the parameters leads to different coupling characteristics thus resulting in various splitting ratios and losses. Therefore, for different parameter values, particular values of other parameters have to be considered.

The maintenance of the device is also simple. The fiber pairs can be used continuously and interchanged with other fiber pairs. The fibers need to be changed with new ones only when the fiber is broken. In this case, since POF itself is very flexible, thus, the flexibility and maintenance of the fibers are quite reliable. The platform and the blocks are made of strong material that is hardly broken even they are dropped several times. Even in high temperature and heat, POF melting point is around $80\ {}^{\circ}C$ whilst the blocks that are made of acrylic material have melting point of $160\ {}^{\circ}C$. The platform based is made of aluminum that have very high melting point. Thus, the device can be used inside medium heat compartment such as in automobile. The reproducibility of the device is in the other hand in small production due to the hand-made fabrication at the research stage. This device is green technology based since the production process is using eco-friendly material, harmless solvent and the LED source is used which is very safe for consumers as compared to other method that use the heat using burner can contributes to CO_2 even in small amount.

The developed device can be innovated into a 'DIY' kit where the installation of the passive device will be easy and customer friendly. Different values of splitting ratios are able to be achieved thus give the advantage of different applications for the users. Moreover, since the device may provide different values of splitting or coupling ratios in one kit, users may no longer need to spend extra on purchasing another splitter/coupler. This device is inexpensive and green technology based due to materials used in the development and utilization.

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