Chapter 3
Wavelength Independent Monolithic 1x4 Couplers: Fabrication and Characterization

A new method for the fabrication of monolithic 1x4 singlemode fused coupler is described along with details of its performance in terms of coupling ratio, spectral response and polarization sensitivity. The device thus fabricated exhibits ultra-broadband performance with low polarization dependent loss. The signature pattern exhibits identical coupling to all interacting fibers, enabling an easy control on fabrication parameters of the device. The effect of different process parameters on the performance of the device is studied. The device performance is also analyzed for bi-directional transmission.
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Wavelength independent splitters are essential components in triple play Passive Optical Network (PON) deployments. Passive optical networks employ a multi-wavelength transmission scheme namely 1310, 1490, 1550 and 1625 nm wavelengths for upward and downward transmission as well as for physical layer monitoring [1, 2]. Hence the signal splitters installed in such networks must handle the signals faithfully and evenly at these wavelengths. Also these splitters shall be able to handle sufficiently high power levels for analog video overlay. High power handling splitters now find application in other areas also such as Erbium Doped Fiber Amplifiers and Fiber Lasers [3, 4, 5]. Integrated planar splitters are less advisable in high power applications due to epoxy in optical path, used to bond the fiber array and splitter chip, which can degrade in a long run. Thus fused biconical taper coupler offers distinctive advantage for broadband high power applications [6].

In fused couplers, coupling ratio is wavelength dependent [7, 8]. But it is well known that by controlling the propagation characteristics of interacting individual fibers and controlling the degree of fusion between the fibers it is possible to control the wavelength dependence [9-12]. The propagation constants can be altered by pre-tapering, pre-etching or pre-polishing one fiber prior to coupler fabrication. Though such technique has been well established for fabricating 1x2 wavelength independent couplers, it has not been explored in the case of truly fused 1xN couplers, where N is greater than 3. This chapter focuses on the theory and fabrication process of 1x4 monolithic couplers and suggests a new easy method for building wavelength independent 1x4 couplers.

3.1 All-Fiber 1xN Splitters

1xN Splitters are fabricated using Planar Lightwave Circuit technology or by fused coupler technology [13]. Fused coupler technology helps in realizing all-fiber 1xN splitters, with no epoxy in optical path. All-fiber 1xN splitters are fabricated by cascading 1x2 fused couplers [14, 15] as shown in Figure 3.1. Couplers are spliced one after another and are routed inside a metallic box enclosure. Here the reliability of the 1xN splitter depends on the reliability of the individual 1x2 couplers as well as on the reliability of each of the splices. Moreover, uniformity of the cascaded 1xN splitter depends on the performance of each of the selected device. Arbitrary selection of the couplers may result in a high uniformity value: careful selection of the couplers from a batch is essential to achieve good performance. The throughput and coupled ports of fused couplers have different behavior as discussed in the previous
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Chapter. When we cascade the 1x2 couplers, the wavelength dependence become prominent in the path where only odd and even ports are spliced. For the paths in which odd and even ports are spliced, the wavelength dependence does not get added, since odd and even ports have different spectral characteristics. The cascaded 1xN splitter has large form factor, since we have to take care of the bend radius constraints and the typical size is 100x80x10 mm³ [16].

In Gigabit PON, a single fiber line is normally distributed among 32 homes. Centralized splitting is not preferred in cases where home clusters are randomly distributed from the Central Office (CO). Splitting in such a situation is shared between the central office splitting cabinet and outside field fiber distribution hub. For instance, the central office splitting cabinet does a 1x8 splitting followed by 1x4 splitting near the premises of customer cluster. Hence in this work, we focus on the fabrication of wavelength insensitive 1x4 couplers. A typical application diagram of such device is shown in Figure 3.2.

Figure 3.1: 1x4 splitter formed by cascading 1x2 couplers

Figure 3.2: Application diagram of 1x4 coupler in a GPON network
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Monolithic Couplers are devices where more than two fibers are fused together as shown in Figure 3.3. Monolithic 1xN couplers are used both as a simple power splitter as well as a building block for larger port-count splitters. Thus singly fused 1xN coupler helps to reduce the footprint as well as the component density of large port count devices. A monolithic 1x4 coupler can replace three 1x2 couplers and two splices in a cascaded 1x4 coupler as shown in Figure 3.1. Less number of components is preferred from a long term reliability perspective. The schematic of a 1xN monolithic coupler is shown in Figure 3.3.

### 3.2 Monolithic 1x4 Coupler: Fabrication Methods

There are different methods, reported in literature, for the fabrication of fused monolithic singlemode 1x4 couplers. It is important to keep the geometry of fibers correctly at the fusion region; different approaches have been suggested for the same. In one approach, four bare fibers are inserted into a Vycor capillary tube having an internal diameter just large enough for the fibers to fit [17-19]. The use of capillary tube helps to keep the relative positioning of the individual fibers. The Vycor material is chosen because its refractive index is lower than that of the silica cladding of the fibers. Leakage of the optical field into the tube will therefore be minimized. In another method, use of dummy fibers is suggested to achieve relative positioning of fiber [20]. In fiber braiding method, fibers are twisted in such a way that, four identical fibers are positioned at the vertices of a square with a void space at the center [21, 22].

#### 3.2.1 Coupling Behaviour

The waist structure of monolithic 1x4 a coupler is shown in the inset of Figure 3.4. It consists of four identical fibers centered at the vertices of a square. If this structure is reduced in size, so that the modal fields of each fiber expand, then coupling between the fibers will occur. The coupling constants $C_s$ and $C_w$ represent the strong coupling
between adjacent fibers and weak coupling between diagonal fibers respectively. If unit power is launched into fiber-1 of this \( z \)-invariant structure, then the power \( P_n \) carried by each fiber after a propagation distance \( z \) is [17],

\[
P_1(z) = \frac{1}{4}[1 + 2\cos(2C_s z)\cos(2C_w z) + \cos^2(2C_s z)]
\]

(3.1)

\[
P_2(z) = P_4(z) = \frac{1}{4}\sin^2(2C_s z)
\]

(3.2)

\[
P_3(z) = \frac{1}{4}[1 - 2\cos(2C_s z)\cos(2C_w z) + \cos^2(2C_s z)]
\]

(3.3)

The coupling behaviour as a function of the propagation distance \( z \) is shown in Figure 3.4. Figure shows the power coupling at 1550nm. The coupling constants \( C_s \) and \( C_w \) are chosen to give sensible coupling over distances observed in practice. This profile, where there is strong interaction between the diagonal fibers, is similar to the power coupling profile in a quadruple core fiber [23, 24]. This complex coupling profile is attributed to different types of interactions among the interacting fibers in the structure, namely the coupling between the through-put and coupled fiber, coupling between coupled fiber and coupled fiber etc.

![Figure 3.4: Theoretically calculated power in each fiber as a function of the propagation distance \( z \) with \( C_s=0.33 \) mm\(^{-1}\) and \( C_w=0.065 \) mm\(^{-1}\) at 1550nm](image)
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It can be seen clearly from this graph that the power guided by the fibers adjacent to the input fiber never carry more than 25% of the total power. At $z = \frac{n\pi}{4C_s}$ ($n=1, 3, 5...$), each fiber carries the same power 25%. Hence, at a point A, as shown in the graph, all fibers carry 25% of the total power and it is possible to fabricate an equal split coupler operating at 1550nm. The propagation distance at which this equal coupling condition occurs only depends on the coupling coefficient $C_s$. The effect of $C_w$ is to modulate the power transferred between the diagonal fibers. The wavelength response of such device is more flattened in port 2 and 4, owing to the reduced power coupling to adjacent fibers, where the maximum power coupling is only 25%.

3.2.2 Pull Signature

Four fibers are twisted and tapered using the fused fiber coupler fabrication station described in Chapter 2. The power coming out of each of the fibers during fusion is monitored in real time at both 1310nm and 1550nm. The pull signature is shown in Figure 3.5, where the coupling at 1550nm is faster compared to 1310nm. At a distance of 8.25mm (point A), the power at 1550nm is equal in all fibers and a 1x4 coupler operating at 1550nm can be realized by stopping the pulling at this point. Similarly, 1x4 coupler operating at 1310nm can be realized at a pull length of 8.45mm (point B). The photograph of the cross-section of the coupler’s waist is shown in Figure 3.6.

Here all the fibers are identical, but the coupling to different fibers is not identical. The coupling ratio exhibits strong dependence on the wavelength. But there is a requirement for fabricating couplers with identical performance at 1310nm and 1550nm wavelength bands. Such broadband couplers are essential for passive optical networks, owing to the multi-wavelength transmission scheme. It is possible to fabricate wavelength insensitive couplers only if we can precisely control the fabrication process. Practically, it is observed that we need to control the propagation characteristics of individual fibers to realize a wavelength insensitive coupler [21]. Such requirements on the control of propagation characteristics of the individual fibers make the process complicated and yields less repeatable results.
Theoretical models have been reported where the power carried by a central fiber is equally coupled among identical fibers surrounding it within an infinite cladding medium [25]. This type of interaction demands the positioning of fibers at the corners of an equilateral triangle with the central fiber placed at the vertex. However, it is difficult to achieve the relative positioning of the fibers and we have to depend on special methods.

### 3.3 Wavelength Insensitive Monolithic 1x4 Coupler: Theory

The operating principle of wavelength insensitive monolithic couplers can be understood by considering the coupling between an array of electromagnetically well separated fiber cores in an infinite cladding medium. Figure 3.7 shows a central core region, labeled 1, surrounded by 4 identical cores with their centers lying on a circle...
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of radius r. The radius and refractive index of each core is denoted by $\rho$ and $n_{co}$ respectively. The infinite cladding medium has refractive index, $n_{cl}$.

![Diagram of central core region surrounded by a ring of identical cores in an infinite cladding medium](image)

Coupling between the array of fiber cores is described by the following set of equations [26]

$$\frac{d a_k}{dz} + i \beta a_k = -i \sum_{s \neq k} a_s C_{ks}$$

(3.4)

where $a_k$ is the fundamental mode amplitude of fiber $k$, and $\beta$ represents the propagation constant of the identical fibers. $C_{ks}$ is the coupling coefficient between cores $k$ and $s$, which may be represented by [27]

$$C_{ks} = \frac{(2\Delta)^{1/2} U^2}{\rho V^3} \frac{K_0(Wd_{ks}/\rho)}{K_1(W)}$$

(3.5)

where $U$, $V$ and $W$ are the usual modal parameters, $\Delta = \frac{(n_{co}^2 - n_{cl}^2)}{2n_{co}^2}$, $d_{ks}$ is the distance between the cores $k$ and $s$ and $K_n$ are the modified Bessel function of the second kind.

Due to the illumination of the central core alone and the geometrical arrangement of the cores as shown in Figure 3.7, Equation 3.4 can be simplified. By considering nearest neighbor interaction only, two coupling constants $C_0$ and $C_1$ are defined. $C_0$ represent the coupling between the central fiber and any identical fibers in the ring. $C_1$ represents the coupling between nearest adjacent fibers on the ring. Considering the modal amplitude of the fibers in the ring are identical and the amplitude is $a_i$, i.e $a_i = a_k$.
(k=1,2,3), coupling of power between the fibers is reduced to a two mode problem and the equations can be written as

\[
\frac{da_0}{dz} + i\beta a_0 = -inC_0 a_r
\]

(3.6)

\[
\frac{da_r}{dz} + i\beta a_r = -i(C_0 a_0 + 2C_1 a_r)
\]

(3.7)

These equations can be solved for the coupled power as a function of the propagation distance \(z\). If unit power is launched into the central fiber then the power carried by each fiber as a function of the propagation distance \(z\) can be written as

\[
P_1(z) = \frac{\cos^2(Cz) + \frac{C_1^2}{C^2} \sin^2(Cz)}{1 + \frac{C_1^2}{nC_0^2}} \quad (3.8)
\]

\[
P_2(z) = P_3(z) = P_4(z) = \frac{C_0^2}{C^2} \sin^2(Cz) P_0
\]

(3.9)

where \( C = \sqrt{C_1^2 + 4C_0^2} \). The maximum power transferred to each fiber in the ring is therefore \( \frac{C_0^2}{C^2} \). In terms of the parameter \( F \) used by Snyder [28], which describes the total power fraction coupled out of the central fiber

\[
F = n \frac{C_0^2}{C^2} = \left[ 1 + \frac{C_1^2}{nC_0^2} \right]^{-1}
\]

(3.10)

The maximum coupled fraction depends on the number of fibers in the ring and the relative degree of coupling between them.

In a fused structure as shown in Figure 3.7, there exists no interaction between the fibers and hence there exists only one coupling and thus the power coupling equations for such a structure can be written as

\[
P_1(z) = \cos^2(\sqrt{3}Cz)
\]

(3.11)

\[
P_2(z) = P_3(z) = P_4(z) = \frac{1}{3} \sin^2(\sqrt{3}Cz)
\]

(3.12)

where \( P_1 \) is the power carried by the central fiber and \( P_{2,3,4} \) is the power carried by each fiber at the corners of the equilateral triangle. The coupling between the central fiber and each surrounding fiber are identical and hence only one coupling constant, \( C \)
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appears in the equations. The coupling coefficient will depend upon the usual large range of parameters such as fiber specification, array geometry, array size and wavelength.

The coupled power as a function of the propagation distance is plotted in Figure 3.8. The $C$ values taken are $0.1\text{mm}^{-1}$ and $0.13\text{mm}^{-1}$ at $1.3\mu\text{m}$ and $1.53\mu\text{m}$ respectively. From this graph it can be seen that at a propagation distance marked $A$, the power in each fiber is equally distributed at both wavelengths. Therefore by stopping at this equal coupling point when fabricating a device, a wavelength insensitive response can be realized.

![Coupling Profile](image)

Figure 3.8: Theoretical estimation of power carried by each fiber as a function of the propagation distance $z$ with $C=0.11\text{mm}^{-1}$ and at $1310\text{ nm}$ and $C=0.13\text{mm}^{-1}$ at $1550\text{nm}$

Compared to the coupling profile described in Figure 3.4, the new profile described in Figure 3.8 is simpler because of the identical and synchronous coupling to the interacting fibers. In the former case, separate control on the propagation characteristics of the interacting fibers is required to get a wavelength insensitive response. However in the latter case such individual processing of fibers is not required. It can be seen that the maximum coupling to each of the fibers is 25% only and no further processing is required to get wavelength insensitive couplers.

### 3.4 Fabrication and Characterization

The device is fabricated from an array of four fibers using fused bi-conical taper technology [29-31]. Standard fused coupler fabrication equipment is used to fabricate
the device. The fiber holding chucks of the fused coupler fabrication station is modified to accommodate four fibers. The fibers are kept in a plane in the holding chuck and are braided suitably to get the required cross-section at the fusion point. The braiding is a skilful job which needs patience.

3.4.1 Fabrication Steps

Four pieces of required length (~2m) of bare single mode fiber is cut from the spool and is centre stripped along a length of ~25mm. The stripped area is cleaned so that there is no dust or residues of the removed buffer. The output end of the fibers are cleaved and connected to a 4-channel detector system. At first 3 fibers are placed in the order as primary, secondary and tertiary fiber and the fibers are clamped at the output side. Hold the fibers between our thumb and forefinger of one hand and using the other hand, separate out one of the end fibers and carefully cross it over the other two without twisting the fiber itself. Repeat this with the next two fibers until the fiber sequence is the same as at the start. Using plastic tweezers adjust the crosses into center of stripped area, looking through the microscope, by flattening and pinching the buffered region of both sides of fibers until crosses are uniformly put. When properly centered, add slight tension to the fibers by firmly grasping the fiber leads and pulling simultaneously. Care must be taken not to touch the tweezers in the stripped region of the fibers. The view of the fiber cross after this step is illustrated in the Figure 3.9 below:

![Figure 3.9: Photograph of the fiber pattern after the first step a) Left side b) Right side](image)

The position of the cross shall be ensured with respect to the torch orifice as indicated in Figure 3.10. If the crosses are not at the correct position, adjust it slightly. Once the adjustment is over, unclamp the fiber chuck at the input side and apply proper tension, by holding the fibers together. This helps to remove the slack on the fibers, that may have occurred during the cross adjustments. Apply a very small drop of epoxy on the
buffer-stripped fiber interface at both ends of the stripped area, just to hold the crosses and cure it. The epoxy layer should not be thick, as it may induce problems in the primary packaging.

![Figure 3.10: Position of torch orifice with respect to the crosses](image)

Figure 3.10: Position of torch orifice with respect to the crosses

Figure 3.11: Photograph of the fiber pattern after four fibers are twisted

Now the fourth fiber is placed close to the primary fiber, such that its stripped region is centralized between the fiber holding chucks. Glue the output side of the buffer-stripped fiber interface with very small drop of epoxy and cure it. Hold the fibers together at input side and unclamp the fibers from left holder, looking through the microscope cross the fourth fiber over the crossed bundle. Cross the twisted 3-fiber bundle over the fourth fiber. While doing this cross, ensure that the fourth fiber is passing through the torch orifice center point. Make the buffers parallel on both sides. Now check the twist pattern, which should be similar to the pattern shown in Figure 3.11. A closer view of the twist patterns on the left hand side and right hand side is shown in Figure 3.12.

![Figure 3.12: Close view of the twist patterns on left and right](image)

The center of the torch orifice has to be at the point as shown in Figure 3.13. If the position of the torch is not at the said point, adjust the crosses. Once the cross adjustment is over unclamp the outer clamp on input side and slightly pull the four fibers holding them together so that equal tension is being transferred to all the fibers. Apply a very small drop of epoxy on the buffer-stripped fiber interface at both ends of the stripped area, just to hold the crosses and cure it.
The fiber bundle is then heated and pulled in the usual manner to form a tapered structure. During the pulling process, light carried by the central fiber and the surrounding fibers are monitored at both 1.3 µm and 1.5 µm. Each fiber is fed to independent detectors and the power coupled to each fiber and coupling ratios are online monitored. When the coupling at the two wavelengths become equal the elongation process is stopped and the device is packaged. A photograph of the typical waist cross-section of the fabricated device is shown in Figure 3.14.
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The fused region is protected inside quartz substrate, whose thermal expansion is similar to that of fiber. The substrate is selected in such a way that the fiber is fully protected inside the substrate even at all the regions. The width of quartz substrate groove is designed in such a way that it is sufficient to accommodate four parallel fibers. The depth is so designed that the braided structure is fully with in the groove at all positions of the bundle. The structure is fixed to the substrate using suitable epoxies so that the fused region is safeguarded from external perturbations. The surface of the quartz groove at both the ends of the substrate is roughened to make the epoxy adhesive bonding stronger. The material used for the quartz substrate is GE214. The typical range of groove roughness is 80 µm. Also the epoxies is mixed with quartz powder to minimize its thermal expansion, as explained in Chapter 7. The unutilized fibers at the input side of the coupler are terminated suitably as in the case of 1x2 couplers with an index matching epoxy. The summary of performance parameters according to the new method is

- Maximum Insertion Loss: 7.2 dB
- Uniformity over a range of 1250-1650 nm: 1.2 dB
- Excess Loss: 0.2 dB
- Polarization Dependent Loss: 0.15 dB
- Back Reflection: 60 dB

3.4.2 Pull Signature

![Figure 3.15: Variation in coupled power with elongation length, when all the fibers have same propagation constants](image)

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Figure 3.15 shows the variation in coupled power with elongation length. Here all the fibers are identical and the maximum coupled power at 1310 nm is around 60%, when the propagation constants are same. The primary fiber is pretapered to a level where the maximum of the oscillatory response coincide to get the 25% coupling ratio as well as the ultra broadband spectral response. Figure 3.16 shows the variation of coupled power against coupler elongation, with the throughput fiber pre-tapered. As predicted, the power coupling from the central fiber is identical to the surrounding fibers. This power coupling behaviour helps a straightforward determination of the pulling algorithm and easy control on the fabrication process. It can be seen that at a distance of about 6.6mm, the power at both the wavelengths is shared among all the fibers. At this equal coupling point pulling is stopped and the device is packaged.

![Graph showing power coupling profile](image)

Figure 3.16: Power coupling profile of the fabricated 1x4 coupler

Power coupling profile of the device with extended length is shown in Figure 3.17, which is similar to the results as in the case of typical fused biconical taper coupler [32]. The profile shows beating, the frequency of which becomes higher with the pulling length. The coupling performance of the devise is almost independent to the state of polarization of the input light, due to the rotational symmetry of the structure. This process leads to a device, which has low loss, all-fiber, is smaller (similar in size to a standard 1x2 coupler). The device offers the same degree of performance and ruggedness as normally demonstrated by fused fiber components.


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![Figure 3.17: Power coupling characteristics of a 1x4 coupler, for extended pull length](image)

### 3.4.3 Measurement of 1x4 Monolithic Coupler Characteristics

The splitting ratio and the excess loss are measured after packaging the device. To characterize a coupler, the device measurement is taken up first followed by the “cut-back” of input fiber for reference measurement. Light from a series of pigtailed laser diodes connected to a Nx1 optical switch is launched into the input port of a coupler by splicing the input fiber with a fiber pigtail FC/APC connector at one end. Optical outputs from all the ports of the coupler namely P1, P2, P3 and P4 are measured using a 4-channel detector system. The input power \( P_i \) at the launching end is measured by cleaving the input fiber after the splice by taking care that the input light coupling condition is not disturbed during this step [33]. This is often referred to as the “cut-back” method in the literature, analogous to conventional cut-back method employed to measure the loss spectrum of an optical fiber [33]. For measurement of power exiting from the directivity port, which is usually carried out at the end of the measurement cycle, the output ports are immersed in an index matching liquid to avoid contribution to the measured power from Fresnel reflections.

Using cutback method the coupling related to the total output power, from the central fiber to each of the output fiber is measured at wavelengths 1310, 1490 and 1550 nm. The mean coupling ratio at 1.55 \( \mu \text{m} \) is 24%. The maximum insertion loss is 6.86 dB. At the operating wavelengths of 1310 nm, 1490 nm and 1550 nm the maximum insertion losses are 6.30 dB, 6.86 dB and 6.77 dB respectively. The maximum loss at 1625 nm is 6.57 dB. The above mentioned insertion losses include the polarization...
sensitivity also. The excess loss of the device is less than 0.2 dB. Table 3.1 shows the measured insertion loss values of a typical 1x4 coupler.

<table>
<thead>
<tr>
<th>Output</th>
<th>Insertion Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1310</td>
</tr>
<tr>
<td>Port 1</td>
<td>6.30</td>
</tr>
<tr>
<td>Port 2</td>
<td>6.25</td>
</tr>
<tr>
<td>Port 3</td>
<td>5.79</td>
</tr>
<tr>
<td>Port 4</td>
<td>6.24</td>
</tr>
</tbody>
</table>

Table 3.1: Measured Insertion Loss of a 1x4 Coupler

Figure 3.18: Measured wavelength response of 1x4 coupler from 1250 nm to 1650 nm.

In addition to measuring CR, IL and Directivity, characterization includes measurement of wavelength response. The wavelength response of the coupler is measured by launching a broadband source into the coupler and recording the response using an optical spectrum analyzer. A broadband light source from HP, which gives wideband output from 800 to 1650 nm has been used. The spectrum analyzer is from Agilent (Model No. 6410B). The spectral response of the fabricated device from input fiber to each output is shown in Figure 3.18. All the coupled fibers have the same wavelength response. The small peak in the wavelength response of all the fibers at 1380 nm corresponds to the water absorption peak. The three-coupled ports have more flattened wavelength response compared to the throughput fiber. This is owing to the incomplete transfer of power from the throughput fiber to the coupled fiber, the technique used in 1x2 couplers. Thus the fabrication method explained in
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section 3.5.1 is simple method to realize 1x4 wavelength insensitive monolithic coupler. However, in the previously reported method, careful control of processing of individual fibers was required to achieve wavelength independent performance.

To measure the polarization sensitivity of the device a laser was spliced to an input fiber via a polarization controller. While monitoring the power output from each fiber in turn, the polarization controller was adjusted so that all polarization states were launched into the coupler. The maximum and minimum power readings were recorded. The results show that the power in the coupled fibers varies by 0.08 dB while the power in the throughput fiber varies by 0.15 dB. Among the coupled fibers, the polarization sensitivity is more in throughput fiber. The spectral dependence of the polarization dependent loss is shown in Figure 3.19. The structure at coupling region makes the process less sensitive to changes in the polarization states, because of the low degree of fusion and the symmetry being preserved.

![Figure 3.19: Wavelength dependence of PDL](image)

3.4.4 Histograms of IL, Uniformity and PDL

Figure 3.20, 3.21 and 3.22 shows the histograms of the insertion loss, polarization dependent loss and uniformity of 30 number 1x4 monolithic couplers respectively, measured as described in section 3.5.3. The maximum insertion loss is 7.2 dB, but 90% of the couplers have an insertion loss less than 6.8 dB. The uniformity of the couplers is below 1.2 dB. The polarization dependent loss is below 0.16 dB as shown in Figure 3.22.
Figure 3.20: Insertion loss histogram of 1x4 monolithic coupler

Figure 3.21: Uniformity histogram of 1x4 monolithic coupler

Figure 3.22: Histogram of polarization dependent loss of 1x4 monolithic coupler
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3.4.5 Stability of Array Geometry

The cross-section of the braided pattern, after fusion, at five different locations is shown in Figure 3.23. From the figure, it is clear that the secondary fibers are disposed around the central fiber, but not symmetrical with respect to each of the secondary fibers. It is observed that the cross-section pattern gets slightly rotated around the central fiber. The cross-section is taken by cleaving the fused region and is inspected with a microscope of suitable magnification. As shown in the cross-section, there exists an acute angle between the two secondary fibers 1&2. Both these fibers make an obtuse angle with the other secondary fiber 3. At the end of the coupling region, the four fibers will again be in the same parallel plane. We have analyzed the cross-sectional pattern of a number of devices and it is observed that the relative positioning of the fibers are not so critical, as it affects the final optical performance of the device very little. However the twist related residual strains can affect the long term reliability of the product. It is important to make sure that there is no interaction among the surrounding fibers. As soon as there is physical interaction between the fibers, the cross-coupling coefficients come into picture and the pull signature is no longer a simple one.

To get identical coupling profile, it is not necessary that each of the secondary fibers shall be symmetrically disposed over the primary fiber, but it is necessary that secondary fibers be separated by at least a distance to avoid the interaction between them. The braided pattern helps to maintain the secondary fibers in close proximity to the primary fiber, along the coupling region, with a waist cross-section as shown in the Figure 3.23. We have tried two different ways for braiding. In the first type, three such fibers are singly twisted three times, among which one fiber is the primary fiber. After that the fourth fiber is twisted over the three-fiber bundle with full turn, so that the relative positions of the four fibers at both ends are 1, 2, 3, 4 and 1, 2, 3, 4. This structure is sufficient to get an identical coupling profile. However, there may be a chance that a small deviation in the relative tension can contribute to the interaction among a pair of fibers, thus slightly affecting the uniformity and repeatability of the process. In the second braiding pattern, three fibers are singly twisted three times, among which one fiber is the primary fiber. Then the fourth fiber is full twisted, followed by a half turn over this bundle. In this case the relative positions of the fibers are 1, 2, 3, 4 and 4, 1, 2, 3 at the ends. Coupling in structures with the latter twist pattern are found to be more efficient than the former twist and offers good repeatability and better uniformity. The four-fiber bundle is properly secured to keep the structure during the fusion and elongation. For the above described fiber braiding patterns no special jigs is required and can be done manually. Thus the same platform
used for the manufacturing of basic FBT coupler can be used for the fabrication of 1x4 couplers.

Figure 3.23: Cross-section drawings of the 1x4 coupler as per the new method, at five different locations (a) cross-section at waist (b) cross-section at 2mm right to the waist (c) cross-section at 2mm left to the waist (d) cross-section at 6mm right to the waist. (e) cross-section at 6mm left to the waist.

At the waist of the fused region, the distance between the fiber cores of each of the secondary fiber and the primary fiber typically ranges from $35\pm3\ \mu m$, where the primary fiber is having a slightly reduced diameter (of the order of 1 \( \mu m \)) compared to the secondary fibers. There exists physical separation between the secondary fibers and the minimum separation is between the secondary fibers 1 & 2 as shown in the Figure 3.23, which is typically in the range of $40\pm7\ \mu m$. At the waist, the lateral area of contact is typically around $10\mu m$. 
3.5 Fabrication Parameter Tuning

There are several important process parameters that control the performance of monolithic fused couplers. The important parameters are pull speed, gas flow and the brush width. This section details the effect of different process parameters on the performance of 1x4 couplers. Different couplers were fabricated at different pull speeds, by keeping the gas flow conditions and the brush width unchanged. The pull speed is varied from 0.5 mm/min to 2.5 mm/min and it is observed that the excess loss of the device is minimum at a pull speed of 1mm/min and it increases thereafter as shown in Figure 3.24.a. However the polarization dependent loss of the device increases linearly with pull speed as shown in Figure 3.24.b. The polarization dependent loss is 0.1 dB at a pull speed of 1mm/min. The port-to-port uniformity value remains unchanged, irrespective of the pull speed as shown in Figure 3.25. Here we have fabricated 20 samples at each condition and the average value is plotted.

Figure 3.24: a) Relationship between pull speed and excess loss b) Variation in polarization dependent loss with pull speed

Figure 3.25: Variation in uniformity with pull speed
Brushwidth is the length of over which the flame is oscillated to get a distribution of the heating zone during the fusion process. The brush speed is kept at 36mm/min. The pull speed and gas flow conditions are kept unaltered and the brush width is varied from 4 to 7.5mm. The variation in insertion loss with brush width is plotted in Figure 3.26.a. The insertion loss decreases first and then increases rapidly. This rapid increase is due to the fact that the flame comes to the twisted region of the coupler. The relationship between polarization dependent loss and brush width is shown in Figure 3.26.b and wavelength dependent loss vs. brush width is plotted in the Figure 3.27. The polarization dependent loss and wavelength dependent loss improves with increase in brush width. The optimum brush width is found to be at ~6mm.

Figure 3.26: a) Relationship between insertion loss and brush width b) Variation in polarization dependent loss with brush width

Figure 3.27: Variation in wavelength dependent loss with brush width

Thus the optimum parameters of the suggested process are:

\[ \text{H}_2 \text{ Flow Rate: 215 sccm} \]
3.6 Directionality Analysis

In passive optical networks, the signals are transmitted in both upstream and downstream directions. Hence the splitter performance needs to be analyzed in both directions. The measurement data of the coupler performance at 1310nm and 1550nm, when different inputs ports are excited is summarized in Table 3.2. It is to be noted that the coupling coefficient is not identical when any fiber other than the central fiber is illuminated. From Table 3.2, it is clear that the coupling ratios are same when light is coupled from central fiber (Input-1) to the surrounding fibers (Output-2, Output-3 and Output-4). But the coupling ratios vary when light is launched to the any of the surrounding fibers (Input-2, Input-3, Input-4). In any case, the coupling ratio between the launched fiber and the central fiber remains at 25%, but the coupling ratio with other fibers significantly reduces; up to 0.06% at 1310 nm and 0.12% at 1550 nm. Hence to use this device as a 1x4 coupler, the central fiber must always be excited.

<table>
<thead>
<tr>
<th>Light launched to</th>
<th>Coupling Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Output</td>
</tr>
<tr>
<td></td>
<td>1 2 3 4</td>
</tr>
<tr>
<td></td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>Input-1</td>
<td>0.24 0.24 0.24 0.24</td>
</tr>
<tr>
<td></td>
<td>0.24 0.24 0.24 0.24</td>
</tr>
<tr>
<td>Input-2</td>
<td>0.24 0.60 0.06 0.06</td>
</tr>
<tr>
<td></td>
<td>0.24 0.52 0.12 0.12</td>
</tr>
<tr>
<td>Input-3</td>
<td>0.24 0.06 0.61 0.06</td>
</tr>
<tr>
<td></td>
<td>0.24 0.12 0.51 0.12</td>
</tr>
<tr>
<td>Input-4</td>
<td>0.24 0.06 0.06 0.60</td>
</tr>
<tr>
<td></td>
<td>0.24 0.12 0.12 0.52</td>
</tr>
</tbody>
</table>

Table 3.2: Coupling Ratios at 1310nm and 1550nm, when different fibers are illuminated

This coupling ratio will remain true when the product is measured from output side to the input side. Thus 25% of light launched to any fiber will get coupled to the input port. Thus this product will work as a combiner with 6dB loss in the reverse direction. This confirms the suitability of the product for bi-directional PON applications. However, it is to be noted that for light applied to any port other than the throughput port, more than 25% of the light (60% at 1310 nm and 52% at 1550 nm) is coming to
the corresponding port. At the input side, fibers at the unused ports are terminated, without affecting the twist region. The termination is done either with an index matching material or with angled cleaving of fiber end. Thus the termination efficiency of the port become critical. Thus this devise can effectively work as a 1x4 coupler in both the directions. However, this configuration is not suitable for 2x4 and 4x4 configurations.

### 3.7 Estimation of Back Reflection

Back Reflection (BR) is a major performance deciding factor for all passive optical components [34]. In fused couplers, back reflection is directly related to the termination effectiveness of the unused input ports. In the present case, three input fibers are terminated to make it a 1x4 coupler; the unused ports are terminated inside the coupler package itself. The factors which contribute to the back reflection are inherent defects in the fused region and the reflection from the terminated optical leads. The former case is usually negligible, unless there is a discontinuity in the path. For the latter case, to eliminate Fresnel reflection from the terminated optical leads, the end surface is prepared and index matching epoxy is applied. The performance of the termination is highly dependant on the end preparation and refractive index matching. For a flat endface, the reflection will be around -14 dB at 1550 nm.

Back reflection is measured by connecting a light source to each of the output port and by measuring the light reflected to the same port. In 1x4 coupler, when light is launched from one of the output ports, it gets branched into the four input ports. The splitting ratio will depend on excited port, as shown in Table 3.2. Light will be reflected back from all the input ports. The reflected light will couple from each of the input ports to all the output ports, depending on the coupling ratio. Thus the back reflected power measured at each port will be a combined effect of the reflection from all the input ports and can be expressed as,

\[
P_R = P_0 \sum_{i=1}^{4} b_i c_i^2
\]

(3.13)

where \(b_i\) is the reflection coefficient and \(c_i\) is the coupling coefficient

When light is input from the throughput port, it will be equally split into the four input ports. In the reverse direction, 25% of the light reflected from each of the input ports will be coupled back to this port. Denoting the reflection coefficient from input fibers as \(b_1, b_2, b_3, b_4\) and considering the typical power coupling coefficients given in Table
Monolithic 1x4 Couplers

3.2, the light reflected back to each of the ports can be estimated. Considering the excitation of the port-1, each input port will receive ~25% of the light and will get reflected back depending on the reflection coefficient. This reflected light will again coupled to the throughput port in accordance with the coupling coefficients. Thus the power reflected back to the port-1 at 1310nm can be expressed as,

\[ P_{r1} = 0.0576P_0(b_1 + b_2 + b_3 + b_4) \] (3.14)

Similarly, we can workout the reflected power to the second port at 1310nm as,

\[ P_{r2} = P_0(0.0576b_1 + 0.36b_2 + 0.0036b_3 + 0.0036b_4) \] (3.15)

When \( b_2 \) has worst termination and when \( b_3 \) and \( b_4 \) are zero, the back reflected power measured at port-2 will be 7.96 dB higher than the value measured at port-1. If back reflection measured from port-2 is 50 dB, then the reading at port-1 will show 57.96 dB. In another case, when all the termination coefficients \( b_2, b_3 \) and \( b_4 \) have equal performance, the back reflected power measured at port-1 will be 3.27 dB higher than that measured from port-2. i.e, if the value measured from port-2 is 50 dB, the reading at port 1 will be 53.27 dB.

The power reflected back to port-1 at 1550nm can be estimated as.

\[ P_{r1} = 0.0576P_0(b_1 + b_2 + b_3 + b_4) \] (3.16)

Similarly, we can workout the reflected power to the second port at 1550nm as,

\[ P_{r2} = P_0(0.0576b_1 + 0.2704b_2 + 0.0144b_3 + 0.0144b_4) \] (3.17)

Hence, if all other ports except port-2 are having the best termination, the power measured at port-1 will be 6.71 dB higher than the value measured at port-2. Thus port-1 will show a value of 56.71 dB, if the value at port-2 is 50 dB. If the ports 2, 3 and 4 have the same reflection coefficient, the back reflected power measured at port-1 will be 2.38 dB higher than that measured from port-2. i.e, if the value measured from port-2 is 50 dB, the reading at port -1 will be 52.38 dB.

The coupling ratio when light is launched from port-3 or port-4 is similar to that when light is input from port-2. Thus the estimation done for port-2 is valid for port-3 and port-4 also. For marginal performance of ports 2, 3 and 4, the BR measured at port-1 will have a value in the range of 3.27 dB to 7.96 dB higher. Hence the product performance can be judged to be good if the back reflection at port-1 is 7.96 dB higher than the specification limit. However, if the BR at port-1 shows a value in the
range of 3.27 to 7.96 dB, it shall be tested from all ports. The product will be a fail, if the BR at port-1 is less than 3.27 dB.

Since the PON systems need to have a minimum back reflection limit of 40dB, the back reflection value of the coupler should not go below 40dB, even if all the four output ports are lightened. So if the ports have marginal performance at 40dB, when tested with only one port illuminated; the back reflection coming to each port will be high, when all ports are lightened. Considering a reflection of 40dB from each port, and all port is lightened with equal optical power, the BR measured at port-1 will differ by 2.7 dB to the measurement with only one port lightened. If only one port is having marginal performance, say port-2, the BR measured at port-1 will be 10dB higher to the measurement with only one port lightened. Thus by adding a margin of 10 dB to the product specification, one can judge the product as good or bad, by measuring the BR at only one port.

![Figure 3.28: Distribution of the BR failed couplers, Port 1 at 1310nm](image)

This model helps in predicting the termination efficiency of the 1xN coupler, by just measuring from a single output port. This model has been validated by testing the back reflection performance of 100 couplers. This helps in saving the time. The BR value of the failed couplers (26#) are analyzed; Figure 3.28 shows the distribution of the values measured at port-1 at 1310 nm. All the failed devices have a value less than 58 dB.
3.8 Fabrication of 1x5 Couplers

1x5 couplers are fabricated based on the new method of 1x4 coupler. As described in section 3.5.1, five single mode optical fibers are prepared and fused. The braiding pattern is adapted to get the required cross-section at the fusion point, i.e. four fibers symmetrically positioned around the central fiber. The braiding of the first four fibers is done in a similar way as done for the 1x4 coupler. The fifth fiber is placed in a way such that it comes at the mirrored position of the fourth fiber. The pull signature of the 1x5 coupler is shown in Figure 3.29. Here also the coupling to the interacting fibers is identical. The insertion loss performance of 1x5 coupler is summarized in Table 3.3.

![Pull signature of the 1x5 coupler](image)

Table 3.3: Measured Insertion Loss of a 1x5 Coupler

<table>
<thead>
<tr>
<th>Output</th>
<th>Insertion Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1310</td>
</tr>
<tr>
<td>Port 1</td>
<td>7.40</td>
</tr>
<tr>
<td>Port 2</td>
<td>7.20</td>
</tr>
<tr>
<td>Port 3</td>
<td>7.05</td>
</tr>
<tr>
<td>Port 4</td>
<td>6.95</td>
</tr>
<tr>
<td>Port 5</td>
<td>7.10</td>
</tr>
</tbody>
</table>

Here a method is reported to achieve wavelength independent coupling in fused 1x5 coupler, where the fabrication control is much easier due to the synchronous and identical coupling between the identical fibers. Even though, the fabrication of 1x5 couplers is described, the same principle can be easily extended to build 1x6 couplers.
But this technique may not be applicable for monolithically fused couplers where \( N \) is greater than 7.

### 3.9 Conclusions

A repeatable and easy method for the fabrication of monolithic, wavelength independent 1x4 single mode fused coupler has been developed. In conventional 1x4 couplers, the coupling profile is complex due to asymmetric coupling among the fibers. However, the new method provides symmetric coupling to all the coupled fibers. The fabricated device offers wideband performance from 1250 to 1650 nm. There is no need to pre-process the individual fibers before fusion, which makes the manufacturing process simple. Moreover, the new structure is formed by braiding the fibers and no special jigs are required. The broadband coupler exhibits low excess loss (<0.2 dB) as well as low polarization dependent loss (0.15 dB). Compared to cascaded 1x4 couplers, monolithic 1x4 coupler offers a reliable and compact solution. The uniformity of the device is around 1.2 dB, which is almost double compared to the planar splitters. Monolithic 1x4 coupler can provide an economical solution for passive optical networks based on distributed splitting architecture. Other applications include high Splitter Array Sub Assemblies (SASAs) and multi output erbium doped fiber amplifiers and fiber lasers.

Many samples were fabricated to establish the device and process reliability. The stability of the array geometry on the performance of the device is studied and it is found that minute differences in the relative positions of the fused fibers are not critical, as long as there is no interaction between the coupled fibers. The effect of different process parameters on the performance on monolithic coupler is analyzed and optimum values were found out. The structure is suitable for bidirectional applications such as power splitting PONs. However, this structure is not useful as a 4x4 coupler, since it yields different coupling ratios depending on the input fiber being illuminated. Based on the coupling analysis a simple way of judging the back reflection performance of the device is suggested. It is shown that the reported method can be extended to make 1x5 couplers.
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