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Monolithic fused 1 × 4 couplers with high uniformity

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ABSTRACT

A new method for the fabrication of high uniformity monolithic 1 × 4 singlemode fused coupler is described together with details of its performance in terms of coupling ratio, spectral response and uniformity. The fabricated device exhibits ultra-broadband performance with a port-to-port uniformity of 0.4 dB. The reliability of such couplers is also evaluated and found to have good stability. Moreover, by controlling the process parameters it is possible to control the power remaining in the through put port of the device, which can be used for dedicated non-intrusive network health monitoring.

1. Introduction

Passive optical networks (PONs) are one of the hottest broadband access technologies today. Fiber-To-The-Home (FTTH) triple-play services based on PON architecture uses a three-wavelength scheme namely 1310, 1490 and 1550 nm for carrying data, voice and analog video. Additional wavelength, normally 1625 nm is used for physical layer health monitoring of the network. Hence signal splitters for such passive optical networks should be wavelength independent. Moreover, good port-to-port uniformity over the entire operating band is essential to get optimum reach conditions in Fiber-To-The-Home network deployments.

Fused couplers are ideal for signal splitting in PON because of wavelength independent performance and high power handling capability. Wavelength insensitive 1 × N splitters are formed by cascading arrays of 1 × 2 couplers, making the final device a bulky one. Also, uniformity of the final device depends on uniformity of the individual coupler. Monolithic 1 × N fused couplers have uses as a simple power splitter and as a building block for high port-count splitters. Thus 1 × N couplers help to reduce the footprint as well as the component density of high port-count splitters. There are different methods, reported in the literature, for the fabrication of monolithic fused single mode 1 × N couplers. The different fabrication methods include twisted fiber fusion method and capillary clad fiber fusion method [1,2]. In one approach a capillary tube, usually Vycore material is used to hold the fibers in position [2]. The internal diameter of the capillary is so chosen that it is just enough for the fibers to fit where N identical fibers are symmetrically positioned around a central fiber. In some cases, use of dummy fibers is suggested to achieve relative positioning of fiber [3,4]. This paper investigates on uniformity performance of 1 × 4 couplers over the entire operating band and reports an efficient method to improve the uniformity of monolithic fused 1 × 4 couplers.

The waist cross-section of a typical broadband 1 × 4 coupler is shown in the inset of Fig. 1, where the coupling constant C represent coupling between central fiber and any one of the surrounding fibers [5]. Theoretically modeled coupling behaviour of such a device as a function of the propagation distance z is shown in Fig. 1, when unit power is launched into the central fiber. The different curves show power coupling profile from central fiber to surrounding fibers at 1550 and 1310 nm wavelengths respectively. $P1$ represents the power remaining in central fiber while $P2$, $P3$ and $P4$ represents power coupled to the surrounding fibers. $P2$, $P3$ and $P4$ curves overlap, at both wavelengths, showing identical coupling to surrounding fibers, due to the symmetric waist cross-section. Moreover, from Fig. 1, it can be seen that at a propagation distance of around 6.5 mm, power in each of the fibers is equal, at both wavelengths. Therefore by stopping at this equal coupling point, during the fabrication of a device, it is possible to get wavelength insensitive response.

The spectral response of a 1 × 4 coupler measured from input fiber to each of the output fibers is shown in Fig. 2 where all coupled fibers exhibit same wavelength response. The three-coupled ports have more flattened wavelength response compared to the throughput fiber (Output 1), owing to the incomplete transfer of power from central fiber to the coupled fiber. The spectral dependence of the port-to-port uniformity of such a coupler is shown in

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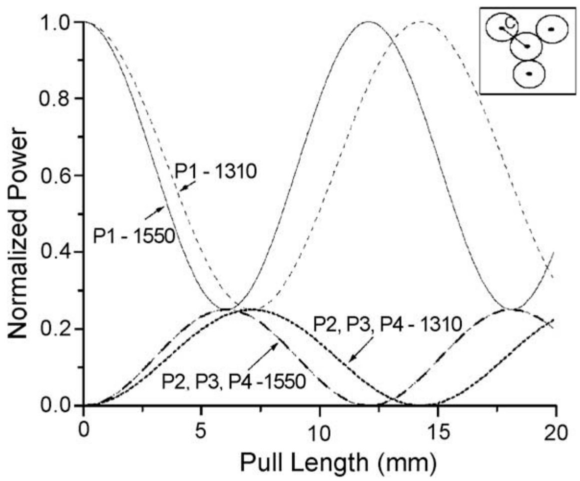

Fig. 1. Theoretically calculated power carried by each fiber as a function of the propagation distance z with $C = 0.11\ \mathrm{mm}^{-1}$ at 1310 nm and $C = 0.13\ \mathrm{mm}^{-1}$ at 1550 nm.

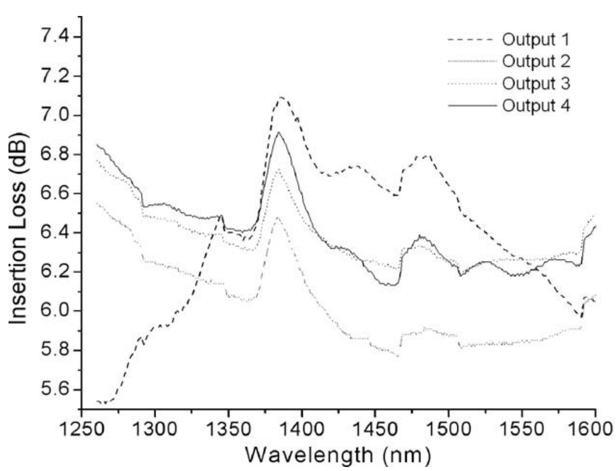

Fig. 2. Spectral dependence of a fused 1 × 4 coupler.

Fig. 3. The uniformity values vary from 0.3 to 1.2 dB over a spectral range of 1250–1650 nm. The uniformity is low at 0.4 dB from 1320 to 1360 nm and 1560 to 1600 nm. The uniformity is high at 1490 and 1625 nm bands, which is undesirable for FTTH networks. The highest contribution to the variations in uniformity comes from the central fiber, owing to its largest spectral dependence. The uneven port-to-port uniformity causes different optimum reach conditions for data transmission at different wavelengths. Thus it is essential to look for new techniques to improve the uniformity over the entire operating band.

It is possible to improve port-to-port uniformity over wide operating range for a monolithic 1 × 4 coupler, if all output fibers have the same spectral response. This is achieved by fusing 5 identical fibers, where power from the throughput fiber is completely coupled to four surrounding fibers positioned symmetrically around the central fiber. The schematic in Fig. 4 shows a 1 × 4 coupler with high uniformity, where O1 is the throughput fiber, O2, O3, O4 and O5 represent the coupled fibers. By controlling the process parameters, it is possible to retain a small amount of power in central fiber, which can be used for in situ health monitoring of the networks.

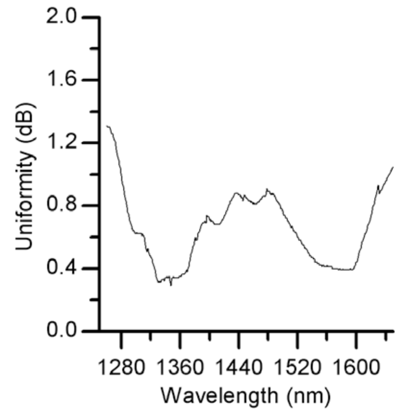

Fig. 3. Spectral dependence of uniformity of a fused 1 × 4 coupler.

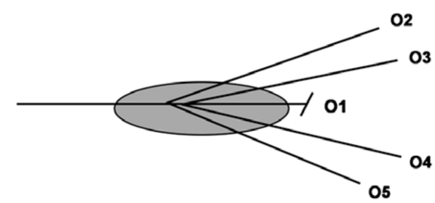

Fig. 4. Schematic of high uniformity 1 × 4 coupler.

2. Theoretical model

Consider an array of five fibers, where four fibers surround a central fiber in a symmetric manner, as shown in the inset of Fig. 5. The central fiber, in which the light is launched, is reduced in diameter to expand the mode field of the propagating light. If this structure is reduced in size, such that mode coupling between the fibers can occur, then light launched into the center fiber will completely get transferred to the surrounding fibers, equally. By considering nearest neighbour interaction only, the equations, which describe the evolution of power with propagation distance z are [5],

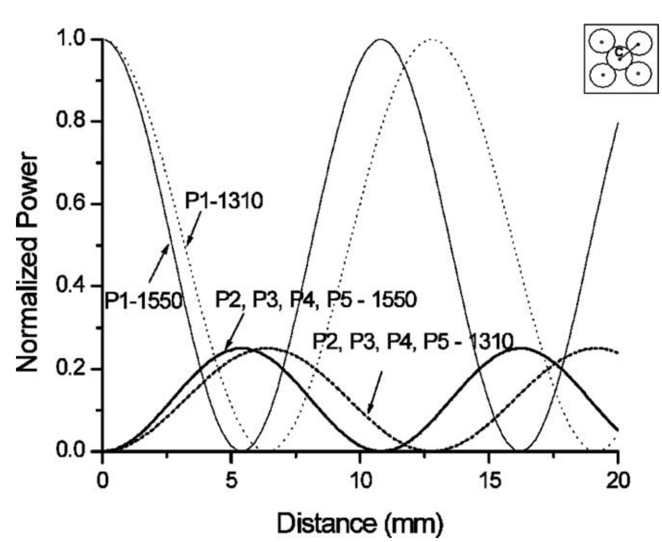

Fig. 5. Theoretically calculated power carried by each fiber as a function of the propagation distance z with $C = 0.11\ \mathrm{mm}^{-1}$ at 1310 nm and $C = 0.13\ \mathrm{mm}^{-1}$ at 1550 nm.

$$P1 = 1 - \sin^2[\sqrt{4}Cz],$$

and

$$P_c = \frac{1}{4}\sin^2[\sqrt{4}Cz]$$

where P_1 is the power carried by central fiber and P_c is the power carried by each of the surrounding fibers. The coupling between the central fiber and each surrounding fiber are identical and hence only one coupling constant appears in the equations. The coupling coefficient depends upon a range of parameters such as fiber specification, array geometry, array size and wavelength. From experimental data, we estimated C around the waist region of the 1×4 coupler, as 0.11 and 0.13 mm^{-1} at 1310 and 1550 nm respectively. The power carried by each fiber as a propagation distance z is estimated in Fig. 5, $P1$ represents power in the central fiber while $P2$, $P3$, $P4$ and $P5$ represents the power carried by surrounding fibers.

3. Fabrication

The device is fabricated from an array of five fibers using fused tapered fiber technology [6]. The central fiber is preprocessed to have a small diameter compared to the other fibers, the reduced diameter is around 122 μm. The fiber used for the fabrication of couplers is SMF-28e made by Corning (USA). The fibers are kept in a plane and braided carefully to get the required symmetric cross-section, at the fusion point. Using equipment designed for the fabrication of standard 1×2 fused couplers, the fiber array is heated and pulled to form a tapered structure. During the pulling, power carried by the central fiber and surrounding fibers is monitored at both 1.3 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 coupling to each of the surrounding fibers become equal and the power remaining in central fiber become zero, 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 Fig. 6.

Fig. 7 shows the measured variation of coupled power with elongation length. The power coupling at 1550 nm is plotted in the figure; coupling from the central fiber is identical to the surrounding fibers, as predicted. This power coupling profile helps in straight forward implementation of the pulling algorithm and easy control of fabrication parameters. It can be seen that at a distance of about 7.5 mm, the power at both wavelengths is equally shared among all surrounding fibers and the power in the throughput fiber is negligibly small. At this point the pulling is stopped and the device is packaged. The throughput fiber with nominal power is angle terminated for low back reflection and protected with an index matching epoxy. The coupling performance of the coupler is almost independent to the state of polarization of the input light, because of the rotational symmetry of the structure. This process leads to a monolithic 1×4 coupler, which has low loss, high port-to-port uniformity and smaller size (similar in size to a standard 1×2 coupler).

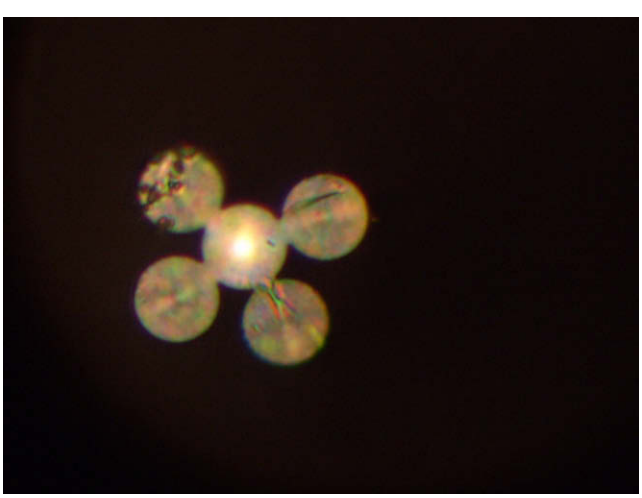

Fig. 6. Photograph of the waist cross-section of fabricated 1×4 monolithic fused coupler.

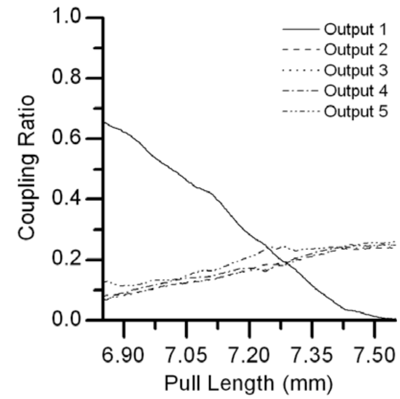

Fig. 7. Typical power coupling data of the fabricated 1×4 coupler.

The power remaining in throughput fiber is controlled by optimizing the diameter of central fiber and fusion parameters. Devices were fabricated with power in central fiber in the range of 1–3%, when the preprocessed diameter of the central fiber was around 124 μm. The power in the central fiber can be used for monitoring power flowing through the splitter, without disturbing the communication path in which splitter module is installed. The spectral dependence of this monitoring port is relatively poor compared to other coupled fibers. However, this spectral dependence doesn't affect the branching uniformity of splitter, as it is used only for monitoring purpose.

4. Results

The coupled power related to 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 μm is 25% with a standard deviation of 0.5%. Table 1 shows the measured maximum insertion loss values of eleven samples of monolithic 1×4 couplers, with high uniformity. At the operating wavelengths of 1310, 1490 and 1550 nm the maximum insertion losses are 6.47, 6.52 and 6.54 dB respectively. The above mentioned insertion losses include the polarization sensitivity also. The excess loss of the device is less than 0.25 dB, which is due to the uncoupled power remaining in the throughput fiber.

The couplers are characterized using ANDO Spectrum Analyzer (AQ6317) and Agilent Broadband Source (83437A). The spectral response of the fabricated device from input fiber to each output is shown in Fig. 8. All the coupled fibers show identical wavelength

Table 1
Maximum insertion loss and PDL data of 1×4 couplers.

Output	Insertion loss (dB)			Polarization dependent loss (dB)		
	1310	1490	1550	1310	1490	1550
Port 1	6.25	6.39	6.47	0.07	0.08	0.12
Port 2	6.47	6.52	6.50	0.08	0.10	0.11
Port 3	6.40	6.47	6.54	0.12	0.14	0.15
Port 4	6.21	6.24	6.28	0.09	0.11	0.14

response. The slight variation in the insertion loss among different outputs is due to the small difference in the average coupling coefficients, arising from the relative fiber positioning and fusion depth variations. The spectral uniformity or wavelength dependent insertion loss in each of the output fiber is less than 0.5 dB and the peak in the response at 1380 nm corresponds to the water absorption peak of standard fiber. Here the spectral response of the throughput fiber is not considered, since it is suggested only for power monitoring. The back reflection of the device is better than −50 dB.

The branching uniformity of the fabricated device over the entire range from 1250 to 1600 nm is shown in Fig. 9. The average branching uniformity is 0.4 ± 0.1 dB. The branching uniformity performance is better at lower wavelengths and increases slightly towards the 1600 nm wavelength region. This increase is attributed to the slight bending stress in the fibers due to the special braiding pattern employed to achieve the waist cross-section. Thus couplers made with new technique offers excellent branching uniformity compared to the other monolithic 1 × 4 couplers.

The polarization sensitivity of the device is measured by splicing the input fiber of the coupler to 1.3 μm laser through 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. Polarization dependent loss of the device is tabulated in Table 1 and the maximum value among all the ports is 0.15 dB. The polarization sensitivity is more at higher wavelengths, and can be controlled by changing the degree of fusion of the fibers and by carefully positioning of fibers around the central fiber.

5. Reliability evaluation

Fused couplers are generally sensitive to mechanical and environmental stresses, causing long term splitting ratio drifts. Hence packaging of the coupler, to keep the integrity of the fused region, is very critical to maintain the performance in field over a period of time. Preferred structure of fused coupler packaging is sketched in Fig. 10, where the fused region is protected inside a quartz substrate, using a thermally cured adhesive. The adhesive is filled with quartz powder to match its thermal coefficient with substrate and fiber. This primary packaged structure is attached inside an invar tube and end sealed. The end sealing prevents the penetration of water molecules and doesn't allow degradation of epoxy and refractive index variations at fused region.

We subjected 11 samples of the couplers for temperature cycling and temperature humidity aging. For cycling test, the temperature is varied from −40 °C to +90 C in 2.4 h. For humidity aging test, samples are kept at 85 °C and 85RH [7]. A failure is defined as a change in the insertion loss above 0.5 dB in the operating regime around 1310, 1490 and 1550 nm. The maximum insertion losses before and after each of the above tests are plotted in Figs. 11 and 12. The results of temperature cycling and humidity aging are summarized in Table 2. The result shows the stability of insertion loss and hence branching uniformity of the couplers, after the accelerated tests. The average increase in insertion loss in all the ports is less than 0.29 dB. In order to analyze the performance of the device at high power, it is exposed to optical power from +23 dBm using in-house built erbium doped fiber amplifier. The devices showed no degradation even after a continuous

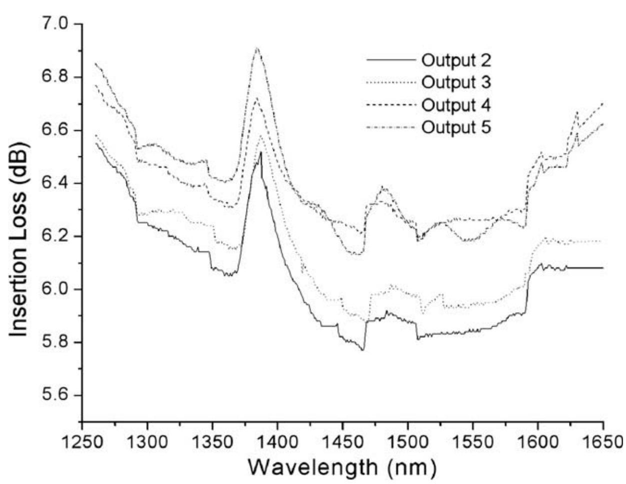

Fig. 8. Measured wavelength response of 1 × 4 coupler from 1250 to 1650 nm.

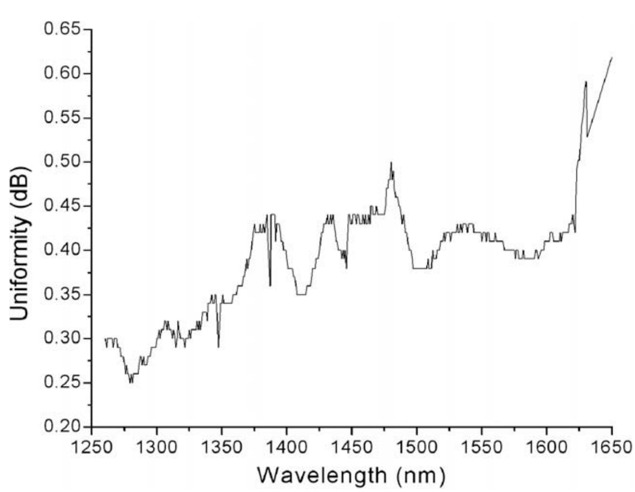

Fig. 9. Spectral dependence of uniformity of new 1 × 4 coupler.

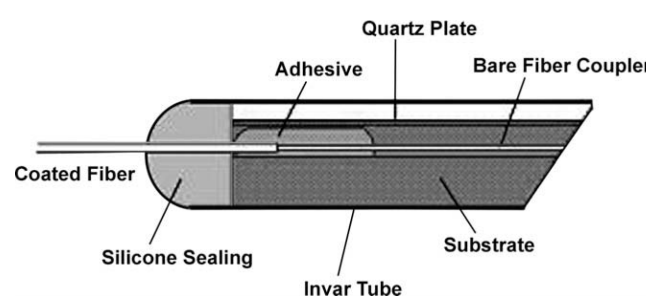

Fig. 10. Sectional view of packaged coupler.

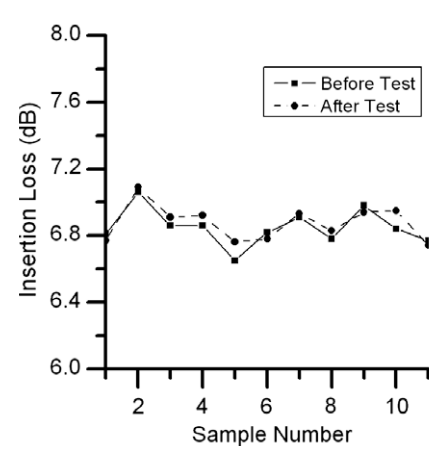

Fig. 11. Insertion loss before and after temperature cycling.

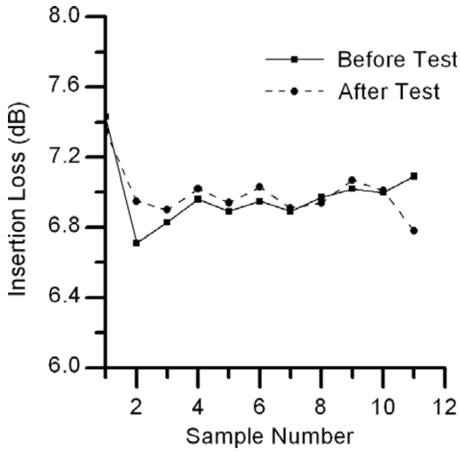

Fig. 12. Insertion loss before and after temperature humidity aging.

Table 2
Changes in optical performance parameters.

Test condition	Number of cycles/days	Average increase in	
		Insertion loss	PDL
Temperature cycling	100 cycles	0.03	0.01
	200 cycles	0.05	0.02
	500 cycles	0.06	0.04
Humidity aging	21 days	0.08	0.08
	42 days	0.13	0.12
	63 days	0.25	0.18
	84 days	0.29	0.17

exposure of 4000 h, at this power level. To test the performance further, we varied the temperature and humidity conditions in which the device is kept, while exposing to high power levels. However the device doesn't show any degradation in performance.

6. Conclusions

An efficient and convenient method for the fabrication of a monolithic, wavelength independent 1×4 single mode fused coupler, with high uniformity has been reported. The insertion loss of the device is slightly increased (by <0.1 dB), due to uncoupled power remaining in central fiber. But the spectral flatness of port-to-port uniformity is greatly improved. The device exhibits good uniformity (<0.5 dB) and low polarization dependent loss (0.15 dB) over the entire operating range. The device offers the same degree of performance and ruggedness as normally demonstrated by fused fiber components. Monolithic 1×4 couplers find applications in Splitter Array Sub Assembly (SASA), high port-count fiber amplifiers and fiber lasers. By controlling the process parameters it is possible to control the power remaining in the through put port, which can be used for dedicated network health monitoring.

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