Empirical Analysis of Widely Tunable Fused Fiber Coupler Assisted by External Medium of High Thermo-Optic Coefficient

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Abstract This article reports the fused fiber coupler whose transmission spectrum is widely tuned or switched with temperature. With a proper choice of the external medium applied on the fused region of the coupler, the tuning range could be expanded up to the free spectral range of the coupler itself. A polymer with a matched refractive index and high thermo-optic coefficient was used as the external medium, and a micro-coil heater was installed to tune or switch the coupler. As the elongation length of the coupler increased in the fabrication process, the tuning range increased also. With the polymer having a thermo-optic coefficient of \(-1.8 \times 10^{-4}/^\circ\text{C}\) and a 1.440 room temperature refractive index, wavelength tuning as wide as 210 nm was experimentally obtained. The fabrication process of the tunable fused coupler and the temperature-dependent spectral properties of the implemented couplers in terms of the elongation length and the polymer index are presented in detail. The feasibility of the proposed device as a tunable filter, optical switch, and variable optical attenuator are also presented.

Keywords fused fiber couplers, thermo-optic effect, tunable coupler, polymer

1. Introduction

Optical fiber couplers are key devices in optical communications and optical sensor systems because they can perform many important functions, such as optical power dividing, wavelength selective coupling, and polarization splitting [1–4]. A fused-type fiber coupler is typically made by pulling two twisted single-mode fibers while heating them. Due to the heating and pulling process, the two fibers are fused together into a combined body whose diameter is slowly tapered at the fused region. The desired characteristics of the coupler can be obtained through the control of the amounts of fusion and tapering in general.

If the characteristics of the coupler can be tuned, including the operating wavelength and the coupling ratio, it can be used as a tunable filter, variable optical attenuator, and optical switch. Recently, the mechanically tunable fused fiber coupler based on the stress-
optic effect of fiber was reported [5]. The device showed a wide tuning wavelength and a highly adjustable coupling ratio; however, it needed an extra moving stage to induce the mechanical stress. The attempt of utilizing an external medium having a high thermo-optic coefficient has been tried. By applying a silica resin over the coupling region of a fused coupler and using a heater or cooler, a highly efficient thermo-optic tunable fiber coupler was implemented a few decades ago [6, 7]. Even though the old experiments successfully showed the feasibility of using an external medium to endow tunability, they were limited by using various external media in achieving various spectral bandwidths and tunable ranges, and in showing their temperature-dependent spectral characteristics in detail.

It is well known that the spectral characteristics of the fused fiber coupler are affected by the external medium surrounding the fused region of the coupler due to an evanescent wave [8, 9]. This article presents the spectral characteristics of the fused fiber tunable coupler, which have been experimentally obtained at various conditions. At first, the changes of the spectra with respect to the external media surrounding the fused regions of the couplers are investigated at various refractive indices of the media. Of course their responses to temperature are presented. It was found experimentally that the thermo-optic effect of the fiber itself was too weak to induce sufficient tuning of the coupler. The experimental results on the tunability of the fused couplers having various elongation lengths are also presented. Finally, the best condition for getting the widest tuning range is presented. By adjusting the current to the micro-coil heater wound around the fused region of the coupler, the thermal tuning could be performed easily. The fabrication procedure and the performance of the implemented tunable fused fiber couplers are described in detail.

2. Device Structure and Operation Principle

Figure 1 shows the schematic of the proposed thermo-optically tunable fused fiber coupler. A 2 × 2 fiber coupler is made by using the conventional fusion and elongation method. The fused region of the coupler is inserted into the groove of a U-shaped quartz rod. The groove is filled with a polymer having a refractive index similar to that of the optical fiber material, fused silica in this case. Finally, the quartz rod containing the coupler is wound with a heating coil, and the temperature of the device is controlled by adjusting the current to the coil of the micro-coil heater.

In general, the coupling ratio of a fused fiber coupler depends on the wavelength of the input beam, and the wavelength dependency can be controlled by adjusting the fabrication condition. The coupler made with strong fusion shows less wavelength sensitivity, but the one of weak fusion is more sensitive to wavelength, thus keeping the dumbbell-like cross-section [7]. The operating principle of the weakly fused coupler, called the wavelength division multiplexing (WDM) coupler, is well known and similar to the mode coupling between two identical waveguides. At first, due to the pulling or elongation of a fiber, the fiber diameter—not only the cladding but also the core—is highly reduced. Thus, the core mode field is no longer confined near to the core region but is expanded out of the cladding surface of the fiber. Through the evanescent field out of the cladding surface, the field of the first fiber is coupled to the second fiber. Generally, the coupling between two fibers can be improved by increasing the evanescent fields expanded out of both fibers. The evanescent field increment can be simply achieved by filling the surrounding of the fibers with the material having the refractive index similar to the index of the cladding material. Of course, the mode coupling
also depends on the length of the coupling region. In this work, the spectral properties of the couplers having various elongation lengths and surrounded with various external media are investigated. To get the spectral tunability of the coupler, the polymer having a high thermo-optic coefficient is used, and the temperature is controlled with a homemade micro-coil heater.

3. Experiments and Discussion

A standard single-mode fiber (SMF 28, Corning, USA) with a cladding diameter of 125 µm and a core diameter of 8.2 µm was used. With the frame brushing method [10, 11], two pieces of the fiber were twisted around each other, heated with two micro torches, and tapered by pulling them together. Three $2 \times 2$ couplers with different elongation lengths were fabricated and named coupler 1, coupler 2, and coupler 3, respectively. Coupler 1 was a standard WDM coupler aimed for two wavelengths of 1,310 nm and 1,550 nm. It was made with a 10-mm brushing length and a 21-mm elongation length. Couplers 2 and 3 had elongation lengths longer than coupler 1 by 3.5 mm and 7.0 mm, respectively. Due to the elongation, the diameter of the coupler waist was reduced to $\sim 30$ µm for coupler 1. Of course, the waist diameters of couplers 2 and 3 became smaller than that of coupler 1 by 4 µm and 7 µm, respectively. Each coupler was packaged into a quartz rod having a U shape, as previously shown in Figure 1.

3.1. Preliminary Experiments

Prior to the main experiment, to determine the optimal refractive index of the external
medium giving wide enough tunability, the groove of the U-shaped quartz rod of coupler 1 was filled with a series of test liquids, and the transmission spectrum was measured for each liquid. The water–glycerin mixed liquids with glycerin concentrations of 20 wt%, 40 wt%, 60 wt%, 80 wt%, 85 wt%, 90 wt%, 95 wt%, and 100 wt% were prepared, and the refractive indices were measured using a prism coupler. At a wavelength of 1,550 nm under room temperature, the indices were 1.344, 1.371, 1.398, 1.427, 1.434, 1.441, 1.448, and 1.456, respectively. The transmission spectra measured at the cross-coupled port are plotted in Figure 2. The transmission peak wavelength was smoothly shifted to the longer wavelength direction with increasing the refractive index of the liquid up to 1.441. However, with the liquid of refractive index 1.448, the peak was slightly moved back to the shorter wavelength direction, and a high transmission loss occurred over the entire wavelength range. Further, with liquid of 1.456, the peak position was not moved any farther, but the loss was appreciably increased. The peculiar behavior of the spectra measured with liquids of 1.448 and 1.456 can be understood by considering the refractive index of the fiber cladding material—1.444 at a wavelength of 1,550 nm [12]. Similar behavior is well known to the field of long period fiber gratings (LPGs) [13]. The resonant wavelength of the LPG depends on the refractive index of the surrounding medium, but the medium index should be less than that of the cladding material. When the surrounding index becomes larger than the cladding index, the total internal reflection no longer occurs; however, Fresnel reflection occurs, which does not shift the phase upon reflection.

Figure 3 shows the locations of the transmission peaks of Figure 2 plotted with the refractive index of the liquid. It was found that the peak was shifted more sensitively as the refractive index of the liquid became bigger, as long as it was smaller than the cladding index. It provides a guideline for selecting the refractive index of the external medium. With the external medium having a refractive index slightly smaller than the effective index of the involved cladding mode, a wider tuning bandwidth can be expected. Of course the medium having a high thermo-optic coefficient is preferred.

Figure 2. Transmission spectrum of fused fiber coupler with change of the external media with different refractive indices.
The thermo-optic coefficient of a polymer is one order higher than that of the silica material [14] in general. Therefore, to check the effect of the polymer as the external medium, a polymer was applied on coupler 1 and the temperature dependency was monitored. The polymer (ZPU series, Chemoptics, Daejeon, Republic of Korea) used for the experiment had a room temperature refractive index of 1.45 at 1,550 nm, slightly higher than the cladding index, and its thermo-optic coefficient was $-1.8 \times 10^{-4}/^\circ C$. The polymer was UV cured under a nitrogen atmosphere. For the preliminary test, the coupler was placed on a hot plate and the transmission spectrum was measured at 22°C, 70°C, and 100°C. The same measurements were made with and without the polymer and are shown with Figure 4. Without the polymer, no significant change in the peak location and intensity was observed. On the other hand, with the polymer, very appreciable spectral shift with the temperature could be seen. It was blue shifted (shifted to the
shorter wavelength direction) and the peak intensity was increased with temperature. It is noted that the refractive index of the polymer decreased with temperature. The high transmission loss at room temperature means that the refractive index of the polymer was very similar, or slightly higher, to the cladding index as checked with Figure 2. With this pre-experiment, it can be concluded that in tuning the coupler characteristics, the thermo-optic effect of the fiber itself does not play a major role, but the one of polymer is mainly responsible.

3.2. Main Experiments

With the result of the preliminary experiment, the thermo-optic tunable couplers could be fabricated successfully. For the temperature variation, a micro-coil heater made of a Ni-Cr wire of a 110-μm diameter was utilized. The winded wire had an inner diameter of 2.0 mm and an electric resistance of 50 Ω. A polymer (ZPU series, Chemoptics) having a room temperature refractive index of 1.440 at 1550 nm was selected, which had the same thermo-optic coefficient of $-1.8 \times 10^{-4}/^\circ\text{C}$. It is noted that the refractive index of the polymer was slightly lower than the one used for Figure 4; thus, even at room temperature, well-developed coupling peaks could be expected.

The polymer was applied to the prepared couplers 1, 2, and 3, and the transmission spectra were measured at both the through and the cross ports with respect to the electric power applied to the coil heater. As depicted with Figures 5, 6 and 7, as also expected, the peaks were blue shifted with the electric power, thus with temperature. However, the shifting amounts, and thus the tunable ranges of the transmission spectra, were different with the operating wavelengths and the type of couplers. At a longer wavelength region, the spectrum was more widely shifted. For example, the tunable range for the cross-coupled port of coupler 1 was 32 nm at around 1,600 nm, while the corresponding one for the throughput port was 11 nm at around 1,330 nm. Similar things happened within the same port also; in Figure 6a, the through port of coupler 2, it can be seen that the peak at 1,270 nm was shifted by 39 nm, but the one near 1,550 nm was shifted as much as 76 nm—almost two times more. The large discrepancy in the amount of peak shift induced by temperature can be understood by two things—the chromatic dispersion and the wavelength dependent modal confinement. The material dispersion of the polymer is much different from the modal dispersion of the elongated fiber modes. And in general, the fiber mode is confined well at a shorter wavelength and, thus, less sensitive to the variation occurred out of the fiber.

Another important feature is that the tuning range of coupler 3 (Figure 7) was much wider than that of coupler 1 (Figure 5), and coupler 2 was in the middle (Figure 6). Especially coupler 3, with the longest elongation and smallest waist size, showed the wavelength tuning range up to 210 nm for the through port, which was almost the same as the free spectral range of the coupler itself. The dependency of the tuning range on the elongation length is simply understood with the evanescent field coupling between two fibers, as mentioned in Section 2. With elongation, the fiber diameter is reduced and the evanescent field is extended more easily into the external medium and, thus, more strongly influenced by the refractive index change of the external medium.

4. Results and Summary

The temperature-induced spectral peak shifts of the three couplers having different elongation lengths but same external media are presented together in Figure 8. The spectral
Figure 5. Shift of transmission spectra in accordance with the electric power applied to the coil heater of coupler 1: (a) throughput port and (b) cross-coupled port.

Positions of the dominant peaks of couplers, one peak from each port, are plotted together in terms of the input electric power and compared with those from other couplers. With all couplers, the spectral shift was fast in the beginning but became saturated as the electric power increased, which is well matched with the pre-experimental result of Figure 3. From Figure 8, it can be said that 0.6 W of electrical power is sufficient for almost full tuning. The coupler having the longest elongation, coupler 3, showed the narrowest free spectral range but gave the fastest shifting rate. It also showed the longest shift in both channels.
Figure 6. Shift of transmission spectra in accordance with the electric power applied to the coil heater of coupler 2: (a) throughput port and (b) cross-coupled port.

The structural parameters and the performances of the three couplers are summarized in Table 1. As mentioned, coupler 3 had the widest tuning range, as wide as 210 nm. It is noted that the tuning range and the insertion loss are in a trade-off relation. The coupler having the longer elongation had the bigger insertion loss. The additional loss due to the absorption by the thermo-optic polymer was less than 0.3 dB.

At a single wavelength, the tunable coupler could control the coupling ratio between the through and the cross ports. For an example, coupler 3 of Figure 7 shows a wide tunable transmission exceeding 18 dB at a particular wavelength of 1,550 nm. In addition,
Figure 7. Shift of transmission spectra in accordance with the electric power applied to the coil heater of coupler 3: (a) throughput port and (b) cross-coupled port.

the optical power switches back and forth between two ports through the control of the electrical power. Therefore, it can be said that the proposed thermo-optically tunable fused fiber coupler can be exploited as a tunable filter, variable optical attenuator, and optical switch.

For WDM applications of the fused fiber coupler, the channel separation, the width of each transmission band, and the optical isolation between adjacent channels are important parameters. The experimental results have shown that these values strongly depend on the elongation length of the couplers. The channel width and the channel isolations between
Table 1
Geometric parameters and specifications of the fabricated couplers

<table>
<thead>
<tr>
<th>Specification</th>
<th>Coupler 1</th>
<th>Coupler 2</th>
<th>Coupler 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elongation length (mm)</td>
<td>21.0</td>
<td>24.5</td>
<td>28.0</td>
</tr>
<tr>
<td>Waist size</td>
<td>≈30</td>
<td>≈26</td>
<td>≈23</td>
</tr>
<tr>
<td>Refractive index of external medium</td>
<td>1.440</td>
<td>1.440</td>
<td>1.440</td>
</tr>
<tr>
<td>Thermo-optic coefficient of external medium</td>
<td>$-1.8 \times 10^{-4}/^\circ C$</td>
<td>$-1.8 \times 10^{-4}/^\circ C$</td>
<td>$-1.8 \times 10^{-4}/^\circ C$</td>
</tr>
<tr>
<td>Maximum tuning range (nm)</td>
<td>32</td>
<td>76</td>
<td>210</td>
</tr>
<tr>
<td>Insertion loss (dB)</td>
<td>&lt;0.7</td>
<td>&lt;1.2</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>Channel width (nm)</td>
<td>40–50</td>
<td>20–30</td>
<td>15–25</td>
</tr>
<tr>
<td>Optical isolation at peak wavelengths (dB)</td>
<td>40–50</td>
<td>23–40</td>
<td>18–37</td>
</tr>
</tbody>
</table>

the cross-coupled port and throughput port decreased with increasing the elongation length. However, when getting dense WDM, the channel separation of the proposed couplers is not short enough. Therefore, applications in coarse WDM and multi-modal biomedical imaging [15] can be considered, in which the large channel separation and the wide channel width can be considered as advantages.

5. Conclusion

This article has demonstrated that the transmission spectrum of the fused fiber coupler could be widely tuned by applying a thermo-optic polymer onto the fused region of the coupler and by controlling the temperature of the polymer. When the refractive index of
the polymer was similar to, but slightly less than, the effective index of the elongated fiber mode, the thermal sensitivity was its maximum. The wavelength tuning range also depended on the type of the coupler itself. As the elongation length of the fused coupler was increased, the tuning range was also increased. With a 28-mm elongation length and a room temperature polymer index of 1.440, a 210 nm tuning range was achieved, which was almost the same as the free spectral range of the coupler itself. The feasibility of the tunable coupler as a tunable filter, variable optical attenuator, and optical switch has been experimentally presented.

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References

Biographies

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