Novel micro-optical waveguide on micro-actuating platform for re-configurable wavelength selective optical switch

W. Shin and K. Oh

Department of information and communications, Gwangju Institute of Science and Technology (GIST), 1 Oryong-dong, Buk-gu, Gwangju, 500-712, KOREA
Tel: +82-62-970-2213, Fax:+82-62-970-2204
koh@gist.ac.kr

Abstract: We propose a novel technique to add new degrees of freedom in fiber optic coupler devices. Micro-optical waveguide (MOW) on a micro-actuating platform (MAP) structure has been proposed and experimentally implemented using fiber waveguides, where the coupling characteristics of MOW are mechanically varied by precise axial stress control by MAP. As an application of the proposed structure, we mounted the coupling zone of fused taper coupler array on a MAP to demonstrate a novel re-configurable 1×4 wavelength selective optical switching function. Robust mechanical tuning among output ports of a four-channel demultiplexer was realized by precise elongation control of the taper region in serially cascaded fused fiber couplers. Simultaneous re-configurable wavelength routing and switching functions were demonstrated among four channels in 1.5 µm coarse WDM transmission window. We report the principle, design concept, and the performances of the proposed device structure along with its potential in re-configurable fiber optics.

©2004 Optical Society of America

OCIS codes: (060.0060) Fiber Optics and Optical communications; (060.2310) Fiber Optics.

References

1. Introduction

In recent optical communications two key technological requirements, “wavelength selectivity and re-configurability”, have been in the center of attention and Micro Electro-Mechanical System (MEMS) technologies [1-3] have demonstrated their potentials to satisfy those requirements in optical access networks. With the recent development of OH-free single mode fibers and broad bandwidth multimode fibers [4,5], Coarse Wavelength Division Multiplexing (CWDM) systems are being intensively proposed to provide photonic solutions to emerging metropolitan access networks [6]. CWDM systems use optical channel spacing of about 20 nm, which will significantly relieve technological burden in design and fabrication of components compared with narrow spaced Dense WDM systems.

Current wavelength routing functions are mainly provided by combining wavelength selective MUX/DEMUX with optical switches. Switches based on micro-machined mirrors, fluid bubble containing planar circuit type, and thermo-optic interferometers are being developed taking advantages of integration capabilities and scalability [7-9]. However, these switches usually accompany MUX/DEMUX, such as Arrayed Waveguide Gratings (AWG), to provide wavelength selectivity. It is, therefore, highly desirable to incorporate switching capability in MUX/DEMUX or vice versa in a single device to cope with demands for versatile re-configurable functions as well as small form factors.

Wavelength tuning in fused taper couplers has been experimentally demonstrated in a limited spectral range by applying strain during packaging process [10]. Thermo-optic tuning of a fiber coupler has been also reported in a laser cavity to provide 40 nm tuning in 1.8 μm region [11]. For a wide channel separation such as used in 1.3/1.5 μm WDM communication systems, the authors have reported a novel 2×2 cross connect switch using the coupling constant change induced by torsional stresses [12-13]. In this study, we further developed the prior idea into a novel concept, Micro-Optical Waveguide (MOW) on Micro-Actuating Platform (MAP). In the proposed scheme, a micron scale optical waveguide, the fused region of a multi-port fiber coupler, was placed on a MAP that provided a precise control of axial perturbation in micron/sub-micron scale to achieve wavelength selective routing among the ports of the coupler. Due to inherent strength of silica fiber against strains along the axial direction, the proposed mechanical tuning can provide robustness in device performances as well. We demonstrate the feasibility of “MOW on MAP” by applying the structure in a novel 1×4 CWDM wavelength selective switching device, for the first time. Its potentials in re-configurable wavelength selective routing for optical communications were also experimentally confirmed.

2. Principles of MOW on MAP

The principle of the proposed device is conceptually shown in Fig. 1. Firstly, by optimization of tapering and fusion conditions, a wavelength selective coupler is made out of two single mode fibers (SMFs) separating λ₁ and λ₂ to port 1 and 2, respectively. Note that the width of the taper in the coupling zone is usually in a few or few tens of micron. This serves as a “MOW” and its micron scale dimension enables axial mechanical perturbation using electrically driven micro-actuating systems. In this experiment we used a computer controlled
high precision motorized stage with nanometer resolution as a “MAP” to provide the axial stress. The “MOW” is then assembled on the “MAP” by steadfast fiber holders to form a “MOW on MAP” structure, where the axial stress can be accurately applied over the coupling region of the tapered coupler.

The mechanical perturbation will, then, alter the coupling constant of the coupler by two notions; 1) photoelastic effect induces the refractive index change, and 2) stress-strain relation will change the geometrical dimensions of waveguide.

The power flow in each port of 2×2 fused tapered coupler is defined by the coupling constant $C(z)$ as [14]:

$$P_1(z) = \cos\left(\int_0^z C(z')dz'\right),$$  \hspace{1cm} (1)

$$P_2(z) = \sin\left(\int_0^z C(z')dz'\right),$$  \hspace{1cm} (2)

$$C(z) = \frac{\sqrt{\sigma U^2(z)K_0(W)}}{bV(z)K_1^2(W)},$$  \hspace{1cm} (3)

where $\sigma = 1 + (n_{\text{substrate}}/n_{\text{cladding}})^2$. $U(z)$, $V(z)$, and $W(z)$ are the normalized frequencies in a circular waveguide. $K_i$ is the modified Bessel function of the second kind of order $i$. $b$ is the radius of the cylindrical waveguide in the coupling zone. $P_1(z)$ and $P_2(z)$ are the power flow through the port 1 and 2, respectively. $C(z)$ is coupling coefficient along the axial $z$ direction. The coupling constant is in deed a function of both the refractive index and the geometrical dimensions. Therefore when the coupler on “MAP” experiences axial stress, the coupling constant will change and consequently we can alter the power splitting ratio and spectral response of the output port, which is the fundamental principle of the proposed device in this study.

![Diagram of MOW on MAP](image)

**Fig. 1.** Principle of proposed “MOW on MAP”: The fused taper waist of the coupler serves as MOW and the electro-mechanical actuating system serves as MAP. When the axial stress is applied on the MOW by precise control of pulling in MAP, the coupling constants change and subsequently the throughput of the “MOW on MAP” device.

The photoelastic effect in silica is known as [15]:

$$\Delta n_i = C_i \sigma_i + C_\theta (\sigma_\theta + \sigma_\varphi),$$  \hspace{1cm} (4)
\[ \Delta n = C_a \sigma_\theta + C_b (\sigma_\theta + \sigma_z), \]
\[ \Delta n = C_a \sigma_\theta + C_b (\sigma_\theta + \sigma_z), \]

where \( C_a \) and \( C_b \) are the photo-elastic coefficients for ordinary and extraordinary rays, respectively. \( \sigma_\theta \), \( \sigma_\theta \), and \( \sigma_z \) are the stress components in each direction. Here we will assume that the dominant stress will be in the axial direction and the main contribution in the photoelastic effects is in \( \Delta n \), \[15\] and \( \Delta n \) versus \( \sigma_z \), is plotted in Fig. 2.

![Fig. 2. Photoelastic effect in silica glass fiber.](image)

The effect of geometrical dimension changes in fiber couplers has been reported elsewhere by the authors \[12\], where we confirmed that the strain level within 4% in silica can significantly alter the coupling characteristics. With an appropriate axial perturbation in “MOW on MAP” we can, therefore, induce \( \pi \) phase shift between the coupled waveguides by these two contributions: photoelastic effect and geometrical deformation.

3. Design of spectral response

![Fig. 3. Schematic structure of 1x4 CWDM demultiplexer and its spectral response.](image)

In order to implement “MOW on MAP” in re-configurable devices, we designed a 4-channel CWDM demultiplexer, whose schematic structure and spectral responses are shown in Fig. 3. In the first stage, a single WDM coupler separates \( \lambda_1, \lambda_3 \) to the left coupler in the second stage and \( \lambda_2, \lambda_4 \) to the right one. In the second stage, the both couplers further separate \( \lambda_1, \lambda_2, \lambda_3, \) and \( \lambda_4 \) into port 1, port 2, port 3, and port 4, respectively. Here the channels, \( \lambda \)'s are 1510, 1550, 1530, and 1570 nm referenced to CWDM specifications in 1.5 \( \mu \)m region. Once
again the tapering zones of these couplers will serve as “MOW” to result in a phase shift by “MAP”. Among the available three MOWs in the demultiplexer, we will consider the taper of the first stage coupler and discuss the effects of its phase shift over the output spectra of the device.

Transmission spectra of individual WDM couplers were designed using Eqs. (1)-(3), to achieve the de-multiplexing throughput characteristics and the results are shown in Fig. 4. The designed initial spectra from the output ports of the 1st stage coupler and 2nd stage couplers before π phase shift induced by MAP are shown in Figs. 4(a), (c), and (d), respectively. The combination of these spectra resulted in a 4-channel demultiplexer as shown in Fig. 4(e) satisfy the schematically proposed structure in Fig. 3. Now let us assume that the tapering zone of the 1st coupler serves as “MOW” and placed on “MAP” and further assume that we induce π phase shift. The result of this perturbation is shown in Fig. 4(b), where the signals λ₁, λ₃ are routed to port 2 and λ₂, λ₄ to port 1 of the 1st stage coupler. These routed signals will be transmitted through the 2nd stage couplers and the effects of the π phase shifted input signals at the 2nd stage are shown in Figs. 4(c) and (d) for each output-ports. Before the phase shift, the coupler in the 2nd stage separates λ₁ and λ₃ to port 1 and port 2, shown in the red shaded region of Fig. 4(c). After the phase shift, the incoming signals are now changed to λ₂ and λ₄ as shown in the blue shaded region of Fig. 4(c), where the coupler shows 50-50 splitting through both of its output ports. In the reciprocal manner, we can also achieve 50-50 splitting of λ₁ and λ₃ through the port 3 and port 4 of the coupler in the 2nd stage as in Fig. 4(d) after the π phase shift in the 1st stage coupler. The spectra of final output ports are subsequently altered as in Fig. 4(f), where the signals were routed among the output ports along with different power levels compared with initial spectra Fig. 4(e).

Note that these significant changes in the spectral response were induced by the π phase shift only in the 1st stage coupler and further wavelength selective routing can be achieved by applying “MOW on MAP” structures for the 2nd stage couplers. The experimental and theoretical discussions on the “MOW” on “MAP” structure, which was applied at the first stage coupler of CWDM demultiplexer, can be readily adopted on the two coupling zones of the second stage couplers. Using the same principle to induce phase shift in these coupling zones, we can further develop switching functionalities among the output ports. Using three separate “MOW” on “MAP” structures in three couplers, flexible routing of channels are enabled among 4 output ports. The allowed routing configurations for the devices are summarized in Table 1, where the output channels and required phase shifts in each “MOW” on “MAP”’s are listed. The impacts of the π phase shift in the 1st stage coupler are schematically summarized in Fig. 5, where a new type of re-configurable wavelength selective routing function can be realized.
Fig. 4. The design of spectra of WDM couplers for 4 channel CWDM demultiplexer and its response to the $\pi$ phase shift in the 1st stage coupler: (a) The transmission spectrum of in 1st stage coupler before the $\pi$ phase shift, (b) The transmission spectra of in 1st stage coupler after the $\pi$ phase shift, (c) The transmission spectra of in 2nd stage Coupler (Port 1 and Port 2), (d) The transmission spectra of in 2nd stage coupler (Port 3 and Port 4), (e) Final throughput transmission spectra before the $\pi$ phase shift in the 1st stage coupler, (f) Final throughput transmission spectra after the $\pi$ phase shift in the 1st stage coupler.
4. Experiments and results

In order to implement the proposed device design, we used the flame brushing technology [14] to fabricate individual 2×2 WDM couplers with the desired spectral responses. The transmission spectra of the output ports of the fabricated demultiplexer are shown in Fig. 6.

The maximum isolation among channels was better than 23 dB and the insertion loss was less than 0.5 dB. The waist dimension of the fused taper of the 1st stage coupler was about 6×8 µm² and the taper zone length was 38 mm. The fused region was mounted on a specially designed MAP as shown in Fig. 7. MAP is composed of high precision motorized stage with spatial resolution of 100 nm along with fiber holders attached to linearly translating rails. The fused region of the 1st stage WDM coupler was mounted on fiber holders steadfast and the distance between the fiber holders was accurately controlled in order to generate axial stress over the coupler.

Fig. 6. Transmission spectra through the fabricated 4 channel CWDM demultiplexer, Port 1 transmission peaks at 1510 nm, while Port 2 does at 1550 nm, Port 3 at 1530 nm, and Port 4 at 1570 nm. This is consistent with the design as in Fig. 4(e).
Before we characterize the throughputs of the demultiplexer, we examined the response of the 1st stage WDM coupler in the “MOW on MAP” structure. After mounting the coupling region of the 1st stage coupler on the MAP, the transmission through the port 1 of the 1st stage coupler, see Fig. 3, was monitored as the axial stress was applied. The port was designed to transmit 1510, and 1550 nm as shown in Fig. 4(a) and fabricated accordingly. In Fig. 8(a), the spectra without axial stress clearly show that the port does transmit 1510 and 1550 nm. As the axial stress was applied over the tapering zone of the 1st stage coupler, the spectrum continuously shifted to the shorter wavelength keeping the sinusoidal behavior. At the strain level of $\sim 9 \text{ m}\varepsilon$ with the elongation length of 180 $\mu$m, $\pi$ phase shift was achieved in the 1st stage coupler and the transmission through the port 1 was then peaked at 1530 and 1570 nm, which is consistent with theoretical prediction in Fig. 4(b). The port 2 of the coupler showed the reciprocal response to Fig. 8(a), which confirms the proposed routing principle. The spectrum regains its initial shape when the longitudinal stress was relieved and no abnormal hysteresis was observed during repeated cycles. It is noted, however, that the channel isolation decreased from 24 dB to 15-18 dB and the insertion loss slightly increased by 0.2-0.3 dB as the phase shift was induced. These are attributed to non-uniform stress distribution along the tapering zone and further localization of stress over the waist region is being investigated by the authors.

In order to measure the temporal response for $\pi$ phase shift in the proposed device, 0 dBm stabilized light from a DFB laser at 1510 nm was launched into an input port and the output power was recorded in an oscilloscope as periodic longitudinal strain was applied. The
The measured trace of output power is shown in Fig. 8(b), where the rise and fall time were measured less than 25 msec. It is expected that shorter response time would be obtained with an optimized taper structure in the coupler so that the stress could be highly localized over a short length to result in shorter elongation length.

After confirming the proposed routing performances in the 1st stage coupler in our device, we further characterized the spectral responses from the four output ports of the device. Broadband light source and four DFB laser diodes were used to measure the output spectra of the device before and after the $\pi$ phase shift in the 1st stage coupler. All of the optical powers of the four DFB laser diodes were set 0 dBm.

![Transmission Spectra](image1)
![Transmission Spectra](image2)
![Transmission Spectra](image3)
![Transmission Spectra](image4)

Fig. 9. Transmission spectra and normalized output from the proposed device before and after $\pi$ phase shift. (a) Port 1 (1510 nm), (b) Port 2 (1550 nm), (c) Port 3 (1530 nm), (d) Port 4 (1570 nm).

The measured results for each port are shown in Fig. 9. The experimental results showed a very good agreement with theoretical predictions in Fig. 4(e), (f) and Fig. 5. For instance the output port 1 transmitted the channel at $\lambda_1=1510$ nm, before the $\pi$ phase shift as shown in Fig. 9(a) and the output changes to $0.5\lambda_3$ (at 1530 nm) + $0.5\lambda_4$ (at 1570 nm) as predicted. The results were confirmed in transmission measurements of both DFB LD and broadband light source. Experimental results clearly showed the wavelength selective routing function to transform the initial single channel port into two-channel port at other wavelengths, as we expected in Fig. 5. This novel re-configurability would be beneficial in handling optical signals in intelligent self-healing networks, which require both routing and switching. Note that the proposed switching mechanism could be further implemented in the second-stages so that individual channels can be fully cross connected.

We further investigated the effects of the $\pi$ phase shift over the transmission quality and the experimental set-up is shown in Fig. 10. Firstly we measured the Bit Error Rate (BER)
before and after the phase shift at 1550 nm. The random bit from 10 Gbps pulse pattern generator (PPG) was fed to DFB laser diode to directly modulate the laser output in Non Return to Zero (NRZ) format. The modulated light signal at 1550 nm was transmitted through the output Port 2 of the proposed devices before the π phase shift and the BER versus receiver power was measured.

![Fig. 10. Experimental set-up for measurement of bit error rate (BER) and polarization dependent loss (PDL).](image)

After the π phase shift, 1550 nm signal then split into Port 3, and Port 4, and BER through each port were measured independently and compared with the result before the π phase shift in Fig. 11. It is noted that 1550 nm signal measured at Port 3, and Port 4 showed power penalty about 3.3 dB at BER of 10⁻⁹. This penalty is attributed to 50-50 splitting of the signal as shown in Fig. 5 and the added insertion loss as shown in Fig. 8(a), after the π phase shift. For multi-channel experiments we can expect similar results but the cross-talk between the channels in the demultiplexer might put additional power penalty in the long distance communications, which is being investigated by the authors.

![Fig. 11. Band routing performance in 1550 nm 10 Gb signal: BER vs Receiver power.](image)

Polarization Dependent Loss (PDL) during the elongation of the fused taper was monitored and the results are shown in Fig. 12. As the elongation length increased the PDL was measured for 1550 nm signal through the Port 2 then through Port 3 and 4 after the π phase shift. The PDL increased up to 0.2 dB before the phase shift and further increased to 0.55 dB. PDL was found to be closely related with the symmetry of the cross-section and further reduction in PDL could be achieved with fused tapers with circular cross-sections.
We have confirmed experimentally that our design to use the phase shift on the fused taper by “MOW on MAP” provides a feasible solution to combine switch and demultiplexer to result in a novel wavelength routing capability. Expanding this “MOW on MAP” structure to the rest of tapers in the second stages, we will be able to have highly flexible wavelength routing among 4 output ports, which can be readily adopted in optical routing sub systems. Based on the experimental and theoretical observations for the $\pi$ phase shift in the 1st stage coupler, we can further predict what this proposed device could achieve when all the couplers are adapted in “MOW” on “MAP” structure. The allowed routing configurations for the devices are summarized in Table 1.

Table 1. The configuration table for the proposed wavelength selective routing device. Here the first and the third columns are the phase shifts induced on the coupler in “MOW on MAP” structure. Columns 4 to 7 are the output wavelengths.

<table>
<thead>
<tr>
<th>1st stage</th>
<th>2nd stage</th>
<th>Port 1</th>
<th>Port 2</th>
<th>Port 3</th>
<th>Port 4</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>0</td>
<td>$\lambda_1$</td>
<td>$\lambda_3$</td>
<td>-</td>
<td>-</td>
<td>OXC($\lambda_2, \lambda_3$)</td>
</tr>
<tr>
<td></td>
<td>$\pi/2$</td>
<td>0.5 $\lambda_3+0.5 \lambda_4$</td>
<td>0.5 $\lambda_3+0.5 \lambda_4$</td>
<td>-</td>
<td>-</td>
<td>ORR($\lambda_2, \lambda_4$)</td>
</tr>
<tr>
<td></td>
<td>$\pi$</td>
<td>$\lambda_2$</td>
<td>$\lambda_3$</td>
<td>-</td>
<td>-</td>
<td>OXC($\lambda_2, \lambda_3$)</td>
</tr>
<tr>
<td>Lower</td>
<td>$\pi/2$</td>
<td>-</td>
<td>-</td>
<td>0.5 $\lambda_3+0.5 \lambda_4$</td>
<td>0.5 $\lambda_3+0.5 \lambda_4$</td>
<td>ORR($\lambda_2, \lambda_4$)</td>
</tr>
<tr>
<td></td>
<td>$\pi$</td>
<td>-</td>
<td>-</td>
<td>$\lambda_3$</td>
<td>$\lambda_4$</td>
<td>OXC($\lambda_2, \lambda_3$)</td>
</tr>
<tr>
<td>Upper</td>
<td>0</td>
<td>0.5 $\lambda_3+0.5 \lambda_4$</td>
<td>0.5 $\lambda_3+0.5 \lambda_4$</td>
<td>-</td>
<td>-</td>
<td>ORR($\lambda_2, \lambda_4$)</td>
</tr>
<tr>
<td></td>
<td>$\pi/2$</td>
<td>$\lambda_2$</td>
<td>$\lambda_3$</td>
<td>-</td>
<td>-</td>
<td>OXC($\lambda_2, \lambda_3$)</td>
</tr>
<tr>
<td></td>
<td>$3\pi/2$</td>
<td>$\lambda_4$</td>
<td>$\lambda_2$</td>
<td>-</td>
<td>-</td>
<td>OXC($\lambda_2, \lambda_3$)</td>
</tr>
<tr>
<td>Lower</td>
<td>$\pi/2$</td>
<td>-</td>
<td>-</td>
<td>0.5 $\lambda_3+0.5 \lambda_4$</td>
<td>0.5 $\lambda_3+0.5 \lambda_4$</td>
<td>ORR($\lambda_2, \lambda_4$)</td>
</tr>
<tr>
<td></td>
<td>$3\pi/2$</td>
<td>-</td>
<td>-</td>
<td>$\lambda_3$</td>
<td>$\lambda_4$</td>
<td>OXC($\lambda_2, \lambda_3$)</td>
</tr>
</tbody>
</table>
5. Conclusion

We demonstrated a new “Micro Optical Waveguide” on “Micro Actuating Platform” structure for novel wavelength routing switch applications. Applying a longitudinal axial strain of less than ~9 mε over the taper region in serially cascade fused fiber couplers, fast and robust routing functions were realized among CWDM channels at 1510, 1530, 1550, and 1570 nm. The device showed an insertion loss less than 0.5 dB and channel isolation over 23 dB. The polarization dependent loss was below 0.2 dB during π phase shift and the switching time was less than 25 msec. With additional implementation of “MOW on MAP” over all coupling zones in the demultiplexer, we could predict very versatile port-to-port routing of optical signals.

Acknowledgments

This work was supported in part by the Korea Science and Engineering Foundation (KOSEF) through the Ultrafast Fiber-Optic Networks Research Center at Gwangju Institute of Science and Technology.