ABSTRACT

This paper proposes an improved design of variable optical attenuator (VOA) using a micromachined elliptical mirror as the movable reflector. We compared the attenuation performances of the three different types of VOAs, which were fabricated by the same deep reactive ion etching process. It is noticed that the proposed VOA (EVOA) has superior performance than the common shutter-type VOA (SVOA) and the flat-mirror reflection-type VOA (FVOA). Based on the focus property of the ellipse, this reflection-type EVOA enjoys low insertion loss while using the normally-cleaved single mode fibers. It achieves a large attenuation of 44 dB at 10.7 V driving voltage. The PDL is 0.8 dB at the 40 dB attenuation level and the WDL is 1.2 dB at the 20 dB level for 100 nm wavelength change. More importantly, the attenuation increases nearly linearly with the mirror displacement. The EVOA also has low polarization dependence loss (PDL), low wavelength dependence loss (WDL) and low back reflection.

1. INTRODUCTION

Variable optical attenuators (VOAs) are essential and basic components used to adapt and control optical power in many different applications. Especially, they have been widely used in the wavelength division multiplexing (WDM) systems to equalize the power levels of multiple wavelength channels and to obtain the flat gain of optical amplifiers. They have also found important applications in the optical add-drop multiplexers (OADM) and in the test equipment. The widespread successful deployment of optical networks based on WDM in long-haul networks forecasts that the number of multiplexed wavelengths will increase from several dozen at present to several hundred. Thus, for future applications, an array structure containing multiple attenuators in a single chip is preferable. Therefore, realizing a VOA with both compact and low in wavelength dependence will increase the degree of freedom in designing system, and lead to a great demand. Moreover, it is necessary to dynamically regulate channel power regardless of fluctuations in polarization. Regarding to the above demands, VOAs using micromechanical structures brought by advances in microelectromechanical system (MEMS) have been created. MEMS are attractive because of their integration ability, inherent small size and cost advantage. The MEMS VOA provides capability of directly reducing the light intensity regardless the difference of wavelength and protocol in an analog control manner.

Various types of MEMS VOAs have been reported [1]-[9]. According to the light attenuation mechanisms, they may be simply classified into two categories: shutter-type VOAs [1]-[4] and reflection-type VOAs [5], [6]. A shutter-type VOA (SVOA) (as shown in Figure 1(a)) makes use of a knife-edge to block the light between the input and output fibers, which are aligned co-axially and very closely. The attenuation is determined by the position of the knife-edge which is controlled by an electrostatically actuated comb drive. Different attenuation level can be obtained by changing the positioning of the knife-edge. This arrangement offers the benefits of a low insertion loss (IL) and a large attenuation range, but also results in a large polarization dependence loss (PDL) and a strong back reflection due to the scattering at the knife-edge and co-axis assembly. On the other hand, a reflection-type flat-mirror VOA (FVOA) (as shown in Figure 1 (b)) controls the coupling efficiency by moving a flat mirror to steer the light beam away from the output fiber. The un-coupled light propagates to the surrounding free space, thus limit the level of back reflection. It provides good attenuation performance, low PDL and low wavelength dependence loss (WDL), but suffers from high IL since a certain separation between the input and the output should be kept for fibers assembly. Although the IL can be reduced by the collimating lens and lensed fibers, it increases the cost.

![Figure 1: Typical arrangements of the MEMS VOAs. (a) Shutter-type VOA; (b) reflection-type flat-mirror VOA.](image-url)
A preferred VOA would be a reflection-type but has low IL and large tuning range while using only the normal fibers. For this purpose, we propose a reflection-type VOA using an elliptical miromirror as the reflector. To compare the performances of the different types of VOAs, a SVOA and a FVOA (with flat mirror as a reflector) are also fabricated on the same wafer. All three VOAs are electrostatically actuated because it has an advantage of low power consumption over other methods like electromagnetic and thermal actuation.

2. VOA DESIGN

Figure 2 illustrates the principle of the proposed MEMS elliptical-mirror VOA (named as EVOA). The beauty of this VOA is its elliptical reflective mirror. According to the focusing property of an ellipse, a ray of light from one focus of the ellipse would pass through the other focus after a single bounce.

![Figure 2(b): Schematic diagram of the MEMS VOA using an elliptical mirror. (a) Initial state; (b) Attenuation state.](image)

In the arrangement as shown in Fig. 2 (a), two single mode fibers (SMFs), as the input and output, are placed on the two foci of the elliptical mirror. Therefore, when an elliptical mirror is used as the reflector, rays originated from the input fiber can be fully directed to the output. This suggests that a low IL can be obtained even with the normally-cleaved SMFs. For this reason, lensed fibers and other collimating lenses are not necessary, which simplifies the packaging and reduces the cost. On the other hand, once the elliptical mirror is displaced, as shown in Figure 2 (b), both input and output are deviated from the mirror foci. Thus the rays are rapidly defocused and the light path is changed according to different mirror position. As the part of the light from the input fiber will not be coupled to the output fiber, a large tuning range can be obtained with a small mirror displacement. In other words, only a low driving voltage is required for the large attenuation range when the electrostatic actuation scheme is adopted. As this VOA is reflection-type, it should have low WDL and low PDL. Additionally, the back reflection is limited as the lights of the input and output are not co-axial.

![Figure 3: Microscopic graph of a packaged MEMS VOA with an elliptical mirror. (a) A packaged VOA with fibers attached; (b) Closed-up of the elliptical micromirror.](image)
SMFs are positioned separately to the two focal centers of the mirror, with their core axes aligned orthogonally to guarantee high coupling efficiency and easy assembly. In order to obtain the symmetry of the overall VOA arrangement to the minor axis, the mirror center is chosen to be the vertex of the minor axis. Additionally, the selected part of the ellipse has small curvature. The mirror has a length of ~ 125 μm, which is large enough to couple most of the incoming light to the output fiber in the initial state (i.e., no mirror displacement). Meanwhile, the curved mirror also helps to couple the input light to the output port as much as possible at the initial position. Furthermore, this arrangement helps to reduce the insertion loss as the two fibers could be arranged very closely.

To improve the reflectivity, the surface of the mirror (as shown in Fig. 3b) is coated with a gold layer of 0.2 μm thick. The electrostatic comb drive is used to control the mirror displacement. The movement of the mirror is along the axis of the input fiber, and its displacement creates a misalignment between the coupled fibers to produce the attenuation. The fiber grooves are fabricated wide enough for active alignment.

3. Experimental Results and Discussions

Figure 4 shows the relationship between the optical attenuation and the driving voltage. For the EVOA, at the initial position, with the two SMFs located at the foci of the elliptical mirror, the coupled lights intensity reaches its maximum level, corresponding to an insertion loss of 1.0 dB. The measured back reflection loss is less than -50 dB at the initial state. When the driving voltage is increased, the mirror moves away, and the attenuation increases accordingly. The maximum attenuation of the EVOA is about 44 dB with 20 μm mirror translation. It is observed that the attenuation is almost linearly with the mirror displacement up to an attention level of 30 dB. As a comparison, the SVOA has 1.0 dB IL, and the attenuation reaches more than 40 dB with a mirror displacement of only 11 μm. However, the attenuation increases exponentially, making it difficult to stabilize at the high attenuation level. The FVOA has 4.6 dB IL, and the attenuation tends to saturate at 27 dB level after 17 μm mirror displacement, presenting an S-shape curve. As the input and output are normally-cleaved SMFs with no additional collimating lenses employed, the coupling efficiency of the reflective light is limited for the FVOA with the flat reflective mirror. This may also result in a limited attenuation range.

Among the three VOAs (as illustrated in Figures 1 and 2), the IL of the EVOA could be as low as that of the SVOA even though the normally-cleaved SMFs are used. It is mostly because of the elliptical mirror and the focusing property of the ellipse. This is one of the merits of our reflection-type EVOA design — low IL can be achieved with the normal SMFs instead of lensed fibers. In comparison, the FVOA exhibits high IL when using the same fibers. Moreover, compared with the strong nonlinearity in most of the other VOAs [1]-[6], the linearity of the EVOA is a special merit of using the elliptical mirror. This feature makes it easy for the VOA control and the power management setups of optical networks.

The PDL of the EVOA at different attenuation levels (at the wavelength of 1550 nm) is shown in Fig. 5. It can be seen that over the entire 44 dB attenuation range, the PDL remains below ~ 0.85 dB. Especially, the EVOA presents low PDL across the first 15 dB attenuation range, and it fluctuates within 0.3 dB. We also measured the PDLs of the three VOAs at 20 dB attenuation level. Results shows that the EVOA has 0.5 dB PDL, the FVOA has 1.3 dB, while the SVOA has 2.2 dB PDL.

![Figure 4](attachment:figure4.png)

**Figure 4**: Optical attenuation versus driving voltage and mirror displacement.

![Figure 5](attachment:figure5.png)

**Figure 5**: Polarization dependence loss (EVOA) at different optical attenuation levels.

The characteristics of the WDL of the EVOA at different attenuation levels are illustrated in Fig. 6, representing the difference of the attenuation over a wavelength range from 1520 nm to 1620 nm (including the C-band). It is seen that the attenuation curve is quite flat at the attenuation levels of 0, 5 dB, 15 dB and 20 dB, and the variations remain less than 1 dB. On the other hand, the deviation also increases gradually. Thus, at higher level, the attenuation becomes
much more wavelength dependent. At 30 dB attenuation level, the peak-peak value of the vibration can be as high as 3 dB. It is maybe due to the scattering of the etched mirror surface and the diffraction in the mirror edge. Therefore, one possible method to reduce the WDL is to improve the fabrication process. Meanwhile, we test the WDL performance of the SVOA and FVOA at an attenuation level of 10 dB. Results show at this level, the WDLs are 0.8 dB, 1.0 dB and 1.6 dB for the EVOA, FVOA and SVOA, respectively.

Figure 6: Wavelength dependence loss (EVOA, wavelength range: 1520 nm ~ 1620 nm) at different optical attenuation levels.

The typical performance of the three types of MEMS VOAs is summarized in Table 1. It shows that the EVOA possesses the advantages over the SVOA and the FVOA in terms of insertion loss, attenuation range, PDL and WDL. In addition, the EVOA has a special benefit of linear relation between the attenuation and the mirror displacement.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SVOA</th>
<th>FVOA</th>
<th>EVOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion loss (dB)</td>
<td>1.0</td>
<td>4.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Attenuation range (dB)</td>
<td>45</td>
<td>27</td>
<td>44</td>
</tr>
<tr>
<td>Linearity (&lt; 30 dB)</td>
<td>Exponential</td>
<td>S-shape</td>
<td>Linear</td>
</tr>
<tr>
<td>PDL (dB) @ 20 dB</td>
<td>2.2</td>
<td>1.3</td>
<td>0.5</td>
</tr>
<tr>
<td>WDL (dB) (1520 ~ 1620 nm) @ 10 dB</td>
<td>1.6</td>
<td>1.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

We have designed and fabricated a reflection-type MEMS VOA with an elliptical micromirror actuated by a comb drive actuator. The mirror structure and the arrangement of coupling fibers improve the performance of the VOA. This EVOA achieves an attenuation of 44 dB with a driving voltage of 10.7 V. By employing normal SMFs instead of lensed fibers, this design offers high coupling efficiency and easy assembly with low insertion loss. Additionally, the attenuation is almost linear with the mirror displacement over an attenuation range of 30 dB. Compared with the other two types VOAs (SVOA and FVOA), the improved EVOA shows low PDL of only 0.5 dB when the attention is lower than 20 dB, but the PDLs of the SVOA and FVOA are both greater than 1 dB. Furthermore, the EVOA presents less WDL than the other two VOAs over the wavelength range of 1520 nm - 1620 nm at the 10 dB attenuation level.

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REFERENCES