MEMS variable optical attenuator with a compound latch

R.R.A. Syms a,*, H. Zou a, J. Stagg a, D.F. Moore b

a Optical and Semiconductor Devices Group, Department of Electrical and Electronic Engineering, Imperial College, Exhibition Road, London SW7 2BT, UK
b Cambridge University Engineering Department, Trumpington St., Cambridge CB2 1PZ, UK

Available online 19 March 2004

Abstract

A variable optical attenuator with a compound latch is described. The attenuator and fibre mounts are fabricated in bonded silicon-on-insulator, using microelectromechanical systems technology. The latch has two stages. Each can be continuously adjusted or fixed into position using a rack and tooth driven by electrothermal actuators. The second stage has a mechanical advantage of 10, giving a tenfold increase in precision compared with the tooth size of 10 μm. The mechanism is used to fix a shutter in the optical path between two fibres. Static and dynamic mechanical and optical characteristics are given, and a dynamic range of >30 dB is demonstrated.

Keywords: MEMS; MOEMS; Variable optical attenuator; VOA

1. Introduction

Micromechanical systems (MEMS) technology has allowed optical components to be combined with mechanisms and actuators. For example, several MEMS variable optical attenuators (VOAs) have been demonstrated. Surface micromachining has been used to construct polysilicon shutters, which are inserted into the path of a beam travelling parallel to the substrate [1]. Deep reactive ion etching (DRIE) of bonded silicon-on-insulator (BSOI) has allowed electrostatic [2] or electromagnetic [3] shutters to be integrated with fibre alignment guides. Alternative designs based on image translation by a mirror have also been developed; these offer lower polarization dependence of loss (PDL) [4].

It may be desirable to fix the attenuation, to allow powerless operation. Brake mechanisms have been demonstrated using electrothermal actuation and elastic clamping [5]. However, they suffer from limited shock resistance. Bi-stable mechanisms have also been developed for switching [6]. However, these obviously lack the number of states needed in a VOA. Recently, we demonstrated a VOA based on a rack-and-tooth mechanism, that may be stably fixed in different states [7]. Here, we extend the principle to a compound latch, to increase the attenuation range without increasing the travel. The principle is presented in...
Section 2, together with the design of a two-stage VOA. Fabrication and performance are described in Section 3, and conclusions in Section 4.

2. Principle and application of a MEMS compound latch

Fig. 1(a) shows a single-stage latch, consisting of a single tooth mounted on a lever (hinged at one end by an elastic flexure) and a toothed rack (also hinged by a flexure). When the beam is deflected upwards, the tooth engages with the rack. If the tooth spacing is $D$, the position $Y$ may adopt a set of discrete values $Y = iD$, where $i$ is an integer. The tooth and rack may be deflected by electrothermal drives [8]. Each drive consists of a pair of flexures, one long and one short. When a current is passed between the two anchors, the temperatures of the two arms are raised. The long arm will expand more, deflecting the structure laterally. The currents $I_A$ and $I_B$ control the tooth and rack, respectively.

The precision is limited by the tooth size, which in turn is set by fabrication processes and clearances. Increased precision may be achieved by the lever principle. For example, the position $y$ at a point nearer to the flexure is $y \approx Y \times L'/L$. As a result, $y$ may take one of a set of values $y = i\Delta'$, where $\Delta' = \Delta L'/L$ is a reduced tooth spacing. However, this improvement is obtained by reducing the range. To increase the range again, mechanisms may be cascaded as in Fig. 1(b). Here, the rack of a first latch is mounted on the lever of a second. This approach may clearly be extended to more stages, giving the deflections:

\[
Y_1 = i\Delta + y_2 = i\Delta + Y_2L'/L; \\
Y_2 = j\Delta + y_3 = j\Delta + Y_3L'/L, \tag{1}
\]

where $i$ and $j$ are integers. Defining $\Delta'' = \Delta(L'/L)^2$ and so on, we obtain

\[
Y_1 = i\Delta + j\Delta' + k\Delta'' + \cdots \tag{2}
\]

Thus, the deflection $Y_1$ is the sum of terms defined by the integers $i, j, k, \ldots$. For example, in a three-stage latch with $L'/L = 1/10$, each might take the values $0, \ldots, 9$. The deflection might then be controlled over the range $0–9.99 \Delta$ with a precision of $0.01 \Delta$. Infinite precision may not be achieved by

![Fig. 1. Principle of: (a) single-stage; (b) multi-stage mechanical latch.](image-url)
extended cascading; the useful limit is set by backlash and other inaccuracies.

A VOA with a two-stage latch may be constructed as shown in Fig. 2. Here, two single-mode optical fibres are mounted co-axially on a substrate, using spring alignment features [2]. The fibres are spaced apart by a short distance, and an electrothermally driven latch mechanism is used to translate an angled shutter into the gap between them. The primary rack is driven via a flexure linkage by a remote actuator, while the secondary rack is driven directly. The secondary latch is inverted, to allow a compact arrangement.

3. Fabrication and testing

Prototypes were fabricated by deep reactive ion etching of 4" dia bonded silicon-on-insulator, with a bonded layer thickness of 75 μm and an oxide interlayer thickness of 2 μm. A single-mask process was used, and etching was carried out in a Surface Technology Systems ICP etcher. The oxide interlayer was then removed from beneath the suspended parts by etching in buffered HF, and the structures were freeze-dried, and metallised with 100 Å of Cr and 300 Å of Au.

The width of all rigid suspended parts was 40 μm and the widths of all flexible arms was 5 μm. The electrothermal drives were 800 μm long, and the hot arms were 16 times longer than the cold arms. The levers were \( L = 7.5 \) mm long and the rack arms 2 mm long. The tooth size was 10 μm and \( L'/L = 1/10 \), giving an overall resolution of 1 μm. The rack travel required to open each latch was 20 μm. The initial shutter position was 37.5 μm from the optical axis. Fig. 3(a) shows an SEM view of a completed VOA; Fig. 3(b) shows a close-up of the shutter and primary latch, and Fig. 3(c) shows the secondary latch. Fig. 3(d) shows an optical view with fibres inserted.

Mechanical deflections were characterised by driving each actuator in turn. Fig. 4 shows the variations of displacement with electrical power. In each case the variation is quasi-linear. The lever displacements are considerably larger than the rack displacements, because of their increased length. Similarly, the displacements of the secondary rack and primary lever are larger those of the primary rack and secondary lever, because the last two must deflect additional elements. However, the primary rack travel is clearly sufficient to open the latch.
Latching was achieved by driving levers and racks in sequence. The primary rack was first driven to open the primary latch. The primary lever was then driven to engage with the rack. The latch was then closed, leaving the primary lever fixed. The secondary latch was then opened, and the secondary lever deflected. Finally, the secondary latch was closed. The loading caused by one latch affected the other. For example, the deflection of the primary rack reduced when the secondary latch was engaged, and by the time it reached the third state, the reduction in deflection was very significant.

AC performance was measured by driving the primary lever from a sinusoidal source. Fig. 5 shows the variation of peak-to-peak displacement with drive frequency, at low and high amplitudes. Because the actuator is power-operated, the mechanical response is at twice the frequency shown. The displacement is constant at low frequencies, but starts to fall as the frequency rises. This feature is characteristic of electrothermal actuators, which are first-order systems. The 3-dB point is at $\approx 100$ Hz. There is a large peak in deflection at high frequency; this is the first order bending mode resonance of the primary lever. It occurs at

---

**Fig. 3.** SEM views of: (a) completed device in BSOI (two shown, back-to-back); (b) close up of primary latch; (c) secondary latch; (d) optical microscope view with fibres in place.
or a mechanical resonance of $f_n = 440$ Hz. The $Q$-factor of this resonance is $Q \approx 27$, so that the damping factor is $\zeta = 1/2Q \approx 0.019$. The settling time following a step excitation may be estimated as $t = 1/2\pi f_n \zeta = 0.02$ s, or 20 ms.

Optical fibres were then attached, and the average transmission was measured using a high-power broadband source (an Agilent 83438A erbium ASE source). The background insertion loss was $\approx 1.0$ dB. First, the primary latch was held open and power was applied to the primary lever. As the shutter moved across the beam, it was verified that the attenuation gradually increased, to 40 dB. The transient response was then measured. The inset to Fig. 5 shows the response obtained when a voltage step is applied to the primary lever. The shutter is initially held away from the optical beam, so transmission is high. When the step is applied, the shutter is inserted. Transmission is reduced, but only after mechanically induced oscillations have decayed. These occur at the first-order resonant frequency, and the time to decay to $1/e$ of their initial value is $\approx 22$ ms, in agreement with the estimate above.

Operation of the compound mechanism was then demonstrated. Fig. 6 shows the variation of transmission with secondary state, with the primary first in state 1 and then in state 2. The fixed loss is ignored here. The attenuation may clearly be held in two ranges. Each range corresponds to one primary state, and, within each range, each value corresponds to one secondary state. One range covers low attenuation, and the other covers higher values. However, the two ranges do not overlap at secondary state 10 as would be expected from the 10:1 reduction, but at state 15. The discrepancy is ascribed partly to elastic relaxation of the secondary stage following removal of the drive power, and partly to loading from the primary.

4. Conclusions

A shutter-insertion variable optical attenuator with a compound latch has been demonstrated.
The device was fabricated by deep reactive ion etching of bonded silicon-on-insulator. In this example, a two-stage system with a mechanical advantage of 10 was used, allowing the attenuation to be fixed in two sets of distinct states that remained stable after the removal of electrical power. The principle may be adapted to related devices such as moving mirror VOAs; all that is required is an additional straight-line mechanism to ensure linear translation. The mechanism may also be used to position other components such as gratings or filters that require linear or angular in-plane adjustment and fixing at manufacture.

Acknowledgements

The authors are grateful to EPSRC for support under Grant GR/R07844/0.

References