REAL PIVOT MECHANISM OF ROTARY COMB-DRIVE ACTUATORS FOR MEMS CONTINUOUSLY TUNABLE LASERS

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Abstract: This paper presented the theoretical and experimental studies on a new mechanism of real pivot by use of a double-clamped beam. Comparison with the conventional virtual pivot formed by a cantilever beam, such real pivot provides large rotation angle and small position shift, which is key for the MEMS tunable lasers to obtain continuous wavelength tuning over a wide range. In experiment, the real pivot is able to produce a rotation angle of 4.7 degrees regardless of a depth variation of 16% over the double-clamped beam due to fabrication error. In contrast, the virtual pivot has only 2.4 degrees in the presence of 4% depth reduction. The real pivot design is more suitable for the MEMS tunable lasers as it is simple, symmetric, robust and allowable for single-chip integration.

Keywords: MEMS, micromechanics, external-cavity tunable lasers, rotary comb drive, pivot.

1. INTRODUCTION

Microelectromechanical systems (MEMS) technology has recently attracted intensive interests of research to construct external-cavity tunable lasers [1-5]. However, little work has been focused on the micromachined rotational structures [1-4, 6], which is indispensable for achieving continuous wavelength tuning [1-3].

Continuously tunable lasers are commonly designed in Littrow configuration [1, 2] as shown in Fig. 1. The collimated light from the gain chip is coupled back by the blazed grating. The tuning is obtained by rotating the grating about a remote pivot. To obtain continuously wavelength tuning, one of the cavity modes should always match the filtered wavelength given by the grating (named as wavelength tracking). Consequently, the position of pivot is critical. It has been proven that a small shift of pivot position relative to its optimized position will drastically reduce the achievable range of wavelength tuning [7]. Such shift can be decomposed into two directions \( l \) and \( y \) as shown in Fig. 1. The former is along the optical axis of external cavity while the latter is along the grating surface. The pivot shift in the \( l \) direction causes the variation of cavity length and may deteriorate the wavelength tracking. As a result, the continuous tuning wavelength range would be reduced. The pivot shift in the \( y \) direction does not change the cavity length, but it would influence the operation of the micro actuators (such as a rotary comb drive). As a result, the achievable rotation angle is restricted, which in turn limits the continuous tuning range.

Based on these considerations, this paper aims at developing a simple pivot structure that has negligible pivot shift. The design of a real pivot beam will be illustrated in Section 2, followed by the experimental results in Section 3.
2. DESIGN & ANALYSIS

2.1 Real pivot using a double-clamped beam

The concept of realizing a real pivot using a double-clamped beam is shown in Fig. 2. A rotary comb drive is used as the actuator to rotate the external reflector (mirror or grating). The movable comb is connected to the center of a soft double-clamped beam through a stiff beam. When a pure torque is applied at the midpoint of the double-clamped beam, it would yield pure rotation and no position shift thanks to the symmetry of the load and structure. In an ideal case that a pure torque \( M \) is applied to the midpoint \( C(x_c, y_c) \) of the double-clamped beam, the deformation \( y \) of the beam is

\[
y = \frac{M}{8L_0EI}(L_0 - 2x)(x^2 + L_0(L_0 - 2x))
\]

where \( E \) is the Young’s modulus, \( I \) is the momentum of inertia, \( L_0 \) is the length of the double-clamped beam. Following the notation in [8], here the point brackets \(<t> = t \) if \( t > 0 \), and \(<t> = 0 \) for \( t \leq 0 \). Under this torque, the rotation angle \( \theta \) at the midpoint can be expressed as \( \theta = M L_0/16EI \). From Eq. (1), \( y|_{x=L_0/2} \) is always 0 for whatever the value of \( \theta \). That is to say, the pivot does not move with the change of rotation angle. However, the design in Fig. 2 is actually driven by an off-centered load \( F \) generated by the rotary comb drive actuator. Consequently, the position shifts \((\Delta x_c, \Delta y_c)\) of the midpoint \( C \) can be calculated by the virtual-work method [8] as given by

\[
\Delta x_c = \frac{L_0^2}{3R} \theta + \frac{2L_0^2}{105R} \theta^3, \quad \Delta y_c = \frac{L_0^2}{12R} \theta^2
\]

where \( t_0 \) is the width of the double-clamped beam.

2.2 Virtual pivot using a cantilever beam

The old design of rotary comb drive supported by the cantilever beam can be regarded as a soft cantilever beam subject to an offset force \( F \) applied through a stiff beam as modeled in Fig. 3. It is assumed the length of soft beam is \( L_1 \) while that of stiff beam is \( bL_1 \). The deformation \( x \) of the cantilever beam and the rotation angle \( \theta \) of the stiff beam can be expressed as

\[
x = [3(1+b)L_1 - y]Fy^2/6EI \quad \text{for} \quad y \leq L_1
\]

\[
\theta = (1 + 2b)L_1^2/2EI
\]

However, the deformation of the soft beam would shift the end point \( E \) since there is no force in the axial direction to elongate the soft beam. As a result, the virtual pivot \( C \) would be shifted. Assuming \( \theta \ll 1 \), after certain derivation it has

\[
\Delta x_c = \frac{(2 + 3b)L_1}{18(1 + 2b)} \theta^3, \quad \Delta y_c = \frac{(1 + 5b + 5b^2)L_1}{15(1 + 2b)^2} \theta^2
\]

In the presence of fabrication error, the virtual pivot would have significant shift. Assume the cantilever beam dimension is changed linearly along its length by \( t(y) = t_1(1 - k_0y/L_1) \) and \( h(y) = h_1(1 - k_0y/L_1) \), where \( k_0 \) is the rate of change, and \( t_1 \) and \( h_1 \) are the designed width and depth, respectively. The additional pivot shifts are

\[
\Delta x_{c_{o}} = \frac{2}{3} k_0 L_1 \theta, \quad \Delta y_{c_{o}} = \frac{2(1 + 6b + 6b^2)L_1}{9(1 + 2b)^2} k_0
\]

Here the \( x \) shift is linear with the rotation angle, but the \( y \) shift is independent.
The shifts of the real pivot and the virtual pivot are compared in Fig. 4. The shifts in the \( x \) direction are negligible for the two pivot types for \( \theta \) direction as shown in Fig. 4, the real pivot has about 7.4 nm at 4 degrees, in comparison to the value of 2 nm for the virtual pivot. However, in the presence of fabrication non-uniformity, the virtual pivot experiences a drastic increase of shift to about 1946 nm. Such a shift would significantly influence the wavelength tuning range of the tunable lasers [7]. The comparison is based on the parameters of the fabricated devices to be discussed later. The two pivot designs have the same comb drive (40 fingers, separation 2.5 \( \mu \)m, width 2 \( \mu \)m). The double-clamped and cantilever beams are both 150 \( \mu \)m long and 2 \( \mu \)m wide. In the real pivot, the radius of the first movable finger \( r_1 = 1059 \) \( \mu \)m, while in the virtual pivot, it is \( r_1 = 160 \) \( \mu \)m. In this way, the two pivot designs have the same rotational stiffness.

3. EXPERIMENTAL RESULTS

The pivot designs are implemented into the tuning structures for MEMS tunable lasers as shown in Fig. 5. The two pivots are intended for two different MEMS lasers, whose tuning properties will not be covered here. The devices are fabricated using a deep reactive ion etching process on a silicon-on-insulator wafer (silicon structure 75 \( \mu \)m thick). Dry release approach by use of notching effect [9] is adopted rather than the wet etching to release the movable structures. This is to avoid the stiction problem.

Due to the dry etching phenomena in the process such as microloading effect and undercut, the fabricated structures have different width and depth as shown in Fig. 6. For the double-clamped beam, the depth is 66.5 \( \mu \)m in the left end and 66.1 \( \mu \)m (-0.6% change) in the right, but has a dip of only 55.8 \( \mu \)m (-16.1% change) in the midpoint. Fortunately, the depth change along the length direction is symmetric to the beam midpoint. For the cantilever beam as shown in Fig. 6 (b), the depth is 66.7 \( \mu \)m at the clamped end, and is reduced to 64.0 \( \mu \)m (-4% change) at the free end.
The static actuation performance of the two pivot designs is compared in Fig. 7. The comb drive supported by the real pivot can be rotated over the whole range of space as shown by the snapshots in Fig. 7 (a). In contrast, the comb drive supported by the virtual pivot can be only rotated within a small range, and then the movable comb is pulled to the fixed comb and cannot be rotated any further. Such pull-in problem can be attributed to the pivot shift as discussed above.

The measured curves of the rotation angle versus the actuation voltage are shown in Fig. 8 for both the real pivot and the virtual pivot. For comparison, the designed relationship \( \theta = 7.4 \times 10^{-3} V^2 \) (\( V \) in volt and \( \theta \) in degree) is also shown. For all the curves, the rotation angle is increased gradually with larger driving voltage applied to the rotary comb drives. With respect to the achievable rotation angle, the virtual pivot can only reach 2.4 degrees as limited by the pull-in problem; in contrast, the real pivot can reach 4.7 degrees until the movable comb is blocked by the stopper. The difference of maximum rotation angles verifies the statement in the previous section that the real pivot has better tolerance to the fabrication error than the virtual pivot design.

5. CONCLUSIONS

A design of a real pivot realized by the double-clamped beam has been presented and then compared with the virtual pivot design. It provides wide rotation angle (4.7 degrees), small pivot shift (< 8 nm), and large tolerance to fabrication error and environment change, which would be very useful for MEMS continuously tunable lasers.

REFERENCES