ABSTRACT
The paper presents the dynamic characteristics of a MEMS-based tunable coupled-cavity laser, constructed by integrating a Fabry-Pérot chip, a gain chip and a deep-etched parabolic mirror. It gains advantages over the previous tunable lasers in the form of high speed of wavelength tuning, since this wavelength tuning is based on free carrier plasma effect to change the refractive index. The currently measured tuning speed is of 1.2 µs. The MEMS movable mirror is employed to actively adjust the cavity length to build up the optimal lasing operation condition. Single-mode operation with a tuning range over 16.55 nm is demonstrated, and its side mode suppression ratio is better than 30 dB.

1. INTRODUCTION
A coupled-cavity laser (CCL) is formed by coupling two or more laser cavities. It has attracted broad attention since it offers single-mode operation and high switching speed, which are required by the modern optical networks [1]. Conventional CCLs (e.g. the two-section coupled-cavity lasers) are fabricated by etching a narrow groove in a single chip to form two cavities. It ensures efficient optical coupling between the cavities and simultaneously makes them electrically isolated [1-3]. The dominant lasing mode of a CCL is determined by the interference of the optical fields in all the optical cavities. However, due to the presence of the etched groove, the conventional CCLs actually have three cavities (two cavities formed by the laser chips and one formed by the air gap), which complicates the wavelength selection. In addition, the etched gap needs to be finely controlled in the fabrication (otherwise, low yield), and the fixed gap is not adaptive to the change of the cavity lengths, which is due to the environmental temperature variation and working point adjustment (e.g. change of driving currents). These problems hindered the stability of the conventional CCLs as single wavelength emission sources. Moreover, difficulties and complexity in the fabrication/alignment are another factor that hampered their applications to optical communications. To tackle these problems, we propose a design of the CCL that consists of a Fabry-Pérot (FP) chip and a gain chip forming the coupled-cavity, with an adjustable air gap between them. Moreover, one facet of the gain chip is anti-reflection (AR) coated. The AR coating simplifies the cavity structure from three cavities to two cavities, facilitating the wavelength control and improving the spectral quality. The adjustable gap provides an additional degree of freedom to optimize the operation state and to adapt the laser operation to the environmental variation. In addition, the fabrication difficulty in controlling the gap is also circumvented. In the paper, we present such a CCL made by using the Microelectromechanical Systems (MEMS) technology, whose capabilities of fine adjustment and single-chip integration have been demonstrated [4-6].

2. DESIGN
The design of the tunable CCL is schematically depicted in Fig. 1, which consists of a lasing chip, a tuning chip and a movable parabolic mirror [7]. The two chips are optically coupled through the parabolic mirror, but electrically isolated. Therefore, this design facilitates independent electrical control of each individual chip. As mentioned above, one facet of the tuning chip is AR coated, the other facet of it is high-reflection (HR) coated. Because of the AR coating, the tuning chip does not form a cavity by itself but together with the air gap forms a cavity. During the operation, the lasing chip is driven beyond its threshold to emit light, while the tuning chip is always below the threshold. According to the operation principle of the CCLs, there is an optimal gap length between the two chips to maintain stable single-mode and high spectral purity. The movement of the parabolic mirror can be used to optimize the gap.

The parabolic mirror is designed with a symmetrical arrangement of a pair of parabolic parts, whose foci are positioned at the two facets of the chips, respectively. According to the geometric optics, the beams from the focus of a parabola can be collimated after reflected by the parabolic
surface and vice versa. Therefore, the parabolic shape enhances the coupling efficiency. In addition, the coupling efficiency is insensitive to the horizontal translation of the mirror, as confirmed in recent study [7]. It was also observed that a 50 µm mirror displacement will only introduce 3dB loss. In the CCL, as for optimization, the mirror only needs to move by less than half of the wavelength; the coupling efficiency is kept almost constant during the gap adjustment, which reduces the fluctuation of the output power. This is an additional merit of using the parabolic mirror. In fact, the movable mirror provides the required flexibility for optimal gap adjustment. It should be noted that once a stable single-mode output is achieved, further mirror movement is not required for the wavelength tuning, since the tuning is implemented by the free carrier plasma effect. Such physical effect enables refractive index change by varying the injection current into a semiconductor chip.

\[
\lambda_1 \quad \lambda_2 \quad \ldots \quad \lambda
\]

Possible modes for the lasing chip

\[
\lambda_1' \quad \lambda_2' \quad \ldots
\]

Possible modes of the tuning chip @ \(I\)

\[
\lambda_1 \quad \lambda_2
\]

Possible modes of the tuning chip @ \(I'\)

\[
\lambda
\]

Coupled-cavity laser output

Figure 2. Principle of the wavelength tuning of the coupled-cavity laser.

The working principle of the wavelength tuning by varying the tuning current is illustrated in Fig. 2. The two chips initially have their individual oscillating modes, which are defined by each laser chip cavity length and the effective refractive index of active chip cavities. Only when the modes from each chip matches each other, such mode can be in oscillation. The present design is chosen in a way that the mode shifts is achieved by varying the effective refractive index, while keeping the cavity length of each chip fixed. This is because the refractive index is a function of the injection current. With the variation of tuning current, the modes of the tuning chip shift, and matching occurs at different position. As a result, the wavelength is tuned.

3. FABRICATION

The MEMS structures within the coupled-cavity laser, which are the parabolic mirror and the comb-drive actuator, are defined by a single photolithographic step and etched into a silicon-on-insulator wafer (which has a structure layer of 100 µm thick, and an oxide buffer layer of 2 µm is sandwiched between the structure layer and the silicon substrate layer). The deep reactive ion etching (DRIE) process is employed for MEMS structures fabrication and dry release method is used for movable parts release. The fabrication procedure is sketched in Fig. 3.

In the DRIE process, the structures are patterned with a silicon dioxide layer as hard mask (Fig. 3a), and then the major etching step of the device layer is divided into two sub-etching steps according to the etch rate of various aspect ratio trenches. The first sub-etching step focuses on the fast etched trenches (as illustrate in Fig. 3b). It is noticed that the widest trenches are etched to the buried oxide layer, although the narrow trenches are not completely etched. To avoid the notching at the bottom of the wide trenches with further etching process, PECVD dioxide is employed to cover the surface of the trenches, including their sidewalls, top surfaces and bottoms (Fig. 3c). In order to continue the next etching process for the other narrower trenches, anisotropic oxide etching step is employed (Fig. 3d). The DRIE process is carried out again until all the structures on the device layer have been etched through (Fig. 3e). Finally, an isotropic oxide etch is followed for oxide removal (Fig. 3f).

\[
(a) \quad (b) \quad (c) \quad (d) \quad (e) \quad (f)
\]

Figure 3. DRIE process flow: (a) Structure pattern on an SOI wafer(with oxide hard mask); (b) first DRIE with wider trenches at faster etching speed; (c) oxide deposition; (d) bottom oxide removal; (e) second DRIE; (f) release and final oxide removal.

The scanning electron micrograph (SEM) of an integrated tunable CCL is shown in Fig. 4. After the MEMS fabrication and release, two semiconductor chips (each with the length of 280 µm) are assembled. Finally, the output fiber is inserted into the etched groove for output detection. The tuning chip has an AR coating (reflectivity \(R < 0.2\%\)) on the front facet and a HR coating (\(R > 95\%\)) on the rear facet. The two parts of the parabolic mirror have been designed to follow a shape of \(y^2 = 4px\) (in which \(p = 250\ µm\)). Consideration behind such design is to ensure an effective optical coupling between the two chips. It has an open angle of 60 degrees relative to the chips so as to handle more than 99% of the powers. In order to improve the reflectivity of the mirror, its surface is coated with a soft layer of aluminum (with a total thickness of 0.5 µm).
4. EXPERIMENTS AND DISCUSSIONS

The mode selectivity by adjusting the gap is first experimentally investigated. The output spectral characteristics are measured with an optical spectrum analyzer. Fig. 5 shows the measured output spectra of the CCL at different gaps/tuning currents (with the fixed lasing current $I_{\text{lase}} = 25$ mA). Initially, the coupled laser has a multimode output as shown in Fig. 5a, which often occurs in the conventional fixed-gap CCLs owing to the non-optimized air gap, deviation of the chip sizes from the nominal values or low accuracy of the assembling process/equipment. After properly adjusting the mirror, the single-wavelength operation is obtained (as shown in Fig. 5b and 5c). As can be seen, the initial wavelength is $\lambda_1 = 1561.52$ nm. When the tuning current is changed, the output wavelength is shifted to $\lambda_2 = 1572.55$ nm. Meanwhile, it is observed that the CCL has superior mode selectivity at an optimal gap $d_0$, where stable single wavelength output with a side-mode suppression ratio (SMSR) of more than 30 dB is obtained. Although some small peaks are still observed, the output SMSR of more than 30 dB is maintained. The dominance of the matching mode is attributed to a higher gain compared to the rest of the existing modes. In the current MEMS CCL, the multimode is no longer a problem because the movable mirror can offset the inaccuracy.

The spectra obtained at various tuning currents are superimposed as shown in Fig. 6. When the tuning current is increased from 1 to 5.7 mA, the wavelength is tuned from 1556.00 to 1572.55 nm, corresponding to a change of 16.55 nm. During the tuning, the output power varies slightly since the lasing current is kept constant at $I_{\text{lase}} = 25$ mA. It is also observed that the output is always in single mode and the SMSR is better than 30 dB. Benefited from the CCL design, the optical power and the wavelength spectra can be adjusted separately and independently by the two control currents ($I_{\text{tune}}$ and $I_{\text{lase}}$). More specifically, the power is controlled by $I_{\text{tune}}$, while the dominant laser wavelength is controlled by $I_{\text{lase}}$. It is observed that the wavelength tunability is controlled by the level of tuning currents.

Figure 5. Single-mode wavelength tuning at different gaps and tuning currents. (a) Multimode emission at $d \cdot d_0$, (b) single-mode output where $I_1 = 1.3$ mA, and (c) single-mode output where $I_2 = 5.7$ mA.

Figure 6. Superimposed spectra at different tuning currents. The wavelength is $1556 \sim 1572.55$ nm in response to an increase of tuning current over $1 \sim 15$ mA.

Figure 7 shows the transient response of the wavelength tuning by monitoring the output powers of two wavelength modes $\lambda_i = 1562.9$ nm and $\lambda_i = 1572.5$ nm. In this way, the switching of the wavelengths is reflected by their optical power change, which is more convenient for measurement. When a step-up signal of $I_{\text{tune}}$ is applied, the power of $\lambda_i$ is reduced quickly, while that of $\lambda_i$ is increased. The fall time corresponding to 90%-10% power change is measured as $t_{\text{fall}} = 1.2$ $\mu$s and the rise time is $t_{\text{rise}} = 1.6$ $\mu$s (10%-90% power change). The switching speed is much faster than those obtained by thermal or mechanical tuning methods, which are typically at the scale of a few milliseconds [7][7]. It should be noted that the present speed is not limited by the CCL device.
but by the slow current pulse source and optical detector used in the experiment. Due to the fast response of free carrier plasma effect, the speed of the CCL is expected to be at the level of nanoseconds [8-9], which is under investigation.

![Graph](image)

**Figure 7. Transient response of the wavelength tuning. Rise time is 1.6 μs and fall time is 1.2 μs.**

### 4. CONCLUSIONS

In summary, a tunable coupled-cavity laser has been constructed using MEMS technology. It uses a micromachined parabolic mirror for optical coupling and gap adjustment. The movement of the parabolic mirror provides an extra degree of freedom to optimize the operation of the CCL, which have been verified by the experimental results. In static characterization, the device obtains a wavelength tuning range of 16.55 nm and SMSR better than 30 dB. In dynamic characterization, the wavelength switching speed is around 1.2 μs, which is limited by the measurement equipments. Theoretically it can be achieved at the level of nanoseconds. Compared with the conventional fixed-gap coupled-cavity lasers, MEMS CCL provides an additional degree of freedom of gap adjustment, which is adaptive to the environmental change. Compared with other tuning methods, the micromachined tunable laser also provides a drastic improvement in the wavelength tuning speed and broad applications such as wavelength-based passive packet switching networks, etc.

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### REFERENCES


