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A miniature tunable coupled-cavity laser constructed by micromachining technology

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This letter presents a miniature tunable coupled-cavity laser by integrating a Fabry-Pérot chip, a gain chip and a deep-etched parabolic mirror using micromachining technology. The mirror is to actively adjust the gap between chips, enabling the optimal mode selection. Single-mode operation with a tuning range of 16.55 nm and a side-mode-suppression ratio of >25.1 dB is demonstrated. The device overcomes phase mismatching and instability problems encountered in conventional fixed-gap coupled-cavity lasers. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2831912]

A coupled-cavity laser (CCL) is formed by coupling two or more laser cavities. It has attracted broad attention since the lasers offer single-mode operation and high switching speed,[1] which are required by the modern optical networks.[2] 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.[1,3,4] 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 have actually 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 chip and a gain chip forming the coupled cavity, with an adjustable air gap between them. However, one facet of the gain chip is antireflection (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 this letter, we present such a CCL made by using the microelectromechanical system (MEMS) technology. The capabilities of fine adjustment and single-chip integration have been demonstrated.[5–8]

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.[9] 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. Due to the AR coating, the tuning chip together with the air gap forms a single 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. 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 in the tuning chip. Therefore, the wavelength switching speed is no longer limited by

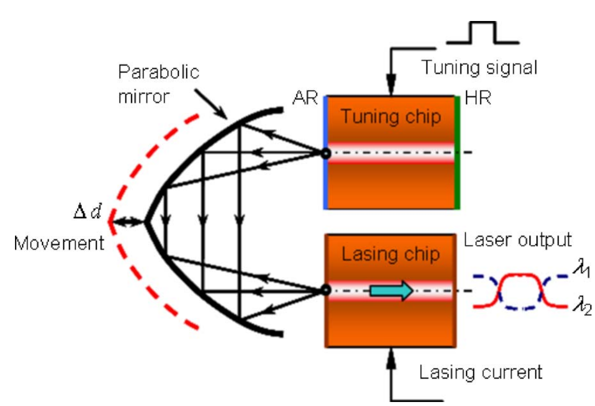

FIG. 1. (Color online) Design of the tunable coupled-cavity laser constructed by the MEMS technology.

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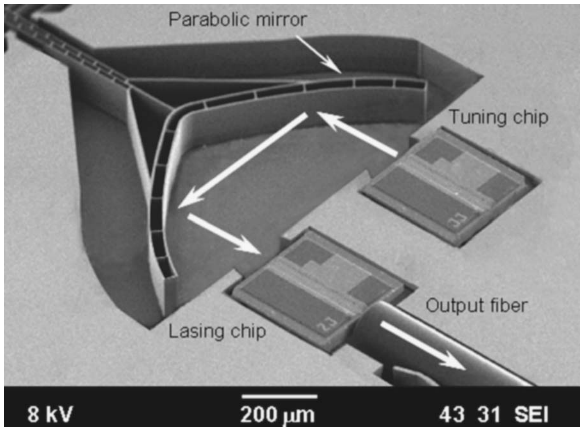

FIG. 2. Scanning electron micrograph of the MEMS coupled-cavity laser formed by integrating a Fabry-Pérot chip (as the lasing chip), a gain chip (as the tuning chip) and an output fiber with a deep-etched parabolic mirror.

the mechanical response (typically 1 ms). Instead, it is determined by the free carrier plasma effect at the level of nanoseconds. The parabolic mirror is a symmetrically arranged pair of parabolic parts, whose foci are positioned at the two facets of the chips, respectively. According to the geometric optics, in the horizontal direction, the beams from the focus of a parabola can be collimated by the parabolic surface, which provides sufficient coupling for the CCL to work. In addition, the coupling efficiency is also insensitive to the horizontal translation of the mirror, as confirmed in a recent study.[9] It was also shown that a horizontal translation as large as 50 μm can be tolerated until the coupling efficiency is reduced by half. In the CCL, 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.

The scanning electron micrograph of an integrated tunable CCL is shown in Fig. 2. All the MEMS structures, including the parabolic mirror and the comb-drive actuator (not shown in Fig. 2) are fabricated on a silicon-on-insulator wafer using the deep reactive ion etching process, with a structure layer of 100 μm thick. After the MEMS fabrication, 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). It has an open angle of 60° relative to the chips so to handle more than 99% of the powers. To improve the reflectivity of the mirror, its surface is coated with a 0.2 μm aluminum layer. The deposited Al layer will have negligible effect on the mirror's surface flatness and horizontal focusing ability. Moreover, to reduce the deformation of the mirror surface, a frame structure is employed to strengthen the parabolic curvature.

The mode selectivity by adjusting the gap is first experimentally investigated. Figure 3 shows the measured output spectra of the CCL at different gap lengths (with the lasing current $I_{\mathrm{lase}}=30$ mA and tuning current $I_{\mathrm{tune}}=3.2$ mA). It is observed that the CCL has superior mode selectivity at an optimal gap d_0, where single wavelength output with a side-

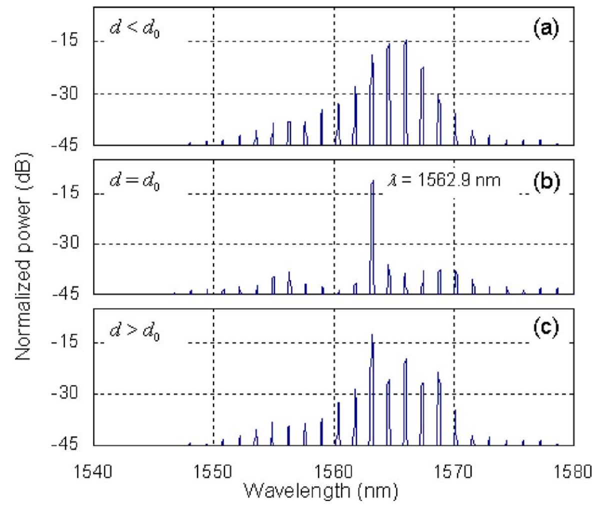

FIG. 3. (Color online) Output spectra of the MEMS coupled-cavity laser at different gaps. (a) Multimode emission at $d<d_0$, (b) single-mode output at the optimal state of $d=d_0$, and (c) multimode emission at $d>d_0$.

mode suppression ratio (SMSR) >25.1 dB was obtained, as shown in Fig. 3(b). If the gap $d\neq d_0$, the output becomes multimode, as shown in Figs. 3(a) and 3(c), 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. In the current MEMS CCL, the multimode is no longer a problem because the movable mirror can offset the inaccuracy. This is another benefit of the current MEMS laser.

The spectra obtained at various tuning currents are superimposed, as shown in Fig. 4(a). When the tuning current

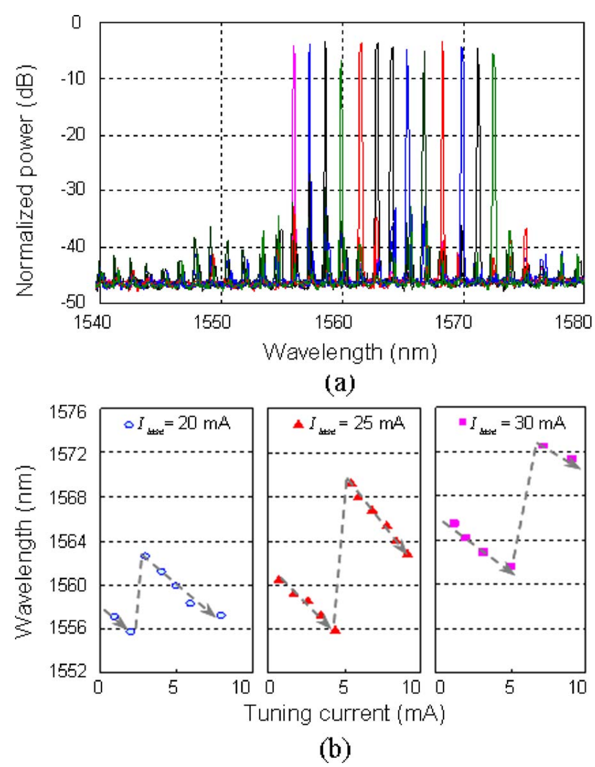

FIG. 4. (Color online) Wavelength tuning characteristics of the MEMS coupled-cavity laser. (a) Superimposed spectra at different tuning currents for a fixed lasing current of 25 mA and (b) measured output wavelengths as a function of the tuning current under different levels of lasing currents.

is increased from 1 to 15 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 more than 25.1 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_{lase} and I_{tune}). More specifically, the power is controlled by I_{lase}, while the dominant laser wavelength is controlled by I_{tune}. The wavelength tunabilities as a function of the tuning current are shown in Fig. 4(b), under different levels of lasing currents ($I_{\text{lase}} = 20$, 25, and 30 mA). With $I_{\text{lase}} = 20$ mA, the output is tuned to shorter wavelengths when I_{tune} starts to be increased from 0; then it jumps towards longer wavelengths once I_{tune} reaches 3.1 mA. It moves to shorter wavelength again with further increase of I_{tune}. Similar trends are observed in the cases of $I_{\text{lase}} = 25$ and 30 mA, but the wavelength at the same I_{tune} is longer for higher I_{lase}.

In summary, a miniature tunable coupled-cavity laser has been constructed by the MEMS technology. Different from the conventional coupled-cavity laser design, an AR-coated gain chip is used for wavelength tuning and a micromachined parabolic mirror is used for optical coupling and gap adjustments. The AR coating of the tuning chip simplifies the cavity structure and hence enhances the laser mode selectivity and stability. The movement of the parabolic mirror provides an extra degree of freedom to optimize the operation of the CCL, which has been verified experimentally. In static characterization, the device obtains a wavelength tuning range of 16.55 nm, with a SMSR more than 25.1 dB. Compared with the conventional fixed-gap coupled-cavity lasers, this device has superior spectral purity/stability and is adaptive to the environmental change.

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