Dual-wavelength lasers have been attractive for many applications, such as ultrashort optical communications, wavelength-division multiplexing, and terahertz radiation generation. Conventional dual-wavelength lasers are mainly based on fiber lasers and semiconductor lasers. Although the fiber lasers provide attractive features such as narrow linewidth and low noise, they usually require the use of a fiber element (such as distributed Bragg reflector) to select the laser modes. Hence, the majority of demonstrated lasers are constructed with relatively long cavities, which may make it difficult to obtain single longitudinal mode at each desired wavelength position and to have undesirable wavelengths due to the sidelobes of the filters. On the other hand, the semiconductor lasers are usually based on the configuration of external cavity, where dispersive elements for wavelength selection are employed. Although some more compact solutions have been exploited, special designed quantum wells are required for simultaneous dual-wavelength emission and the output could be with multiple frequency mode emission. Consequently, those schemes involve complicated fabrication and/or packaging procedures. As miniaturization has been a continuing trend in the existing technologies toward even smaller scales, a compact monolithically integrated device with broadly and independently tunable dual-wavelength output may be of interest to numerous scientific and practical applications. With the continuous maturation of microelectromechanical systems (MEMS) technology, it has become one of the key enabling technologies to downscale the devices and even the whole systems to the size of micrometers or millimeters. Meanwhile, this technology has shown very promising abilities in miniaturizing laser-related devices. Inspired by such development, this letter aims at constructing a dual-wavelength laser using the MEMS technology, which may overcome the drawbacks of conventional methods. In this letter, the physical phenomena of this MEMS laser are addressed and its tuning capabilities are demonstrated.

The proposed tunable dual-wavelength laser is arranged in a Littman configuration, as illustrated in Fig. 1. The external cavity is formed by an antireflection coated facet of the gain chip, a collimating lens, a grating element, and two mirrors. The grating diffracts different wavelengths to different directions and the lasers (mirror 1 and mirror 2) select two wavelengths ($\lambda_1$ and $\lambda_2$) in the cavities. The zeroth order diffraction from the grating is coupled as the output, which contains both $\lambda_1$ and $\lambda_2$. The tuning of dual-wavelength laser can be implemented by rotating mirror 2 while keeping mirror 1 fixed (as shown in Fig. 1). Based on the laser cavity resonance and the grating diffraction conditions, the spectral separation ($\Delta \lambda = \lambda_2 - \lambda_1$) is determined by

$$\Delta \lambda = \frac{m_2}{p_0}(\sin \phi_2 - \sin \phi_1),$$

where $p_0$ is the grating period, $m_1$ and $m_2$ stand for the diffraction orders, and $\phi_1$ and $\phi_2$ are the diffraction angles.

A MEMS tunable dual-wavelength laser for operating in the swing mode is fabricated and integrated on a silicon chip, with an overall footprint of $3 \times 3$ mm$^2$. The scanning electron micrographs of the integrated laser and the close-up of grating and mirrors are shown in Figs. 2(a) and 2(b), respectively. The MEMS structures, including a grating, a microlens, two micromirrors, and a rotary comb drive actuator (for rotating mirror 2) are all fabricated on a silicon-on-insulator wafer at the same time using the deep reactive ion etching process. The structure layer is 75 $\mu$m thick. After being patterned and etched, the MEMS structures are released by dry method. To improve the reflectivity of grating and mirrors, their surfaces are coated with a layer of aluminum (0.2 $\mu$m thick). The gain chip is an edge emitting chip with a cavity

![FIG. 1. (Color online) The schematic diagram of the dual-wavelength laser, where mirror 1 is fixed and mirror 2 is rotatable.](Image)
length of 300 μm. The chip has a high reflectivity coating (reflectivity $R > 95\%$) on the rear facet and an antireflection coating (reflectivity $R < 0.1\%$) on the front facet, and its active region is formed by multiple InGaAsP quantum wells. The grating has a period of 4 μm, mirrors 1 and mirror 2 are designed to reflect the +1st and −1st diffraction orders, respectively. The rotation of mirror 2 is provided by the rotary comb-drive actuator.14 The fiber is aligned along the designed fiber groove to collect the zeroth order as the output. The far-field profile of the original beam emission from the gain chip has a vertical opening and horizontal opening of 37° and 30°, respectively. With our lens, grating, mirrors, and cavity design, a sufficient light is coupled back to the gain chip cavity.

In the experiment, simultaneous two wavelength emissions are observed in the output. An output power of 2.9 mW is obtained when the driving current of 30 mA is applied on the gain chip. Higher output power of up to 10 mW can be achieved with a higher driving current (e.g., 80 mA), provided a thermoelectric cooler employed to stabilize the MEMS laser operating at 25 °C. An example of optical spectrum in different output states is illustrated in Fig. 3. $\lambda_1$ (corresponding to mirror 1) is always locked at 1549.04 nm, while $\lambda_2$ (corresponding to mirror 2) is tuned from 1556.78 nm [Fig. 3(a)] to 1538.00 nm [Fig. 3(b)]. Correspondingly, it demonstrates the change of $\Delta\lambda$ of +7.74 and −11.04 nm. All the wavelength outputs ($\lambda_1$ and $\lambda_2$) are in single frequency modes. Such oscillation spectra of the dual-wavelength laser are measured at 25 °C.

Experimental result shows that the output of $\lambda_2$ is dependent on the rotation angle of mirror 2, as presented in Fig. 4. Initially (no rotation of mirror 2), $\lambda_2$ is at 1549.04 nm. When the rotation angle is increased by 1°, $\lambda_2$ almost drops to 1520.66 nm. On the other hand, the decrease of the rotation angle by 1° results in an increase of $\lambda_2$ to 1573.22 nm. It also shows that the tunable wavelength is almost linearly decreased with the increase of rotation angle. As a result, $\lambda_2$ has a maximum tuning range of more than 50 nm and the maximum spectral separation can be tuned from −28.38 to +24.18 nm. During the experiments, it is noticed that there is a slight line broadening as the spectral separation decreases, especially when the spectral separation goes below 2 nm. The reason could be the combining effects of inhomogeneous broadening and mode competition for the gain. As the two wavelengths are both the modes of the cavity, the effects mentioned above have shown strong impact when the two longitudinal modes are close to each other.

In summary, a compact tunable dual-wavelength laser has been developed using the MEMS technology. By the rotation of the mirror, the wavelength tuning range over
50 nm has been obtained, with the spectral separation changed from −28.38 to +24.18 nm. Benefited from the Littman configuration, this laser has a stable dual-wavelength output after the integration with MEMS components on a single silicon substrate. Meanwhile, by employing the MEMS technology, the dual-wavelength laser bears the advantages of batch fabrication, low power consumption, and low cost. Compared with other methods, this single-chip integrated solution is very appealing due to its attractive features, such as high compactness and wide tuning range.