A MEMS DIGITAL MIRROR FOR TUNABLE LASER WAVELENGTH SELECTION

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ABSTRACT
This paper presents a digital mirror for tunable laser wavelength selection using microelectromechanical systems (MEMS) technology. The digital mirror which has discrete reflection spectrum is totally different compared to the current broadband mirrors MEMS tunable lasers [1-3]. The reflection of the digital mirror can be tuned by digital pumping signals which promise fast output wavelength switching. The experimental results show that the output wavelength of the MEMS tunable laser using the digital mirror has high tuning resolution without increasing the physical length of the internal cavity of the tunable laser. The output wavelength of tuning resolution can reach 0.2 nm and the bandwidth is around 0.04 nm.

KEYWORDS
Photonic MEMS, Digital mirror, Tunable laser, Thermo-optical effect.

INTRODUCTION
MEMS tunable laser has promising potential in many applications, such as the coherent light source, biological detector within highly integrated chips and terahertz (THz) wave generators [4-5]. The resolution of wavelength tuning is an important criterion for tunable lasers. However, the wavelength resolution is limited by the internal cavity lengths of the typical tunable external cavity lasers which suffer from the mode hopping effect [6]. It is not a major problem for the bulk tunable lasers with large cavities. But the beam divergence becomes one of the main reasons for the cavity loss when the tunable laser is minimized to micrometer scale. For example, if the wavelength resolution is required to be 0.1 nm, the internal cavity has to be 3.5 mm which is more than ten times of the typical internal cavity length of the MEMS tunable laser thus increases the cavity loss by hundreds of times. Therefore, there are always trade-offs between the loss and the wavelength tuning resolutions. One solution for fine wavelength tuning is to tune the internal cavities together with the external cavities [7-9] which complicates the mechanical design and fabrication processes of the MEMS tunable lasers.

In this paper, a digital mirror is designed for the MEMS tunable laser. This is totally different compared to the traditional MEMS tunable lasers which are tuned by using movable mirrors [10]. The reflection spectrum of the designed digital mirror is tuned together with the internal cavity of the MEMS tunable laser. Therefore, the output wavelength of the MEMS tunable laser can be finely tuned without increasing the internal cavity length or introducing complex design to the mechanical part.

This paper is organized as follows. First, the design of the digital MEMS mirror with MEMS tunable lasers is described. Then, the theoretical results are analyzed. Finally, the experimental results and conclusions are presented.

DESIGN OF DIGITAL MIRROR
Figure 1 shows the schematic of the MEMS digital mirror tunable laser. The tunable laser consists of three parts: a single mode fiber with a facet coated with gold, a laser diode and a group of silicon slabs as a digital mirror. The laser diode works as the gain medium. The internal cavity of the MEMS tunable laser is formed by the coated fiber facet on the left side and the digital mirror on the right side. The digital mirror consists of ten silicon slabs. The working wavelength is smaller than the thickness of silicon slabs which work as resonant reflectors [11, 12]. Therefore the digital mirror processes two merits: Firstly, the digital mirror reflects discrete wavelengths which are further selected by the resonant conditions of the internal cavity of the MEMS tunable laser. Secondly, the reflected wavelength is more dependent on the refractive index (RI) of one silicon slab which makes it possible to tune the output wavelength of the MEMS tunable laser through the RI change of the silicon slab of the digital mirror.

Figure 1: The schematics of the MEMS coded laser.

Light reflected by the digital mirror is selected by the resonant modes of Fabry-Perot (F-P) cavity between the digital mirror and the coated fiber facet and thus achieving the single wavelength output through Vernier effect. The refractive index of each silicon slab is controlled by an electrical signal individually through thermo-optical effect. The change in the refractive index of any slab introduces a defect to the digital mirror and changes the output of the digital laser. When the refractive index of any silicon slab...
is changed, the resonant condition of the digital mirror is changed and the output wavelength of the MEMS tunable laser is tuned.

**NUMERICAL ANALYSE**

The effects on the digital mirror reflectivity of single silicon slab RI change are simulated by using Finite difference time domain (FDTD) method. The incident light is inputted form the left side to the right side as shown in Fig. 2. The width of the waveguide within the laser diode is 2 µm and the width of each silicon slab is 3 µm. In order to achieve the best coupling efficiency, air spacing between the laser diode and the digital mirror is optimized. The numbers of silicon slabs are sequenced from 1st to 10th.

The incident light wavelength (1571 nm) is chosen to have high transmission coefficient (> 99.5%) at initial state. The incident light is propagated through the digital mirror by the coupling of the adjacent F-P cavities that is formed by the silicon slabs as shown in Fig. 2 (a). The coefficient of silicon RI change at room temperature is approximately $1.74 \times 10^4$ per Kelvin. When the temperature of the 2nd silicon slab is increased by 60º approximately, the RI of the silicon slab is changed around 0.01. This is how the defects are introduced to the digital mirror through the thermo-optical effect. When the 2nd silicon slab breaks the coupling between the adjacent F-P cavities, the incident light is reflected back to the waveguide of the laser diode. The reflection coefficient is above 90% as shown in Fig. 2 (b). It is pointed out that the defect is located at different sequence of the silicon slab and the actual length of the internal cavity is also different.

![Figure 2: FDTD simulation results of the incident light at 1571 nm are coupled into the digital mirror when 2nd silicon slab is heated. (a) before and (b) after.](image)

Since the mechanism of the F-P cavities can support many modes within the gain region, one of the modes is selected in order to achieve single mode output. The digital mirror can choose a narrow band reflection region that is dependent on how to pick one lasing mode. The conditions are as follows. Firstly, the relatively higher reflection coefficient of the digital mirror ensures the interaction between the gain medium and simulated light. Secondly, the resonant conditions between the coated fiber facet and the digital mirror are satisfied. The transfer matrix method is applied to analyze the mode competition mechanism of the MEMS tunable laser.

The peak position of the reflection can be expressed as follow [13]:

$$R_{\text{max}} = \frac{[1-(1/n)^{2N}]/[1+(1/n)^{2N}]}{2}$$  \hspace{1cm} (1)
where $n$ is the refractive index of the silicon slabs and $N$ is the number of the silicon slabs. The reflection versus the incident light wavelength for the digital mirror is shown in Fig. 3 (a) by the dark line. The resonant modes of the F-P cavity between the digital mirror and the coded fiber facet are shown by the gray line. The overlap between the reflection peak and the resonant modes stands for the high resonant wavelength in the MEMS tunable laser as shown in Fig. 3 (b). As a result, the tunable laser has single mode output within the gain region through design of the digital mirror.

The F-P cavity length of the MEMS tunable laser is not the physical distance between the first silicon slab of the digital mirror and the coated fiber facet. As the distributed feedback digital mirror, the cavity length also depends on how the silicon slabs is penetrated by the incident light. In this way, the cavity length change depends on which silicon slab is heated in the digital mirror as shown in Fig. 2. The reflection spectrum is tuned along with the internal cavity length by introducing the defects to the digital mirror at different locations. It takes over the mode hopping effect of the MEMS tunable laser and achieves fine tuning resolution without further increasing the external cavity length.

**EXPERIMENTAL RESULTS**

The MEMS tunable laser is fabricated on a silicon-on-insulator wafer with the structure layer thickness of 75 µm. The width of each silicon slab is 3 µm. A laser diode with the scale of $250 \times 250$ µm$^2$ is coated with anti-reflection (AR) film to serve as the gain medium.

![SEM photograph of the MEMS coded laser.](image)

The output laser is coupled to a single mode fiber which is passively aligned to a laser diode by a fiber groove. The facet of the fiber is coated with gold as a broadband mirror. The MEMS tunable laser is tested using fiber end-fire alignment system. A micro-scope and a CCD camera are applied to monitor the alignment of the device setup. The nano-probes are used to pump the laser diode and heat up the silicon slabs. The laser diode is lasing under the pumping voltage of around 6.9 V. The laser output is monitored by an optical spectrum analyzer (OSA) when different silicon slab is heated up.

![Experimental results of the transmission spectrum after heating on each silicon slab. Output wavelength as the function of the slab index is shown.](image)

The output wavelength after heating different silicon slab of the digital mirror is shown in Fig. 5. The bandwidth of the output laser is around 0.04 nm that is narrower compared to the simulated results (in Fig. 3). This is because the mode competition further narrows down the bandwidth within the gain region. The MEMS tunable laser has five different modes within 1 nm region when heating the corresponding silicon slab. The wavelength tuning resolution is 0.2 nm approximately. The insert shows the output wavelength versus the sequence number of the silicon slab. Therefore, it is noted that the output wavelength of the MEMS tunable laser is dependent on the tuning of the digital mirror.

**CONCLUSIONS**

A digital mirror for MEMS tunable laser is designed, fabricated and experimented. The digital mirror provides wavelength selection for the MEMS tunable laser and the reflection spectrum of the digital mirror can be tuned along with the internal cavity length of the MEMS tunable laser through the change in the refractive index of the silicon slabs. Based on the experimental results, the wavelength tuning resolution is 0.2-nm which is ten times higher than the traditional MEMS external cavity tunable laser.
REFERENCES


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