CHARACTERISTICS OF MICROMACHINED INJECTION LOCKING LASERS

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ABSTRACT
This paper reports a theoretical and experimental study of a MEMS injection-locked laser (ILL). The micromachined injection-locked laser consists of a MEMS tunable laser (master) and a Fabry-Perot multimode laser (slave) that is integrated by using deep RIE processes onto a single chip. Based on the experimental results, hysteresis property in asymmetrical tuning curve is observed and optical bistability is found. Superior performances in terms of stability and narrow linewidth have been achieved.

KEYWORDS
Photonic MEMS; tunable lasers; injection locking laser; Deep RIE fabrication process.

INTRODUCTION
Injection locking is a technology of locking the oscillation state of a resonance cavity (called the slave) by injecting an external laser light (called the master). It has been extensively used to improve laser performance, such as reducing laser noise and optical spectral width, improving spectral purity of diode laser, etc. [1]. Current semiconductor laser diode has a low Q factor cavity with a broad passband and gain region, but its disadvantages are an insufficient frequency stability and large spectral linewidth. The theoretical and experimental injection locking properties of the semiconductor lasers have been reported [2-4]. The active actions of the injection locking to the semiconductor lasers can be roughly categorized into two ways: one is to improve the characteristics of the slave; and the other is to synchronize the master and the slave. In the former, the locking is able to improve the properties of the slave laser in terms of spatial, spectral and time domains, making it indispensable for many applications. For instance, the high power lasers are commonly multiple longitudinal modes and have wide diverging angle. After being locked by a low-power single-mode master laser, the high power slave lasers are able to achieve even higher power output, single wavelength emission, high side-mode-suppression ratio (SMSR), narrow linewidth and diffraction-limited beam quality [5]. Additionally, it can significantly reduce the frequency chirp under modulation and improve the laser intrinsic frequency response. In the latter, the synchronization of the master and slave in wavelength, phase and chaos state has led the injection locking into broad applications in the coherent communications [6]. However, the conventional injection-locked lasers (ILLs) are bulky and require complicated driving and adjusting mechanism. A simple way of forming the injection-locked laser might be through the microelectromechanical systems (MEMS) technology [7-8]. Previous studies have shown the physical properties of the injection locking, including optical spectrum change, locking depth and drifting of peak wavelength in the steady state.

In this paper, the theoretical analysis and experimental results of bistability and hysteresis of the MEMS ILLs are presented. It is shown that the hysteretic behavior of the MEMS ILLs could be demonstrated by changing wavelength detuning while leaving injection current constant.

THEORETICAL ANALYSIS
Injection locking is a complex competition of an amplified spontaneous emission and an amplified master laser signal, and the beating of these two fields. The configuration of the MEMS ILL is shown in Fig. 1 where the master laser provides an external locking source for the slave laser. In this paper, the master laser is a MEMS tunable external-cavity laser [9-10], and its wavelength is tuned by using MEMS movable curved mirror.

Figure. 1: Sketch of the MEMS injection-locked laser.

Assuming the two facets of the slave have the same reflectivity (r = r1 = r2) as R. Taking into account the refractive index dependence on the injected carrier density, the relationship between the input and output optical power of the slave laser can be expressed as [11]:

\[ P_{out} = \frac{P_{in} \eta T^2 G}{(1 - RG)^2 + 4RG \sin^2 \phi} \]  

(1a)

\[ G = \exp[(\Gamma g - \alpha)/t] \]  

(1b)

\[ g = g_0/[1 + (P_{out}/P_1)] \]  

(1c)
where $T (= 1 - R)$ is the transmittance, $\eta$ is light coupling efficiency into the slave laser, and $\phi$ stands for the single path phase change across the slave chip. $g$ is saturated gain coefficient and $g_0$ denotes the small-signal gain coefficient. $P_{\text{in}}$ and $P_{\text{out}}$ is the input and output power, respectively. $P_s$ represents the saturation output power of the slave. $\alpha$ is the scattering loss inside the cavity, and $I$ is the optical confinement factor.

Figure 2: Calculated output power of the FP laser chip versus injected power for different mistuning ($\phi_0$).

Based on Eq.(1), Fig. 2 illustrates normalized output power against injected power for different detuning parameters $\phi$, which corresponds to the wavelength difference ($\lambda_{\text{in, ILL}} - \lambda_{\text{0, ILL}}$) between the injection and the slave supported lasing mode. It is shown that the operating properties are strongly dependent on the wavelength detuning. Especially, when there is no detuning (e.g. $\phi = 2m\pi$, $m$ is an integer), the injected slave system operates in power limit for the input range (i.e. curve “a”), and without bistability. However, when the wavelength detuning is introduced, then the system is in a state of bistable. Therefore, the output power is a multi-valued function of wavelength detuning.

Figure 2 shows a general type of bistable input-output hysteresis behavior. Take for instance the curve “b”. When the injection level is low, the output power of the slave only raises slowly with the increase in the injection power. Once the injection power level reaches the first turning point, the slave is fully locked, the output power jumps abruptly upward to an upper branch. Even when the injection power is reduced, the output power moves down, but continues to stay in the upper branch keeping the locking state. When the slave is below the locking state, the output power falls down abruptly below a lower branch, and then the hysteresis between the input and output is shown in Fig. 2. It is noticed that the portion of the input-output curved between the two discontinuities, marked by the dashed line, correspond to an unstable state of the output. The experimental results of the input-output hysterisis behavior are discussed in the next section.

FIGURE 3: Calculated output power versus wavelength detuning for different injection power.

Similar to the influence of the injection power on the output of the locked modes, the output is certainly related to the wavelength detuning. Fig. 3 shows the relationship between the stable output power and the wavelength detuning ($\Delta \lambda = \lambda_{\text{in, ILL}} - \lambda_{\text{0, ILL}}$) at various injection powers ($\eta P_{\text{in}}$). It can be seen that the detuning curve becomes asymmetrical with respect to $\lambda_{\text{in, ILL}} = \lambda_{\text{0, ILL}}$. Therefore, the maximum output is obtained for any injection power strength at a positive wavelength detuning. It predicts a red shift property of the injection locked laser system. When the driving current is fixed, the higher the injection power, the wider the wavelength detuning range (loop bandwidth). Therefore, the limitation of the detuning wavelength is determined by the locking condition. As a result, when the injection power is stronger, the absolute value increases.

**DESIGN AND FABRICATION**

Based on the theoretical study of the injection-locked laser chip, the MEMS ILL device is designed and fabricated using SOI wafers and DRIE process [12-13]. The Si structure layer has a thickness of 75 $\mu$m. The structure layer is deeply etched to form trenches using DRIE. An aluminum evaporation coating process with the shadow mask is used for the bonding pads, electrical routing and mirror reflection surfaces deposition etc. After that, the single mode optical fibers are aligned into the fiber grooves on the dies and glued by the UV-curable epoxy.

The scanning electron micrograph (SEM) of the integrated MEMS injection-locked laser is shown in Fig. 4. The MEMS external-cavity tunable laser is used as the master laser to provide the external optical locking light source for the slave laser. The injection-locked MEMS laser has a dimension of 3 mm × 2 mm × 0.8 mm. The wavelength tuning is obtained by the movable mirror through the control of the MEMS comb-drive actuator.
Based on the experimental results of the master laser, the tuning range from 1540 to 1570 nm with a resolution of 0.01 nm is measured. Additionally, the master laser provides certain wavelength for optical injection and also controls the injection power to the slave. The output power is -2 dBm when the slave laser is driven by a DC current at 14 mA.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The hysteresis of the locking states is shown in Fig. 5. For certain given optical injection power, the higher the slave laser is biased driven, the narrower its stable detuning range is (e.g. shadow region a→b→f→e). In Fig. 5, the stable detuning range is 0.124 nm and 0.026 nm, corresponding to the driving current of 8 mA and 15 mA, respectively. Meanwhile, it is noticed that higher driving current (bias current) is needed in order to increase the bistable loop bandwidth for the given injection power. For example, \(\Delta \lambda_{d=8mA}\) is 0.011 nm and \(\Delta \lambda_{d=15mA}\) is 0.014 nm, corresponding to the driving current of 8 mA and 15 mA, respectively.

Fig. 6 shows the output spectra of the slave FP laser at different operation states. It can be seen that in the free-running state, the slave has a multimode output as shown in Fig. 6a (\(\lambda_0 = 1552.94\) nm). After subjected to a certain external injection, the slave is a single-mode output (\(\lambda_0' = 1553.10\) nm) with a SMSR of 32 dB that is the full-locked state as shown in Fig. 6b. The simulation results have predicted a red shift, and the measured final locked output wavelength is red shifted by 0.16 nm comparison with the free-rung FP resonance mode as shown in Fig. 6c. It is also observed that the total output power in the full-locked state is increased by 10% and the linewidth is reduced by 0.05 nm.

Figure. 4: Scanning electron micrograph of the integrated MEMS injection-locked tunable laser.

Figure. 5: Measurement results of the hysteresis cycle of the wavelength detuning at various driving currents. The detuning range (\(\Delta \lambda\)): (a) \(\Delta \lambda = 0.124\) nm when \(I_d = 8\) mA, (b) \(\Delta \lambda = 0.026\) nm when \(I_d = 15\) mA.

Figure. 6: Output spectra in different states. (a) Multi-mode output of the slave in the absence of the external injection, (b) single-mode output of the slave at the fully-locked state, and (c) red-shift in the injection-locked laser.
CONCLUSIONS

In conclusion, a MEMS injection-locked tunable laser is designed, fabricated and experimented in this paper. Hysteresis of wavelength detuning and linewidth reduction have been observed by varying the wavelength of a master laser. A larger injection power can increase bistable loop bandwidth. The stabilized wavelength output reaches SMSR of 32 dB. The MEMS injection-locked laser is not only small in size with low power consummation and low cost, but also improves reliability and stability significantly with strong potential in optical networks applications.

REFERENCES
