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High speed micromechanically tunable Surface Emitting Laser with Si-MEMS technology

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We have developed a novel high-speed micromechanically tunable surface emitting laser with Si-MEMS technology. This laser consists of a half VCSEL (Vertical Cavity Surface Emitting Laser) chip without a one-side dielectric mirror and a micromachined SOI (Silicon on Insulator) substrate with a concave mirror. These two chips are bonded together using a high-accuracy metal thermo compression bonding method. High-speed, wide-wavelength tuning is achieved by applying a variable voltage between the silicon membrane with the mirror and the silicon substrate. In the prototype, we have achieved high-performance wavelength modulation over 500 kHz, a wide tuning range of 55 nm without any mode-hop, and a side mode suppression ratio of over 60 dB. This is a world-class product in its field.

INTRODUCTION

To address recent issues concerning social safety, security and environmental problems, there is a growing need for fiber optic sensors in the field of optical measurement for detecting intrusion or structural distortion, and also for real-time and ultra-sensitive flue gas sensors for detecting poisonous gases or high-temperature combustion gases. As the optical source of these real-time sensors, a wavelength-tunable optical source is required which has features such as a wide tunable wavelength range, high speed sweep, phase continuous sweep, compact size and low price. We have developed a micromechanically tunable surface emitting laser which meets these requirements, as described in this paper.

BASIC STRUCTURE AND OPERATING PRINCIPLE

Generally, there are two types of semiconductor laser structure: a transverse edge emitting laser with the structure of a lateral optical cavity resonator, and a vertical cavity surface emitting laser (VCSEL) with that of a longitudinal optical cavity resonator, as shown in (1) and (2) in Figure 1 respectively. The characteristics of those semiconductor lasers are compared in Table 1.

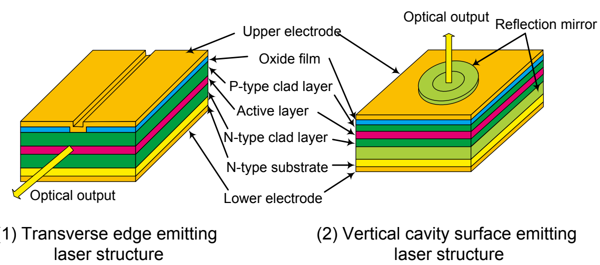

Figure 1 Comparison of semiconductor laser structures

Table 1 Comparison of semiconductor laser characteristics

Item	Edge emitting laser	Surface emitting laser
Lasing threshold	High	Low
Optical output power	High	Low
Optical cavity resonator length	Long	Short
Longitudinal mode	Multi mode	Single mode

The key difference between them is the length of the active layer of the cavity resonator that amplifies light. While the edge emitting laser allows a length of several hundred micrometers, a thousand times the wavelength, the surface emitting laser allows a length of only several micrometers, equal to the thickness of the active layer, which is around

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ten times the wavelength. The longitudinal mode interval in a cavity (under oscillation) is inversely proportional to the length of the cavity. Therefore, whereas there are more than 100 longitudinal modes within the gain bandwidth of the semiconductor with the edge emitting laser, only one longitudinal mode exists with the surface emitting laser. To obtain single-mode oscillation, which is important for the source of optical measurement, the edge emitting laser requires the structure of a distributed feedback (DFB) laser or a distributed Bragg reflector (DBR) laser in which diffraction gratings are integrated so that one mode can be selected from among many. By contrast, the surface emitting laser does not require such mode selection and generates single-mode oscillation with a simple structure. Furthermore, by making the mirror on one side of the laser movable, phase continuous wavelength sweep can be achieved merely by controlling the mirror position.

Although the surface emitting laser has the disadvantages that the cavity resonator is small and optical power output is low, it has advantages such as an extremely low lasing threshold and low power consumption, which makes it preferable as the wavelength tunable optical source for measurement applications. Thus, we chose the surface emitting laser. As for the movable mirror structure, we adopted a Si-MEMS structure which can oscillate with a high resonance frequency and has been used in actual sensors.

Figure 2 is a conceptual drawing of a prototype of the wavelength tunable emitting laser. It consists of a half VCSEL chip without a one-side dielectric mirror shown in the upper part and a movable mirror chip utilizing a silicon on insulator (SOI) substrate shown in the lower part.

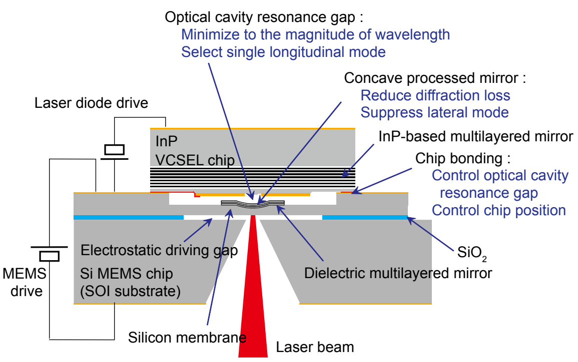


Figure 2 Conceptual drawing of the wavelength tunable emitting laser

The movable mirror is a thin-membrane structure on which a concave shaped dielectric multi-layer membrane is formed to avoid diffraction loss. When a voltage is applied between the membrane and the lower part of the SOI substrate, the membrane is drawn towards the substrate by the electrostatic force generated. As a result, the distance between the reflection mirror composed of semiconductor within the half-VCSEL chip and the dielectric mirror composed of the multi-layer membrane becomes wider, causing the lasing wavelength to become long.

KEY TECHNOLOGIES AND FABRICATING PROCESS

In order to fabricate a tunable laser as shown in Figure 2, we have developed new key technologies, a concave forming technology and a bonding process. The fabricating processes including the new key technologies are as follows.

Concave forming technology

There are four requirements for creating a concave laser mirror on the silicon membrane: a) Semiconductor processes can be used for the microfabrication, b) The concave shape is highly repeatable, c) The target curvature can be achieved, and d) The roughness of the mirror surface is small.

Concave forming methods using semiconductor processes include wet or dry etching and a method for forming a concave shape by warpage using the internal stress of the material. However, we have developed a technology which forms a concave shape by using the conventional wafer polishing method usually used for silicon flattening. [1]

Figure 3 is a conceptual drawing of our new method. First, a silicon oxide film or nitride film is formed on the silicon substrate as a mask. Then the part of the film where a concave shape is to be formed is removed, and chemical mechanical polishing (CMP) is performed. The method is relatively simple. Because a conventional silicon polishing method is used, the roughness of the mirror surface is equivalent to that of a silicon substrate.

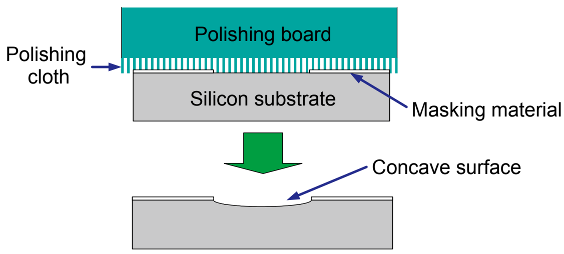


Figure 3 Conceptual drawing of concave polishing

Figure 4 shows the created concave shape imaged by a scanning electron microscope (SEM), revealing a good concave shape. The radius of curvature of the concave surface depends on the polishing area, polishing time, masking materials and others.

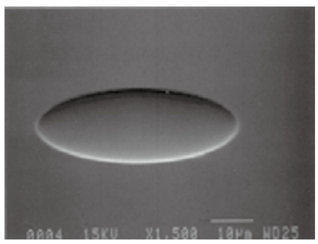


Figure 4 Picture of concave polishing by SEM

Fabricating processes

Figure 5 illustrates the fabricating processes. The procedure is as follows.

1) Prepare a SOI substrate. The thicknesses of the active layer and the oxide film constituting the sacrificial layer determine the driving voltage, driving range and resonance frequency of the membrane.
2) Form a concave shape by selective CMP with the silicon nitride film pattern as a mask.
3) Create a spacer structure of silicon that decides the length of the cavity resonator. Scrape off the back side of the silicon substrate by anisotropy etching.
4) Remove the oxide film by sacrificial etching using hydrofluoric acid and create a silicon membrane.
5) Form a dielectric mirror on top of the concave part and a contact hole for extraction electrodes of the substrate.
6) Create an electrode for bonding and an extraction electrode.
7) Bond a half VCSEL chip [2] by metal thermocompression bonding.

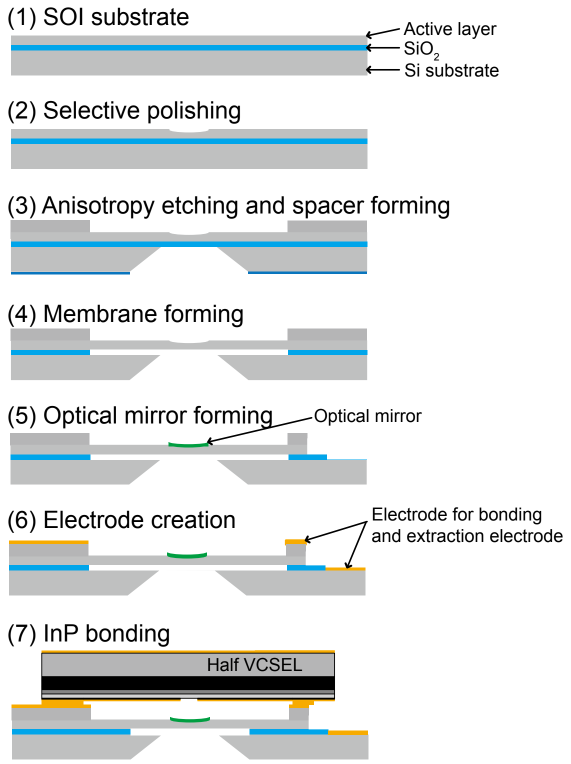


Figure 5 Fabricating processes

EVALUATION OF THE PROTOTYPE MODULE

We prototyped a module where the fabricated tunable laser chip is mounted in a can package and is connected with a single mode fiber, and evaluated its optical characteristics and wavelength sweep frequency response characteristic. Figure 6 shows the module.

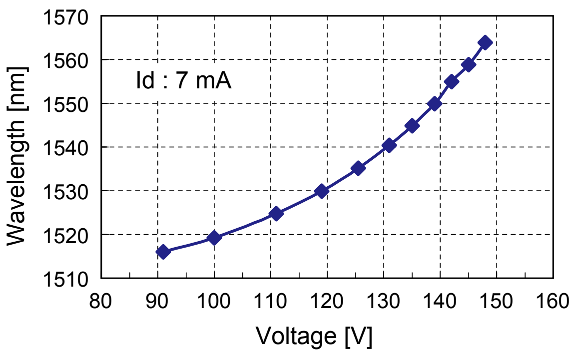
Evaluation of laser output characteristics

Figure 7 presents the wavelength tunable characteristics of the tunable laser module. Lasing spectra were measured using an optical spectrum analyzer. It was observed that as the voltage between the silicon membrane and the silicon substrate was increased from 91 V to 151 V, the lasing wavelength changed from 1515 nm to 1570 nm. The tunable wavelength range is 55 nm, sufficient to cover the C band in optical communications.

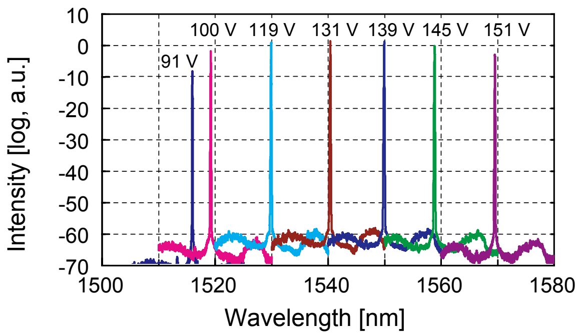
Figure 8 shows the optical output spectrum at the lasing wavelength of 1550 nm. The spectrum distribution reveals that the side mode suppression ratio is 60 dB or more, and a favorable single-mode resonance was achieved.

Figure 9 shows the relationship between laser-diode driving current and optical output power at the wavelength of 1550 nm. The maximum power of 2.7 mW was acquired at the driving current of 13 mA.

Figure 6 Prototype module connected with optical fiber



(a) Applied voltage and optical output wavelength



(b) Applied voltage and optical output spectrum

Figure 7 Wavelength tunable characteristics

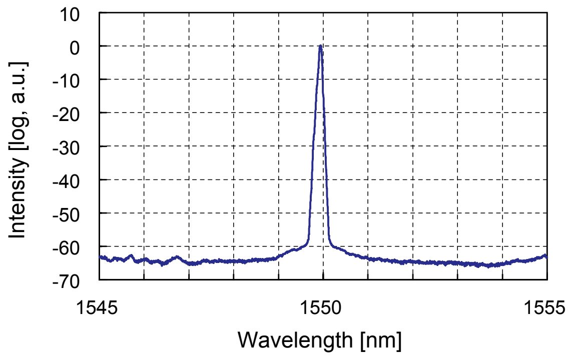


Figure 8 Optical output spectrum

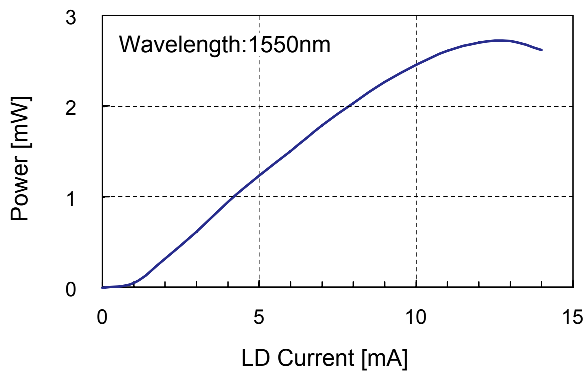


Figure 9 Relationship between laser-diode driving current and optical output power

Evaluation of wavelength sweep response characteristics

In order to evaluate the responsiveness during the wavelength sweep, we measured the change of the oscillating wavelength of the tunable laser by applying sinusoidal wave modulation signals to the MEMS structure. The oscillating wavelength was measured using a system that was capable of high-speed, high-accuracy measurement of Lissajous signals by interferometry. [3] The voltage amplitude of the applied signal was 20 mV, which is equivalent to an oscillating wavelength fluctuation of 40 pm. This magnitude is due to the limitation of the measuring system.

Figure 10 shows the change of amplitude of the optical output when signals are applied and the modulation frequency is changed from 100 Hz to 800 kHz. When the frequency is low, lowering of the amplitude and phase lead are observed. This is because the coupling condenser and the decoupling resistance, through which the modulation signal is applied to the MEMS structure, act as a high-pass filter (fc = 300 Hz). The peak due to resonance is seen at around 350 kHz. This value corresponds with the design value of resonance frequency as well as the experimental value by mechanically generated vibration. As the frequency increases, the amplitude eventually drops. This is because of the so-called squeezed film effect, where a surrounding air layer acts as damping media when a diaphragm structure is operating at high speed.

By the measurement described above, a high-speed and mode-hop-free tunable laser with response frequency exceeding 500 kHz was confirmed. [4]

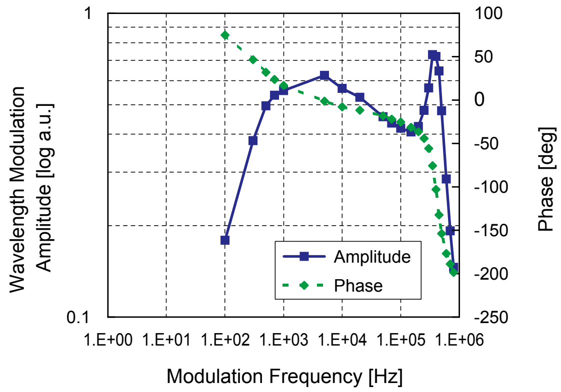


Figure 10 Frequency response of the tunable laser

CONCLUSION

We have developed a novel wavelength tunable surface emitting laser utilizing micromachine technology. It is configured such that the MEMS structure with a movable concave mirror and half VCSEL are accurately integrated. With the prototype module developed based on this concept, we attained features such as high speed and wide range of tunable wavelength, mode hop free and good single-mode oscillation. These are world-class performances among VCSEL structure lasers. We will continue to improve the performance and reliability as well as develop new laser sensing technology utilizing these novel features.

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