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Micromechanical tunable vertical-cavity surface-emitting lasers*

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We report the study on a short wavelength-tunable vertical-cavity surface-emitting laser utilizing a monolithically integrated bridge tuning microelectromechanical system. A deformable-bridge top mirror suspended above an active region is utilized. Applied bridge-substrate bias produces an electrostatic force which reduces the spacing of air-gap and tunes the resonant wavelength toward a shorter wavelength (blue-shift). Good laser characteristics are obtained: such as continuous tuning ranges over 11 nm near 940 nm for 0–9 V tuning bias, the peak output power near 1 mW and the full-width-half-maximum limited to approximately 3.2–6.8 nm. A detailed simulation of the micromechanical and optical characteristics of these devices is performed, and the ratio of bridge displacement to wavelength shift has been found to be 3:1.

Keywords: microelectromechanical devices, vertical-cavity surface-emitting lasers, tunable bridge, electrostatic tuning
PACC: 4255P, 4280K, 6480G

1. Introduction

Microelectromechanical system (MEMS)-based tunable vertical-cavity surface-emitting laser (VCSEL) has been developed in various designs.[1−3] Due to the unique structure of VCSELs, they have several attractive characteristics that differ from other types of tunable lasers, such as wafer level testing capability, intrinsic single longitudinal mode, low threshold current and low power consumption.[4] Especially, the tunable VCSELs can perform one-dimensional (1D) and two-dimensional (2D) integrations which are highly desirable for wavelength division multiplexing (WDM) applications, local-area networks, long-distance optical fibre communication, optical interconnection, a number of optical spectroscopy, and sensor applications.[5,6] In addition, tunable VCSEL shows the characters that its wavelength tuning is continuous and can be controlled simply by a voltage applied to the MEMS and easy to operate.[7] The ability to tune the lasing frequency also relaxes fabrication tolerance and allows a longer repeater spacing in optical fibre communication.

In this paper, a top-emitting micromechanical VCSEL with a tuning range of 11 nm near 940 nm for 0–9 V tuning bias is demonstrated. This was achieved by utilizing a deformable-bridge suspended above an active region. The peak continuous-wave (CW) power is 1 mW at room temperature without heat sink, the aperture diameter is approximately 22 μm, and the typical result for threshold current is 4.8 mA. In the numerical simulations, we have developed the deformable-bridge model incorporating the displacement, voltage, and wavelength. The potential performances of the tunable VCSELs are investigated. A brief description of the device's principle of operation is followed by measurement results as follows.

2. Design of device structure

The schematic of the device is shown in Fig.1. The bridge is tuned by applying a reverse-biased voltage between the top and middle contacts. Electro-

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static attraction deflects the top mirror toward the substrate, causing the Fabry–Perot mode to shift to shorter wavelengths. The active region is pumped by forward-biased p-n junction between the middle contact and the substrate. An oxidized $Al_{0.98}Ga_{0.02}As$ layer is used for efficient current confinement which has been reported in Refs.[8] and [9].

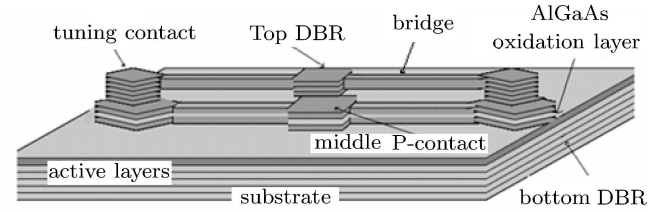


Fig.1. Schematic of the micromechanical tunable VCSEL showing 3D view. In the figure, note that the oxidized layer confines the current and the light underneath the tuning top DBR.

The layers were grown by means of metal-organic chemical vapour deposition (MOCVD) system. Firstly, the n-doped bottom mirror was grown consisting of 22 graded $Al_{0.9}Ga_{0.1}As$–GaAs mirror pairs on n-GaAs substrate. The active region was a one λ-spacer sandwiching three 8 nm $In_{0.2}Ga_{0.8}As$ quantum wells (QWs) which were separated by 10 nm GaAs barriers. Then the p-layers were grown starting with the $Al_{0.98}Ga_{0.02}As$ oxidation layer, followed by two $Al_{0.9}Ga_{0.1}As$–GaAs mirror pairs. The P^+–GaAs ohmic contact layer was also used for etch-stop layer. Next the undoped $Al_{0.9}Ga_{0.1}As$ sacrificial layer was grown which was designed to be of 1.5 μm thick. The top n-DBR (distributed Bragg reflector) layers were grown, consisting of 19 $Al_{0.9}Ga_{0.1}As$–GaAs mirror pairs. This was followed by an $Al_{0.9}Ga_{0.1}As$–GaAs sacrificial layer. This last layer was included so that it could be selectively etched away, leaving a smooth interface for top emission.[10]

The main fabrication processes of tunable VCSEL devices were carried out as follows. Firstly, epitaxial wafer was wet etched into a large square (see Middle P-Contact of Fig.1). At the same time, the $Al_{0.98}Ga_{0.02}As$ oxidation layer was exposed. Secondly, an anisotropic inductively coupled plasma (ICP) etching was then used to form the bridge using a mucus mask.[11] Placing the tuning square in the centre of the large square ensures that the oxidized aperture was underneath the tuning square. Finally, an isotropic selective wet etch was used to release the bridge from the substrate. The three contacts were automatically isolated by the undercut of the $Al_{0.9}Ga_{0.1}As$ sacrificial layer and after that we obtained an air gap of 1.5μm.

3. Experiments and performance

The maximum reflection and bandwidth of DBR are important characters of tunable VCSEL.[12] Using the transmission matrix equation in Ref.[13], we have the typical calculated reflectivity spectra of the tunable VCSEL as shown in Fig.2. The dotted curve is obtained before etching the sacrificial layer. When the sacrificial layer is etched and replaced by an air-gap, we obtain the solid curve. Comparing these two lines, we can see that there are two dips near the wavelengths of 988 and 946 nm in the dotted curve, but only one dip in the solid curve at the wavelength of 980 nm as can be seen. This is accordant to the different refractive indices of the sacrificial layers. Both the wide pass-bands of them are 120 nm. We can conclude that there will be one resonance wavelength when the bridge is released. But which of the two dips will become resonance and lasing, is determined by the range of gain spectrum of the active region and the pass-band width of reflectivity.[14]

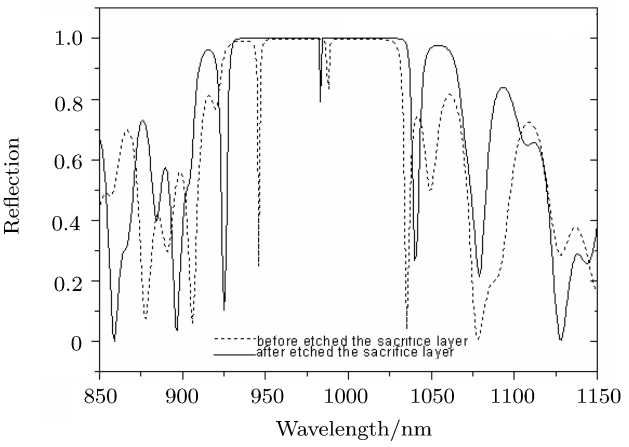


Fig.2. Typical reflective spectra of tunable VCSEL curve showing simulated result.

The devices are biased for continuous-wave (CW) operation at room temperature on wafer, and light is collected through the transparent top DBR. The power output and voltage versus current are shown in Fig.3. The aperture diameter is 22 μm and the single-mode output power is near 1 mW. The threshold current is 4.8 mA and the differential quantum efficiency is 1.2%. The threshold voltage of the laser is

approximately 2.0 V. Threshold current and quantum efficiency are worse compared to our previous results of VCSEL.[15] This is because the sacrificial layer is replaced by an air-gap, the thickness of which is changed by the bend of the bridge. In addition, the absorption of the etched surface also affects the light output power.

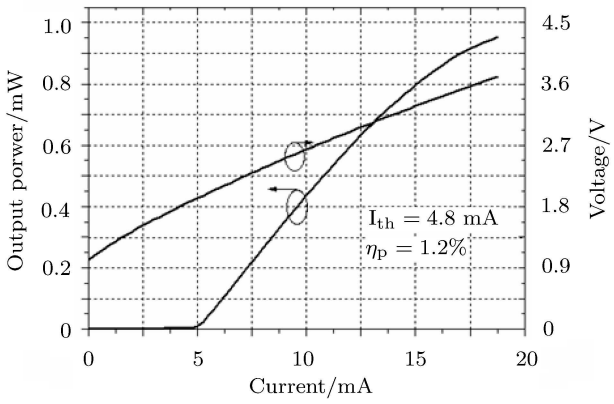


Fig.3. Output power and diode voltage vs. diode current at 0 V tuning bias.

The output spectrum at different values of tuning voltage is shown in Fig.4 in three dimensions with the injection current being 20 mA. The lasing wavelength shifts from 942 nm at 0 V tuning bias to 931 nm at 9 V continuously. The full width at half maximum (FWHM) is in the range of 3.2 to 6.8 nm, which agrees fairly well with the FWHM for an idealized RCE/VCSEL device.[16] The centre of the tuning range is near 940 nm, which is different from the desired wavelength of 980 nm since there is an error in the spacing of air-gap.

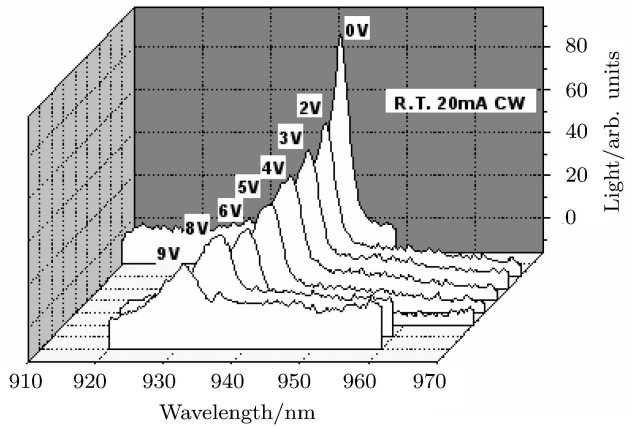


Fig.4. Tuning spectra for a device oxidized to an aperture of approximately 22 μm. At a constant injection current 20 mA.

Following the reduction of the wavelength (blueshift), the gain of cavity mode decreases, which results in the decrease of the output power as shown in Fig.4. We believe that a large tuning range will be obtained through improving the semiconductor coupled-cavity and quantum wells design.

The tuning range of the VCSEL is governed by the deflection of the bridge. A simple analytic approximation is given by[4]

$$z = \frac{\pi r^3 \varepsilon}{E} \times \frac{2l^3}{wt^3} \times \frac{V^2}{(d-z)^2}, \qquad (1)$$

where z is the vertical displacement of the bridge, ε is the dielectric constant of the air, d is the spacing of the air-gap without applied voltage, V is the applied voltage, E is the Young's modulus of the bridge, r, l, w, and t are radius, length, width, and thickness of the bridge, respectively.

The lasing wavelength as a function of voltage is calculated by using Eq.(1). According to the measurement of the tuning spectrum, the vertical displacement of the bridge can be calculated, as shown in Fig.5. The monotonically varied and well-behaved tuning curve attests that a very simple wavelength locking mechanism can be sufficient to insure wavelength accuracy during tuning. As shown in Fig.5, the vertical maximum-range of bridge displacement is approximately 36 nm and the average ratio of mirror displacement to wavelength shift is 3:1. Given that the bridge has a linear mechanical response to external forces, our estimate of the spring constant of the bridge is 6.51 N/m and the bridge resonance frequency is predicted between 0.19 and 0.478 MHz by calculation.

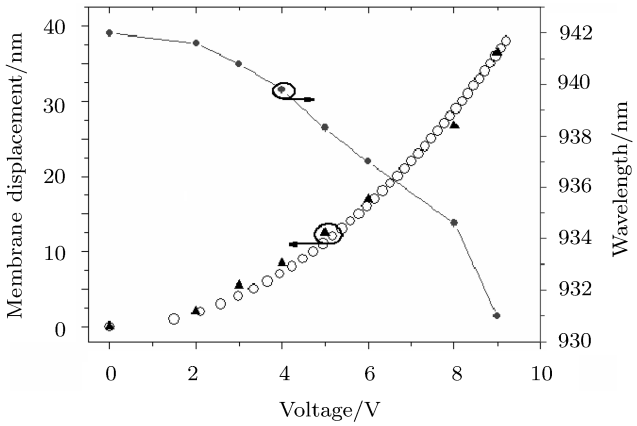


Fig.5. Lasing wavelength and membrane vertical displacement versus tuning voltage for spectra from Fig.4.

4. Conclusions

A short wavelength VCSEL has been studied. The continuous tuning range of the device is more than 11 nm near 940 nm for 0–9 V tuning bias. The devices utilize a deformable-bridge top mirror suspended above an active region, which enables a lower tuning voltage. The characters of tunable VCSELs are also discussed, the single-mode output power is near 1 mW with a threshold current of 4.8 mA, the differential quantum efficiency is 1.2%, and the threshold voltage of the laser is 2.0 V. We could obtain a wider tuning range by improving the micromechanical and optical characteristics of the tunable VCSELs for optical communication applications

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