Novel Subwavelength Grating Surface Emitting Laser
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Abstract: We present a new class of surface emitting lasers utilizing a single-layer high-index-contrast subwavelength grating, instead of conventional DBR. Single polarization mode emission with low threshold current and 1mW output power was obtained at 850nm wavelength.

The realization of VCSELs has been significantly limited by the choice of material available for making highly reflective distributed Bragg reflectors (DBRs). This remains to be one major bottleneck for blue-green and mid-wavelength infrared (MWIR) regimes. Furthermore, it is challenging to make wavelength-tunable VCSELs, where the requirements on mirror bandwidth and reflectivity are stringent [1]. Recently, we reported the experimental demonstration of a novel mirror design using a high-contrast subwavelength grating (HC-SWG), which exhibited with a very broad 1.3-1.8µm (∆λ/λ>30%) reflection spectrum with high reflectivity (R>99%) [2]. The SWG consists of only ONE single layer 1D grating structure formed by periodic stripes of high and low index materials (e.g. Si and air) that is sandwiched in-between two low index cladding layers (e.g. SiO₂ or air) on the top and below. The simplicity of the design and versatility to adapt to various wavelengths make HC-SWG an excellent reflector candidate to integrate with various optoelectronic devices. However, it was uncertain whether the HC-SWG can yield high enough reflectivity and substantially large angular tolerance required for a VCSEL. Here, we demonstrate a novel surface emitting laser using integrated HC-SWG as the top mirror of VCSEL, rather than conventional DBR, for the first time.

Fig. 1 shows the device structure consisting of an active region with GaAs quantum wells in-between a SWG-based top mirror and 34 pairs of bottom DBR. The top mirror of the VCSEL comprises 4 pairs of DBR layers and a highly reflective SWG to provide optical feedback, where the gratings (periodic stripes of AlGaAs and air) are freely suspended, with air as the low index cladding layers on the top and bottom. Since the SWG design contains 1D symmetry, it is polarization sensitive – TM light polarized perpendicular to the grating lines sees higher reflectivity than the TE light. The calculated reflectivity for the TM polarized light is >99.9% for 0.83-0.88µm wavelength ranges while that for TE polarized light is merely 95%, hence making the SWG an excellent candidate for 850nm VCSEL with excellent polarization control.

The SWG was defined on VCSEL mesas using electron-beam lithography on PMMA resist, which was then etched by reactive ion etching. A wet chemical based selective etching was required to remove the sacrificial material underneath the SWG and form the suspending grating structure. Fig. 2 shows the SEM image of the fabricated SWG integrated VCSEL and the inset shows the freely suspended SWG structure after the selective etching. A novel C-shape trench surrounding the grating was used to eliminate buckling of the suspended gratings after the release process, which arises from the residual stress in the material accumulated during material growth.

With the SWG integrated as the top mirror, continuous wave (CW) operation of SWG-VCSEL was demonstrated for the first time at room temperature. Fig. 3 plots the SWG-VCSEL device characteristics for output power versus the input current (LI) and voltage versus input current (IV). The device exhibits low lasing threshold current <0.5mA and excellent output power ~1mW. The low threshold current is a directly illustration of the extremely high reflectivity of SWG exceeding 99.5%. Fig. 4 shows the emission spectra of the SWG-VCSEL at various injected current. The SWG-VCSEL emission shows side-mode suppression ratio ~45dB, which can be accounted by area-dependent of reflectivity of SWG that suppresses higher-order transverse modes. Due to the thermal heating effects mentioned above, current generation SWG-VCSEL exhibits a large wavelength dependence on its current (~1nm/mA) than typical VCSEL (~0.4nm/mA). This can be elevated with proper VCSEL design.

Fig.5 shows the measured emission spectral power of SWG-VCSEL at different injected current for both the TM and TE polarization. Not only does SWG provide high reflectivity, it controls the polarization of the emission (lithographically determined) with polarization suppression ratio (OSPR) of 15dB. This intrinsic polarization selectivity nature can be utilized to control the polarization of VCSEL and hence minimize the polarization-dependent noises of the output VCSEL light.

As a comparison, the emission spectrum for the VCSEL with SWG of grating duty cycle (DC) of 0 and 1 are also shown in Fig. 6. DC=0 corresponds to no SWG layer and DC=1 means a single layer of AlGaAs is used to provide extra reflectivity. The emission for those devices are strongly dominated by spontaneous emission from the active region, indicating that merely 4 pairs of fixed p-DBR (DC=0) or a single uniform high-index layer cannot
provide sufficient reflectivity for lasing. These results further verify the high reflectivity of our fabricated HC-SWG required for lasing operation.


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Fig. 1 – Schematic cross-section of the SWG integrated VCSEL

Fig. 2 – SEM of fabricated SWG integrated VCSEL.

Fig. 3 – Measured LI and IV characteristics.

Fig. 4 – Emission spectrum under various current bias.

Fig. 5 – Polarization selectivity between TM and TE.

Fig. 6 – Measured emission spectrum for control devices with no SWG (DC=0) or one solitary single AlGaAs layer (DC=1).
NEMS Tunable VCSEL
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Abstract: We present a novel electrostatic actuated nano-electromechanical (NEMS) tunable surface emitting lasers utilizing a movable single-layer large-index-contrast subwavelength grating. Single mode emission and continuous tuning were obtained at room temperature under CW operation.

Tunable VCSEL has been extensively studied [1] for various applications including signal routing and switching in optical networks, biomolecular or chemical sensing and spectroscopy, and optical excitation of rubidium in an atomic clock system. MEMS tunable structures are desirable because they provide for a large and continuous tuning range. However, the distributed Bragg reflector (DBR) thickness of 3-10µm imposes a significant design trade-off on the tuning speed, range, voltage, as well as fabrication difficulties [1]. Recently, we proposed a new class of high-reflectivity mirror using a single-layer (thickness ~0.25µm) high-index-contrast subwavelength grating (HC-SWG) instead of conventional DBR [2]. The design consists of only ONE single layer of grating structure of high refractive index material entirely surrounded by low index material (e.g. air). Using this design, a VCSEL can be fabricated with a top mirror having <10% DBR thickness [3].

Here, we present a novel electrostatic actuated nano-electromechanical structured (NEMS) tunable surface emitting laser using a movable HC-SWG, for the first time. The NEMS mirror is both 10 times thinner and shorter, and is 5% the mass of a regular DBR MEMS. This results in a similar k value (Hook’s constant) with a much smaller mass, resulting in a similar tuning voltage but a much faster tuning speed, estimated 20 times. With further optimization of NEMS width and mirror aperture, the novel VCSEL tuning speed is expected to be ~GHz range. One significant advantage is that this design will be readily adapted for different wavelength regimes.

The schematic of the electrostatic actuated NEMS tunable SWG VCSEL is shown in Fig. 1. The device consists of a bottom n-DBR, a cavity layer with the active region, and a top mirror. The top mirror is comprised of three parts (starting from the substrate side): a fixed p-DBR, a variable airgap, and a freely suspended n-doped HC-SWG that is supported via a cantilever structure. Electric current injection is conducted through the middle contact (via the p-DBR) and backside contact. An aluminum oxide aperture is formed on an AlAs layer in the p-DBR section above the cavity layer to provide efficient current and optical confinement. The tuning contact is fabricated on the top n-doped HC-SWG layer. Wavelength tuning is accomplished by applying a reverse voltage bias across the top n-layer and the middle p-DBR. The applied reverse voltage results in an electric field across the airgap, which attracts the cantilever toward substrate. This produces a deflection that reduces the airgap size, which then varies the emission wavelength of the VCSEL.

The fabrication process of the NEMS tunable VCSEL includes three metal depositions, cantilever structure formation, VCSEL mesa formation, oxidation, HC-SWG formation. The grating was defined on the center of VCSEL mesas using electron-beam lithography on PMMA resist, which was then etched by reactive ion etching. A wet chemical-based selective etching followed by critical point drying was required to remove the sacrificial material underneath the SWG layer and form the freely-suspending grating structure that is supported by a cantilever beam. Fig. 2 shows the top view SEM image of the fabricated device and the inset shows the freely suspended SWG structure supported by two-parallel cantilever beams.

Continuous wave (CW) operation of electrostatic actuated NEMS tunable VCSEL was demonstrated for the first time at room temperature. Fig. 3 shows the VCSEL characteristics (without applying tuning voltage) for output power versus bias current (LI) and voltage versus bias current (IV). The device exhibits a lasing threshold current ~1.4mA and output power ~0.5mW with a slope efficiency of 0.3mW/mA. Currently the device performance is mainly limited by large metal contact and series resistance, thus the device performance could be improved by further optimization of the fabrication process. Single mode emission with a ~40dB side-mode suppression ratio was obtained.

When applying a reverse bias voltage across the tuning contacts, the electrostatic effect deflects the cantilever beam, which translates to a decrease in the laser emission wavelength. Fig 4 shows the CW emission spectra of the device when the active region is electrically pumped at 1.8Ith under various applied voltage. A continuous wavelength tuning range of ~2.2nm was obtained towards shorter wavelength. The laser emission remains single
mode output throughout the entire tuning range. Fig. 5 shows the emission wavelength as a function of the applied voltage across the top tuning electrodes and the corresponding spectral intensity under those tuning conditions. The wavelength tuning exhibits a quadratic-like behavior that is similar to typical electrostatic actuation. In addition, the emission spectral intensity remains fairly constant throughout most of the tuning range.

Interesting wavelength switching effect was observed for the first with and without the VCSEL being turned on. We believe this may be due to the very light mass of the cantilever, less than 5% that of the conventional tunable MEMS. We will discuss this effect at the time of the meeting. In addition, the tuning speed and voltage dependence for various NEMS dimensions are being characterized. We expect to report both theoretical and experimental results.


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Fig. 1 – Schematic cross-section of the NEMS tunable VCSEL.

Fig. 2 – SEM of fabricated NEMS tunable VCSEL.

Fig. 3 – Measured LI and IV characteristics.

Fig. 4 – CW tuning spectra for the NEMS tunable VCSEL.

Fig. 5 – Emission wavelength and intensity under various tuning.

Fig. 6 – Schematic layers of the NEMS tunable VCSEL.