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MEMS-Based C-Band Tunable 16-Array Vertical Cavity Surface Emitting Laser

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Abstract—This paper elaborates a C-Band Tunable MEMS 16-array Vertical Cavity Surface Emitting Laser (VCSEL), which is suitable for wide use in WDM applications. Optical detectors, optical filters and Wavelength-tunable lasers play a pivotal role in the future ultrahigh bandwidth dense-wavelength-division-multiplexed (DWDM) optical network, enabling emerging innovative applications such as wavelength-on-demand in a reconfigurable all-optical network. VCSEL is the key optical source in optical communications. The advantages of VCSEL include simpler fiber coupling, easier packaging and testing, ability to be fabricated in arrays at low cost. The VCSEL array was made tunable in C-Band (1520-1550nm) by varying the length of the Fabry Perot cavity. The Fabry Perot cavity length is varied by using fixed-fixed beam electrostatic actuation. The VCSEL array is designed on to a single wafer using Intellisuite software and the optical analysis is done by using MATLAB.

Index Terms— VCSEL, Tunable LASER, Optical Communication, Optical MEMS, DWDM, Fabry Perot optical filter, fixed-fixed beam Electrostatic actuator.

1 Introduction

To mitigate the growing demand for additional bandwidth, new means of transmitting more bandwidth were desperately sought after, particularly for internet, wide area networks, regional and long haul communications. Dense wavelength division multiplexing (DWDM) is the most sought after technology used to increase communication bandwidth [1]. A DWDM system allows multiple wavelengths (each a different channel in 1530-1610 nm wavelength regime) to be transmitted in the same fiber and thus, enabling service providers to gracefully upgrade their systems with the increase of demand.

One key advantage of DWDM is the tremendous scalability of aggregate bandwidth. By adding wavelength as an additional degree of freedom for routing and switching, it is possible to architect new all-optical switching systems, that can be reconfigured dynamically, to minimize congestion, increase performance, and ensure cost effective. This presents an exciting enabling application for tunable lasers.

Tunable lasers are recognized as a highly desirable component for the present point-to-point DWDM systems. Tunable lasers are vital, however, for enabling the future intelligent optical networks, with applications in all-optical switching and dynamically reconfigurable optical add/drop multiplexers, etc. Tunable VCSELs can play a vital role in the new intelligent optical network era with a potentially low-cost, ability to fabricate in arrays compact and easy wavelength-locking solution [2].

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2 Micro Electro Mechanical System

Micro Electro Mechanical System (MEMS) is also referred as micro machine or micro system technology. MEMS is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro fabrication technology. In MEMS devices, the component dimensions are in µm range (1-1000 µm). MEMS devices are fabricated using modified semiconductor device fabrication technologies, normally used to make electronics. These include molding and plating, wet etching (KOH, TMAH) and dry etching (RIE and DRIE), electro discharge machining (EDM), and other technologies capable of manufacturing small devices. MEMS technology can be implemented using a number of different materials and manufacturing techniques. Materials employed are silicon, polymer, and metals etc [3]. Micro-opto-electromechanical system (MOEMS) is a special class of MEMS which involves sensing or manipulating optical signals on a very small scale using integrated mechanical and electrical systems. MOEMS includes a wide variety of devices such as optical switch, optical cross-connect, tunable VCSEL, micro bolometer and amongst others. The advantages of Optical MEMS ensure very high-speed switching, low-cost per unit. These are fabricated by using Micro Machining techniques such as either surface micromachining or bulk micromachining. Surface micromachining uses a succession of thin film deposition and selective etching. In bulk micromachining, the structures are made by selectively etching inside the substrate, for this photolithography is used to transfer a pattern from a mask to the surface [3].

3 Vertical-Cavity Surface-Emitting Laser

Tunable lasers are highly dwesirable for DWDM applications. The vertical cavity surface emitting laser (VCSEL) is a type of semiconductor laser diode with laser beam emission perpendicular to the top surface[2], contrary to to conventional edge-emitting semiconductor lasers which emit from surfaces formed by cleaving the individual chip out of a wafer. VCSEL is advantageous over edge emitting lasers. Edge-emitters cannot be tested until the end of the production process. If the edge-emitter does not work, whether due to bad contacts or poor material growth quality, the production time and the processing materials would be wasted, whereas, VCSEL can be tested at several stages throughout the process to check for material quality and processing issues. In addition to that, because VCSEL emit the beam perpendicular to the active region of the laser as opposed to parallel as with an edge emitter. The structure of VCSEL [2] is shown in Fig .1.

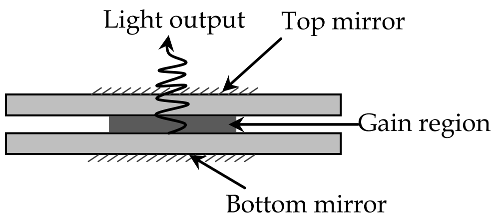

Fig 1. Structure of VCSEL

Tens of thousands of VCSELs canbe processed simultaneously on a three inch Gallium Arsenide wafer. The characteristics of VCSEL are [2]

a) VCSELs can be built not only in one-dimensional, but also in two-dimensional arrays because they emit from the top surface of the chip. They can be tested on-wafer, before they are cleaved into individual devices. This reduces the fabrication cost.
b) The wavelength tunability of VCSEL can be achieved, within the gain band of the active region, by adjusting the thickness of the reflector layers.
c) The high reflectivity mirrors, compared to most edge-emitting lasers, reduce the threshold current of VCSEL, resulting in low power consumption. VCSEL have lower emission power compared to edge-emitting lasers. The low threshold current also permits high intrinsic modulation band widths in VCSEL.
d) The larger output aperture of VCSEL, compared to most edge-emitting lasers, produces a lower divergence angle of the output beam, and makes possible high coupling efficiency with optical fibers.

4 Wavelength Engineering In VCSEL

A typical VCSEL consists of two oppositely-doped distributed Bragg reflectors (DBR) with a cavity layer in between. In the center of the cavity layer lies an active region, consisting of multiple quantum wells. There is typically only one Fabry-Perot wavelength within the gain spectrum and hence the Fabry Perot wavelength (and not the peak gain) determines the lasing wavelength. Optical thickness variation of the layers in a VCSEL changes the Fabry Perot wavelength and hence lasing wavelength [4]. To achieve wide tunability the thickness must be varied mechanically. In 3-contact device, the attainable optical thickness variation is very small, due to a limited change of refractive index with current. As for the external-cavity device, although a very large optical thickness variation is expected, the variation is placed too far away from the cavity center to achieve significant results.

Figure 2 & 3 shows a top-emitting VCSEL with an integrated MEMS structure. The VCSEL structure with 40 pairs of bottom n-DBR, an active region with 3-quantum wells and 3-pairs of top p-DBRs emits the optical signal of wavelength 1550 nm [5]. The structures of VCSEL array shown in Fig. 2 and 3 are fabricated on to a single wafer to achieve the multi wavelength tunability in C-Band.

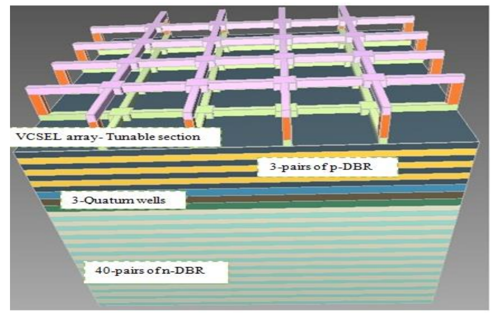

Fig 2. Side view of tunable 16- array-VCSEL structure

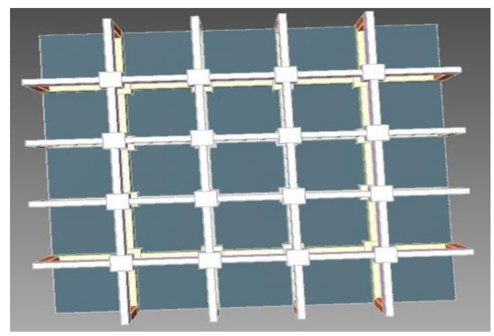

Fig 3. Top view of tunable 16- array-VCSEL structure

5 Fabry Perot Filter

Fabry Perot filter is an optical filter that uses a Fabry Perot cavity which consists of two highly reflecting parallel mirrors, separated by a small distance 'x'. A very high mirror reflectivity is required to obtain good isolation of adjacent channels. The Fabry Perot filter exhibits a peak transmittance at resonant wavelengths of the cavity. If no phase change is present in the mirrors, the resonant wavelengths are given by $\lambda = 2x/m$, where m is an integer known as the order of the peak. The power transfer function T (f) is the fraction of the input light power that is transmitted by the filter [2].

$$T = \frac{(1-A-R)^2}{(1-R)^2 + [2\sin(2\pi f\tau)]^2} \quad (1)$$

where A is Absorption loss of each mirror, R is Reflectivity of each mirror, τ (=x/c) is the one way propagation time, c is velocity of light, λ is wave length, n is Refractive Index of cavity. The resonant condition of the optical cavity (x = mλ/2) is altered dynamically, by moving one of the mirrors, In this proposed Fabry Perot filter, one of the mirrors is moved by electrostatic actuator. This Fabry Perot filter can be made tunable in C-Band from 1550nm down to 1520nm. The initial cavity length of the filter is selected using its power transfer function. The power transfer function T(f) of the Fabry Perot filter is modeled in MATLAB by assuming zero absorption loss of the mirrors. The power transfer function is maximum, when the cavity length of the resonator x= mλ/2. High tuning range can be achieved when the filter operates in first order mode [6]. So, the initial cavity length is chosen as 775nm for filtering a wavelength of 1550nm.

The sharp response from the Fabry Perot filter can be obtained when the reflectivity R of the mirrors is high. When the reflectivity of mirror is 95%, highly sharp response can be observed. For R=35%, the sharpness of the filter response is moderate and for R=5%, a very low sharpness in its power transfer function can be observed. The corresponding simulated MATLAB results are shown in Fig. 4.

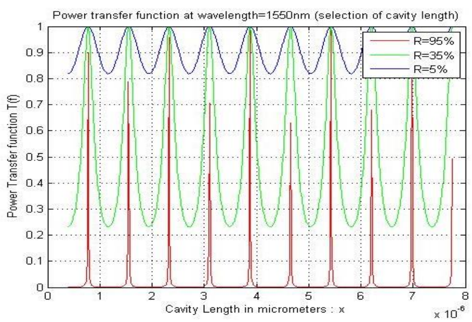

Fig 4. Selection of cavity length for filtering a wavelength of 1550 nm based on filter's power transfer function.

In order to achieve high tuning range, the filter must be made to operate in first order, and in this juncture the maximum tuning range of the actuator becomes an issue [6]. Electrostatic actuation is a popular choice for MEMS-based Fabry-Perot filters [6]. The commonly employed parallel-plate actuator is able to tune over one-third of the initial separation between the two mirrors that define the cavity [3]. So, fixed-fixed beam electrostatic actuator is used here. Electrostatic actuators exhibit fast response time and are easily integrated into micro systems because they can be fabricated with standard IC micromachining processes and materials [7]. The key factors to be considered in Fabry Perot devices are the free spectral range (FSR) and the finesse (F). The FSR defines the spectral distance between two consecutive interference peaks, while F is the FSR divided by the full width at half maximum of the interference peaks. FSR indicates the spectral tunability of the Fabry Perot device, while F specifies its spectral resolution. The Finesse of a Fabry Perot cavity involves a function of fabrication imperfections and the reflectance of the mirrors. Tunable MEMS-based Fabry Perot filter is fabricated by using inexpensive batch micromachining, is attractive, because fabrication defects can be minimized, device-to-device variability can be optimized, and on-chip micro optical system integration can be achieved.

6 16- Array VCSEL Tuning Mechanism Using Fabry Perot Cavity

The 3-layer structure the VCSEL tuning section with electrostatic actuator was designed using INTELLISUITE, which is shown in fig.5.

Wavelength tuning is accomplished by fixed-fixed beam Electrostatic actuation. In the Intellisuite TEM analysis, a voltage range of 0-18.53V is applied to the fixed electrode and 0V is applied to the free electrode. Due to the electrostatic force of attraction the free electrode is moved down towards the fixed electrode. The free electrode can be restored back to its original position when the voltage is removed, if an appropriate mechanical design is implemented.

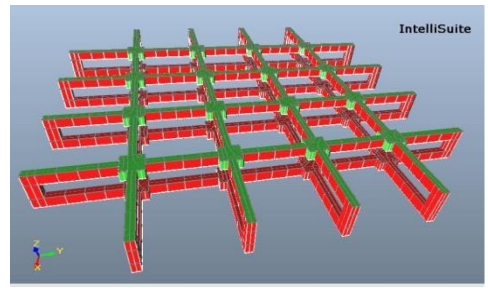

Fig.5. Tunable section in VCSEL Array

Initial gap between the mirrors is taken as 775nm. The voltage to be applied to the electrodes [3], [8], to achieve a desired displacement 'd' is

$$d = \frac{2\varepsilon A L^3 V^2}{E W t^3 \left(g_0 - d\right)^2} \tag{2}$$

Where g_0 is the initial air gap between the mirrors, d is displacement to be achieved, V is voltage to be applied, E is young's modulus of the electrode material, A is the area of the electrode. L, W, t (0.5 µm) is the length, width, and thickness of the electrodes respectively [3].

But pull in voltage (V_{PI}) is the major constraint. The growth of the electrostatic force becomes dominant over the increasing mechanical restoring force and the upper electrode quickly pulls down to the bottom electrode. Pull in voltage and spring constant (k) of the material are given by [3].

$$V_{PI} = \sqrt{\frac{8 k g_0^3}{27 \varepsilon A}} \text{ and k = } \frac{E W t^3}{4 L^3} \tag{3}$$

Beyond this V_{PI} the upper electrode is suddenly pulled down by the lower electrode. Hence the maximum displacement between the electrodes will be considered at V_{PI}. To achieve a large tuning range, given the 1/3-rule [9], it is natural to assume the larger air gap to be the best. However, increasing the air gap leads to a longer effective cavity length which results in a narrower Fabry Perot mode separation, and thus a smaller overall tuning range. Hence, an optimum design exists.

7 Fabrication Steps Of 16-VCSEL Array Tunable Section

The tunable section of 16-array vessel is designed in three layers as shown in Fig. 5. It consists of three Masks. Mask-0 and Mask-2 consist of bottom and upper electrodes respectively. Mask-1 consists of the supporting beam. The fabrication process steps of 16 array VCSEL is shown in Fig. 6 screen shot.

#	Type	Material	Process	Process ID	Process Option
1	Definition	Si	Czochralski	100	
2	Deposition	Al	Bulk	Standard	Conformal Depo.
3	Definition	UV	Contact	Suss	
4	Etch	Al	Wet	Al_Etch_A	Etch Through
5	Deposition	SiO2	Bulk	Standard	Conformal Depo.
6	Definition	UV	Contact	Suss	
7	Etch	SiO2	Wet	BOE	Partial Etching
8	Deposition	Al	Bulk	Standard	Conformal Depo.
9	Definition	UV	Contact	Suss	
10	Etch	Al	Wet	Al_Etch_A	Partial Etching

Fig 6. IntelliFab process steps of VCSEL array tuning section.

The starting material is Si wafer with the thickness of 50 µm as shown in Fig 7.

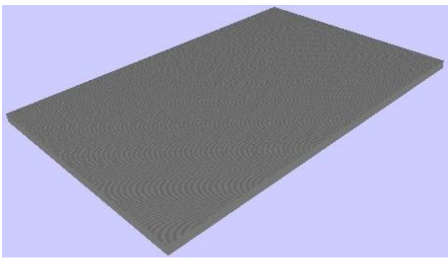

Fig 7. Si wafer definition

Aluminum is deposited by standard bulk conformal deposition process as shown in Fig 8.

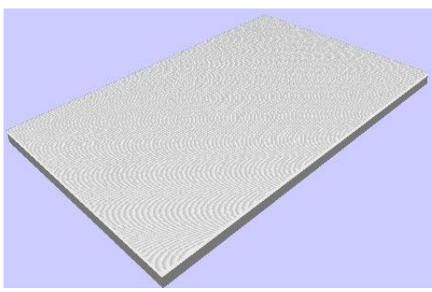

Fig 8. Al conformal deposition

Mask-0 of the VCSEL array tuning section is patterned by wet etch through process as shown in Fig 9.

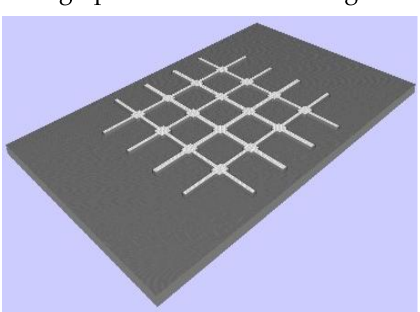

Fig 9. Mask-0 pattern Etching.

SiO_2_LPCVD_TEOS is deposited by standard bulk conformable deposition process as shown in Fig 10.

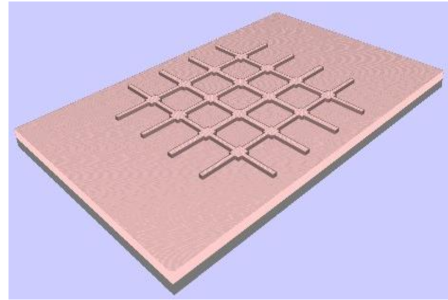

Fig 10. SiO2_LPCVD_TEOS_conformal deposition.

Mask-1 of the VCSEL array tuning section is patterned by partial etching process as shown in Fig 11.

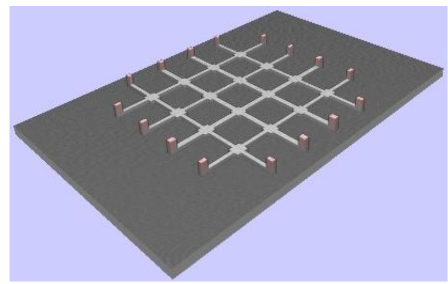

Fig 11. Mask-1 pattern Etching.

Aluminum is deposited by standard bulk conformal deposition process as shown in Fig 12. Mask-2 of the VCSEL array tuning section is patterned by partial etching process as shown in Fig 13.

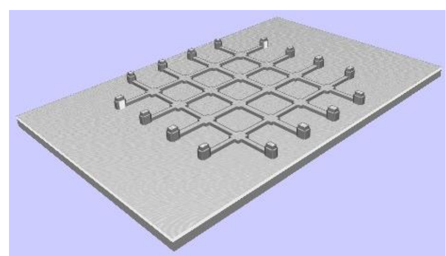

Fig 12. Al conformal deposition

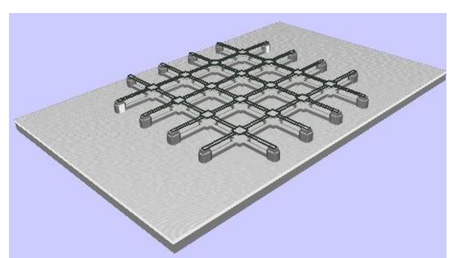

Fig 13. Mask2 pattern etching

8 Simulated Result And Optical Analysis

To tune Fabry Perot cavities in 16-array VCSEL in the C-band transmission window, the initial gap between the electrodes is chosen as 775 nm to allow the wavelength of 1550 nm. Fabry Perot filter shown in Fig 5 is tuned by varying the gap between the electrodes. The gap between the electrodes is varied by applying various voltages from 0 to 18.53 V. Intellisuite simulated results are shown in Table 1.

TABLE I. INTELLISUITE SIMULATED RESULTS

Initial Gap =775 nm				
S.No	Voltage applied (V)	Displacment achieved (nm)	Final gap between electrodes (nm)	Wavelength allowed (nm)
1	0	0	775	1550
2	8.2	-2.5	772.5	1545
3	11.64	-5	770	1540
4	13.5	-7.5	767.5	1535
5	15.2	-10	765	1530
6	16.85	-12.5	762.5	1525
7	18.53	-15	760	1520

The Fabry Perot filter allows the optical signals, whose wave length is twice that of the cavity length of the resonator [6]. The Intellisuite simulated results that show various displacements achieved by the electrostatic actuation. The emitted wavelengths at various Fabry Perot cavity lengths are analyzed by using Matlab. The filtered wavelengths at initial and final cavity lengths are shown in below Fig 14 and 15. Figure 14 indicates that, the Fabry Perot cavity allows the optical signals, whose wave length is twice that of the cavity length of the resonator. It ensures that, for the initial Fabry Perot cavity length of 775 nm, the optical signal of wavelength 1550 nm is emitted from the VCSEL.

Figure 15 ensures that the Fabry Perot cavity allows the optical signals, whose wave length is twice that of the cavity length of the resonator. It shows that, for the final Fabry Perot cavity length of 760 nm, VCSEL emits the optical signal of wavelength 1520 nm.

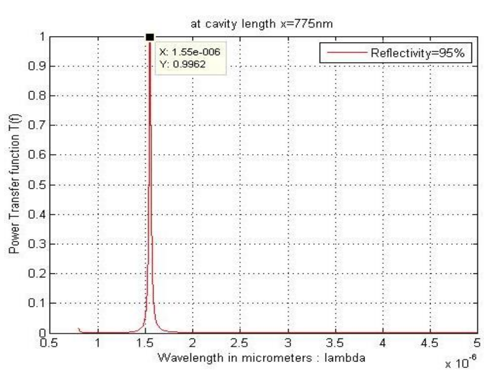

Fig 14. Filtered wavelength at a cavity length of 775nm

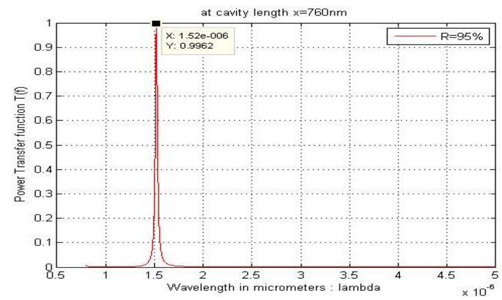

Fig 15. Filtered wavelength at a cavity length of 760nm

9 CONCLUSION

The optical and mechanical design of C-Band Tunable MEMS 16-array Vertical Cavity Surface Emitting Laser was discussed. It was modeled on 1mm x 1mm Si wafer, by using IntelliSuite software. The tunability is achieved by varying the cavity length of Fabry Perot cavity, by using fixed-fixed beam electrostatic actuation. The 16-array VCSEL can emit the multiple wavelengths that are in the C-Band transmission range (1550 nm down to 1520 nm). When the initial gap between the mirrors of Fabry Perot cavity is 775 nm, it emits the optical signal of wavelength 1550 nm. By applying various voltages ranging from 0-18.53, it can emit multiple wavelengths which are in C-Band transmission window that can be used in WDM applications.

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