

# Feedback-induced voltage change of a Vertical-Cavity Surface-Emitting Laser as an active detection system for miniature optical scanning probe microscopes

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**Abstract:** We propose a novel detection technique for scanning probe microscopy based on the measuring of the feedback-induced voltage change of 780-nm VCSEL operating at constant current in far-field regime when we modulate mechanically the length of a coupled-cavity generating the feedback conditions. The voltage change of the VCSEL is produced by light back reflected from the sample to the laser cavity. Two-dimensional image probing is successfully demonstrated with high temporal resolution, offering a viable solution for miniature parallel scanning probe optical microscopes, such as confocal microscope, where the use of a photodetector is avoided. This approach opens the possibility to perform imaging tasks in a low cost and hand-held miniature device with much improved effective-space.

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**OCIS codes:** (180.5810) Scanning microscopy; (140.5960) Semiconductor lasers; (120.3940) Metrology

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## 1. Introduction

The influence of optical feedback on conventional edge-emitting lasers is well-known and was particularly well studied in single mode lasers [1-2]. The dependence of the laser power on the feedback conditions has been successfully used as a detection principle in Doppler velocimeters, displacement interferometric sensors and confocal microscopy [3-5]. The feedback of semiconductor or gas lasers has already been used in atomic force microscope (AFM) to measure the displacement of a cantilever [6] as well as a read-out system in a near-field fiber laser probe [7]. More recently, a cavity-SNOM (scanning near-field optical microscope) head using a laser diode has been proposed [8-9]. Since the mid-1980s VCSELs (Vertical Cavity Surface Emitting Lasers) have received a considerable attention due to their high speed, low threshold current, low divergence and high integration capacity. On the one hand, the very short cavity length makes VCSELs operation inherently single longitudinal mode, avoiding mode hops typical of conventional diode lasers. On the other hand, VCSELs potential in integration with micro-electro-mechanical systems (MEMS) has been demonstrated [10]. In particular, recent advances in batch fabrication of probes with sub-wavelength apertures and the progress in laser techniques have pushed the conventional SNOMs to be applied routinely to a wide range of applications such as high-density optical recording and optical data storage [11]. Hashizume *et al.* [12] proposed a technique of VCSEL-based probing for optical storage, based on reflection induced voltage change of a VCSEL in near-field regime. More recently, we have demonstrated the viability of VCSEL-based feedback as an active detection system in high resolution SNOM imaging [13-14] with an alternative for miniaturisation of the microscopy device [15]. Such a detection system is based on the monitoring power modulation induced in the laser cavity by the backscattered light coming from the specimen. Here, a sharp tip is tapered by commercial puller and an evanescent wave is emitted from the aperture of the tip, interacting with the sample. Evanescent wave is reflected by the sample, transformed in propagating one by the tip, and then is propagated into the VCSEL cavity, modifying the optical properties of emission of the laser. Because of a very weak SNOM signal this imaging technique required the use of an external detector to measure the feedback effects.

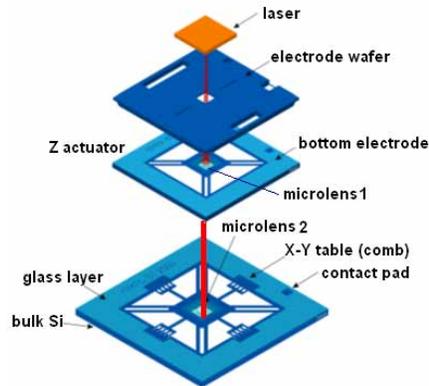


Fig. 1. Architecture of SOMOC.

In scanning confocal microscopy the power of the backscattered light coming from the specimen is not limited by extremely low aperture of fiber optic tip and the measuring of feedback signal directly from the voltage change of a VCSEL is possible. Thus, the use of an external detector is avoided. In confocal microscopes, the micro-scale samples are observed and analysed via a large measuring head, too bulky and heavy for individual use in specialised key missions such as in situ or in vivo measuring. There is a need for miniature, low cost, highly portable analytical instruments, able to read the data with high areal density. Integration of a whole confocal microscope by use of MEMS technologies will enable compact handheld biological imaging systems. Our long-term goal is precisely to propose a miniature confocal microscope using the optical feedback of VCSEL as an active detection system. This approach simplifies the microscope design because the light source and detector are unified parts of the VCSEL itself. The architecture of such scanning confocal optical microscope on-chip (SCOMOC) is shown in Fig. 1. It is based on full integration of all required components of confocal microscope on a millimeter-size microsystem. SCOMOC consists of a VCSEL laser and two electrostatically driven MOEMS scanners: one parallel plate z-scanner and an x-y scanner with four comb-drive actuators. The 3-D transmissive steering of the laser beam is possible due to integration of two convex glass microlenses on the movable silicon plates of these scanners. The microlenses work as a doublet objective lens of the microscope. The z-axis scanner provides a vertical motion of the first microlens, controlling the depth of focus. The z-scanning range of  $100\ \mu\text{m}$  is expected. Raster scanning of the focused illumination spot is made by actuating of second microlens by x-y scanner. Optimised design of comb-drive actuators will ensure the  $50\ \mu\text{m}$  scanning range in both directions. When a 2-D section of a small partial volume of the specimen centered on the focal plane is measured, the 3-D reconstruction of a specimen is obtained by stacking 2-D optical sections collected in series.

In this paper, our purpose is to perform the demonstration of the detection principle for SCOMOC. Such detection principle is demonstrated in a semi-massive configuration. To avoid the use of a detector, we measure the feedback signal directly from the voltage change of a VCSEL. Here, the VCSEL is operating at constant current when the length of coupled-cavity, formed by the VCSEL and the sample to be measured, is modulated mechanically by a triangular-ramp motion, periodically modifying the amount of light backscattered within the laser cavity. In the next Section, the efficiency of such original detection system, based on monitoring the voltage modulations induced by the backscattered light coming from the specimen, is demonstrated. The perturbed VCSEL cavity plays the role of both illumination source and a detector.

## 2. Experiment

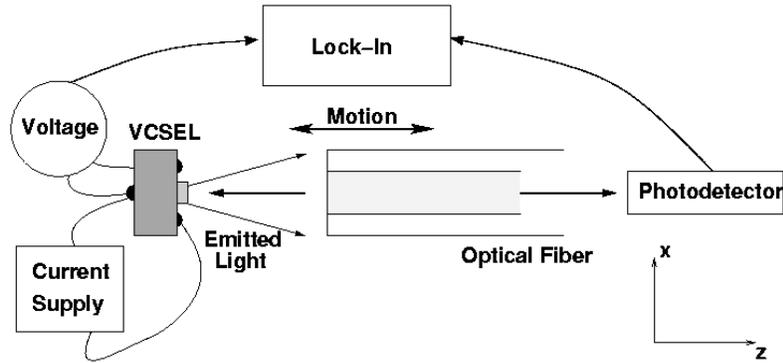


Fig. 2. Experimental setup.

First, we have investigated the effects of optical feedback in far-field detection regime, where the compound-cavity used was typically 150- $\mu\text{m}$  [16]. The experimental set-up is shown in Fig. 2. The compound-cavity is formed by the back facet of the VCSEL and the cleaved endface of a single-mode fiber facing the VCSEL. A part of light is reflected back from the fiber end, then collected by the same fiber and the power modulation measured by a photodetector. We used a commercially available VCSEL from the company Avalon, operating at a wavelength of 780 nm.

The endface of optical fiber is driven by a piezoelectric positioner with nanometre accuracy, modifying the length of compound-cavity. Figure 3 shows at the centre the voltage applied to PZT driver as a function of time: this is a triangular ramp operating at low frequency of 20 Hz. This excitation signal, used for adjusting the length of compound-cavity, is compared to the curves of optical power modulation. The curves are obtained respectively for two different values of current injection of VCSEL: 4.5 mA (on top) and 3.5 mA (on bottom). The displacement of fiber endface produces the variation of length of the compound-cavity with maximum amplitude of 5  $\mu\text{m}$ . We can see that the feedback produces an optical modulation oscillating periodically with the change of distance between the laser and reflective facet of fiber endface. The same periodicity of half-wavelength ( $\lambda/2$ ) of power modulation, demonstrated by Dandrige *et al.* [4], was used for measuring of distances between the output facet of an edge-emitting diode laser and a moving target. Here, the power modulation is, of course, obtained by a pigtailed photodetector. But this semi-massive configuration is not well adapted for the MEMS version of the microscope.

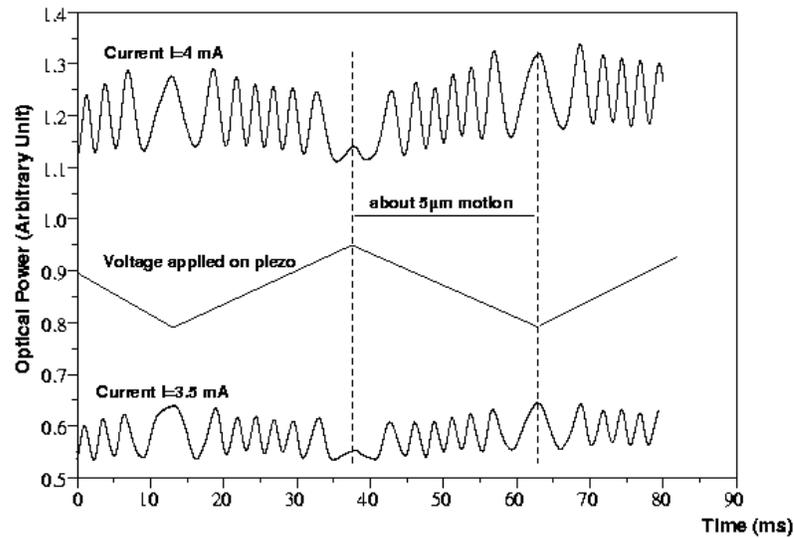


Fig. 3. Curves of power modulation, obtained for two values of VCSEL injection current, compared to the excitation signal of PZT driver.

If the direct optical power monitoring for edge-emitting lasers by a photodiode is relatively easy [16] (these diode lasers emit light from both front and back facets), the power monitoring is more complex for VCSELs not emitting light in the rear direction, i. e., through the substrate wafer. For VCSELs operating in the 780-nm region the VCSEL die is placed in an enclosure fitted with a partially reflective window above the VCSEL aperture and a photodiode onto which the partially reflective window projects some of the light from the VCSEL. This solution cannot be used in our application because it measures the back reflected light and is not able to monitor the power modulation due to the feedback of VCSEL cavity. Other solutions that have been proposed, including photodiodes integrally built in the VCSEL structure [17,18]. These potential structures have not been used in production devices as a result of the significantly higher manufacturing complexities involved (vertical integration of VCSEL on top of a detector), or because of the fact that they do not directly monitor the emission modes propagated by the VCSEL through its aperture (lateral detection). Recently, it was demonstrated that optical feedback induces a modification of VCSEL voltage [19]. If this simple technique permits the use the standard VCSELs, the change of voltage is very weak, ranging the volt region [19]. To improve the sensitivity of voltage-based detection, we propose to use the signal derivative which improves the sensitivity to the modifications of compound-cavity length. To implement this approach we modulate mechanically the feedback and detect the voltage change induced by using a lock-in amplifier, thus increasing the signal to noise ratio. The influence of feedback modulation has been studied both from the optical signal collected by a pigtailed photodetector and from the voltage signal monitored directly on VCSEL's electrodes. To investigate both resulting modulations for different values of injection current of VCSEL, a triangular wave is applied at a frequency of 0.05 Hz, covering the injection current within the interval from 1.2 mA to 7.4 mA. As the endface of optical fiber is vibrating at a frequency of  $f_0=200$  Hz with an amplitude much less than  $\lambda/2$ , we assume that the DC current is constant during the time of lock-in demodulation. Figure 4(a) shows the ramp of injection current as a function of time, while Figs. 4(b-c) represent the curves resulting from of the optical power modulation (b) and from voltage modulation (c). These results are obtained after the lock-in amplifier demodulation in presence of weak optical feedback. The maximal amplitude of Figs 4(b-c) is about 10 Volts, corresponding to

maximum amplitude of 500  $\mu\text{V}$  before the synchronic detection processing. Even if the dynamic range of voltage modulation is 1 decade less than the dynamic range of optical modulation (depending from photodetector sensitivity), both modulation curves exhibit similar sensitivity behaviour. Letters A and B report two different levels of injected current corresponding to the high sensitivity (7.4 mA - letter A) and the low sensitivity (4 mA - letter B) of optical feedback, respectively. The position of letters A and B is similar on both modulation curves.

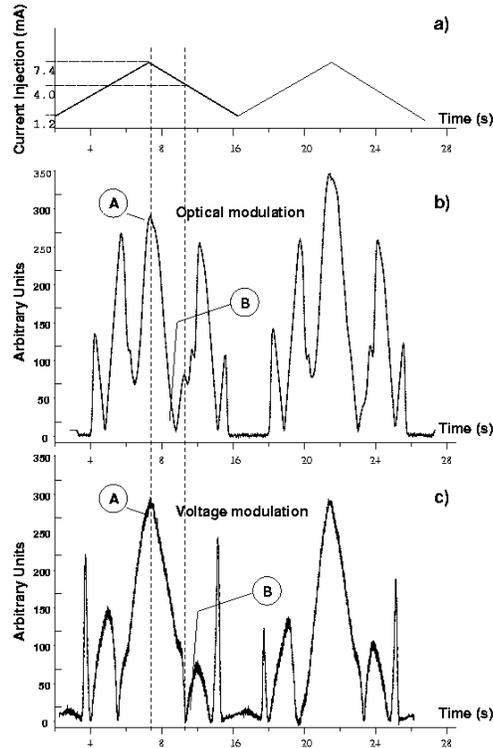


Fig. 4. Curves of optical and voltage modulation induced by the mechanical modulation of the optical feedback.

Figures 5(a-b) show the physical significance of this pair of points of different sensitivity. If we assume that the optical power modulation of Fig. 5(a) is a sinusoidal function, depending from the length  $z$  of VCSEL compound-cavity, the measured power distribution is:

$$I = I_0 \left( 1 + C \cos\left(\frac{\pi}{\lambda} z\right) \right) \quad (1)$$

where  $C$  represents the contrast and  $I_0$  is the average incident intensity.

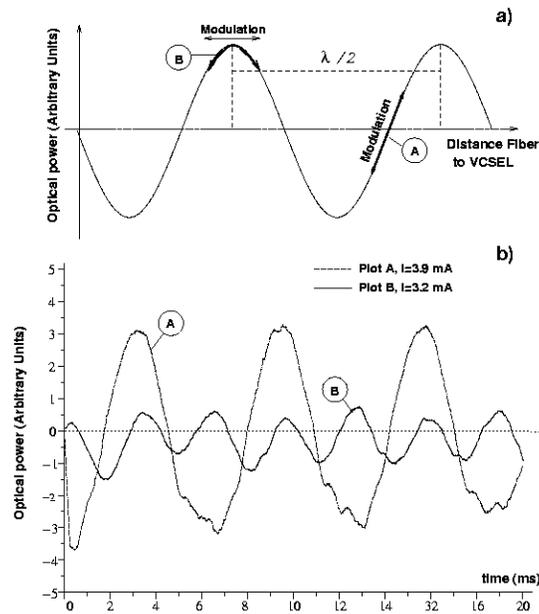


Fig. 5. Physical significance of results of Fig. 4.

By application of periodic oscillation to the length of compound-cavity (amplitude of motion  $< \lambda/2$ ), we introduce an oscillation around the maximal slope with injection current (letter A) or around one of optima (letter B) of the sinusoid. The drift of this operating set point is due to the modification of wavelength emission with the injected current. Figure 5(b) represents the modulation of optical power as a function of time, obtained for the pair A and B of injection current. The curve of injection current A oscillates at a carrier frequency of  $f_0$  while the curve of injection current B oscillates at twice frequency  $2f_0$ . The lock-in amplifier is adjusted to filter only the signal with carrier frequency  $f_0$ . It is why we obtain a good sensitivity at A and a low sensitivity at B. After the lock-in amplifier demodulation, we obtain a signal varying between 0 and 10 Volts, corresponding to a modulation depth of 500  $\mu$ Volts of the voltage, collected on VCSEL's electrodes. Thus, the improvement of almost 2000 of the signal to noise ration is obtained for the integration time in the range of 100 ms.

To demonstrate the potential of voltage-based detection in 2-D imaging, we replace the endface of fiber by a sample containing a thin layer of gold (Au) deposited on a glass substrate. The experimental set-up is shown in Fig. 6. The VCSEL light is coupled into a single-mode optic fiber Y-junction, splitting the incident light within arms of Y-junction with a ratio of 5%:95%. One arm of the Y-junction is connected to a photodetector, monitoring the power modulation of VCSEL. The other arm is carried by a piezoelectric actuator, ensuring the vertical displacement of its cleaved endface, flying few microns above the sample. The vertical actuator maintains an oscillation of short amplitude, modifying the distance fiber-sample and modulating mechanically the optical feedback. A piezoelectric scanning stage is used to ensure the x-y scan of the sample. The VCSEL light transmitted through the measuring arm is reflected by the sample and then collected by the same fiber. The back reflected light passes inside the VCSEL cavity, resulting in a modulation of VCSEL power accompanied by a voltage modulation. The cavity formed by the fiber endface and the specimen plays the role of a tunable Fabry-Pérot cavity with a variable length of cavity.

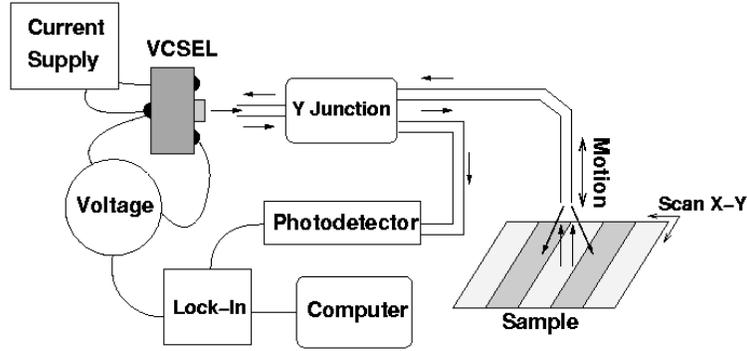


Fig. 6. Experimental set-up for 2-D imaging.

First, an optical image of the sample is obtained in absence of z-scan of fiber endface, as shown in Fig. 7(a). This is achieved by measuring the power modulation via the photodetector, the scanning area being  $60 \times 60 \mu\text{m}^2$ . We can see a system of fringes due to the inclination of the sample, with fringe period in agreement with Eq. (1) and curves of Fig. 3. We observe an increase of fringe contrast when passing from the glass to Au layer, due to the reflectivity jump between both layers.

Secondly, an optical image of the specimen is achieved by moving vertically the fiber endface and measuring the optical signal at the output of a lock-in amplifier, as shown in Fig. 7(b). Here, the period of fringes is twice compared to the Fig. 7(a). The oscillation of fiber endface performs a mathematical operation of first derivative on the probed optical image, corresponding to the ratio between the variation of intensity induced and the variation of vertical displacement. This can be simply shown from Eq. (1), if we consider the superimposition of DC ( $z_0$ ) and AC components. Thus, the length of compound-cavity can be written as:

$$z = z_0 + \delta \cos(\omega t) \quad (2)$$

where  $\delta$  and  $\omega$  represent the amplitude and the angular frequency of the motion, and  $z_0$  is the static position.

Assuming  $\delta \ll \lambda$ , the detected intensity can be expressed in agreement with the Eq. (1):

$$I \cong I_0 \left[ 1 + C \cos\left(\frac{\pi}{\lambda} z_0\right) - C \frac{\pi \delta \cos(\omega t)}{\lambda} \sin\left(\frac{\pi}{\lambda} z_0\right) \right] \quad (3)$$

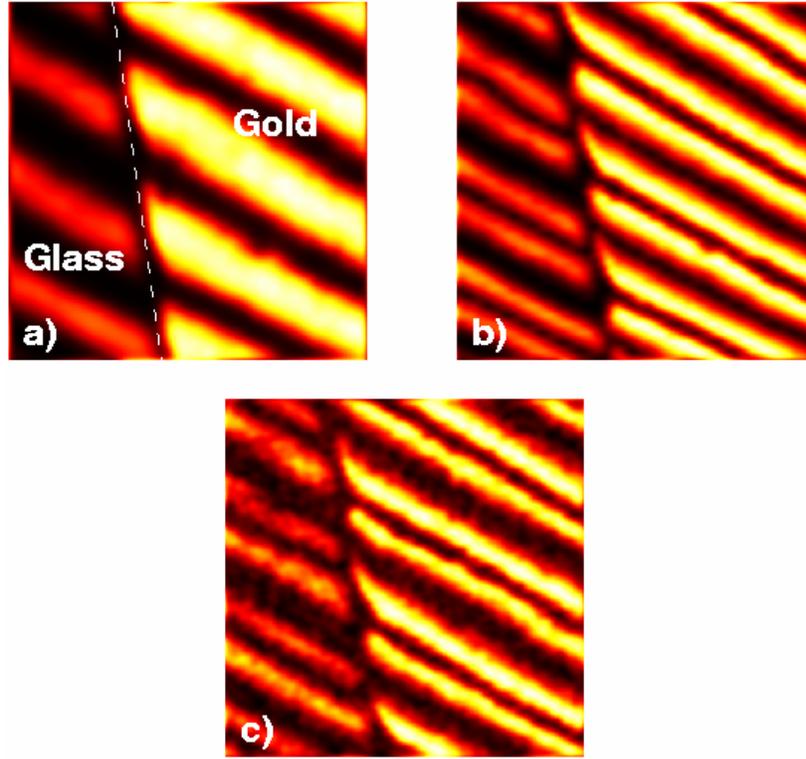


Fig. 7. 2-D imaging of the sample: (a) optical image without z-scan; (b) optical image with z-scan; and (c) voltage image with z-scan.

The lock-in amplifier extracts amplitude and phase of the AC component; the intensity  $I_M$  of the resulting image is proportional to the amplitude of the detected intensity:

$$I_M \propto \left| \sin\left(\frac{\pi}{\lambda} z_0\right) \right| \quad (4)$$

where the fringe period is  $\lambda/4$  (spatial frequency doubling).

The voltage image is obtained in presence of z-scan of fiber endface, as shown in Fig. 7(c). This is achieved by measuring of feedback-induced voltage changes on VCSEL electrodes for a fixed value of injection current. This high-contrast image originates in the modulation of the position  $z$  at easily filtered frequency. The main advantage of lock-in detection based on the derivative extraction is the simultaneous possibility to obtain the sample image and control the distance  $z$ . This will be particularly interesting in the implementing of SCOMOC configuration where a precise control of focus will be obtained by the proposed technique. To illustrate this, we assume that the control of distance  $z$  is performed within in a short interval  $[-z_M, +z_M]$  (shorter than one fringe period). The principle of distance control is based on the measuring the phase of the AC component which depends on the position  $z_0$ . For a small value of  $z_0$ , the AC intensity can be expressed:

$$I_{AC} \cong -CI_0 \frac{\pi^2 \delta \cos(\omega t)}{\lambda^2} z_0 \quad (5)$$

In this short interval, the phase of the detected signal is 0 or  $\pi$ . The set-point is chosen at  $\pi/2$  (experimentally, this value is not exactly instantaneously controlled because the phase oscillates due to the noise, but the lock-in amplifier gives an averaged value which can be

used to drive the actuator of the control loop). The limitation of a control loop using a lock-in amplifier as phase detector is the time constant which slows the distance control [20,21] but, conversely, the noise is highly rejected and, in this case of low SNR there is a significant advantage to use this technique.

### **3. Conclusion and perspectives**

We studied an original detection system for optical scanning microscopy, based on the monitoring of feedback-induced voltage changes of commercially available VCSELs, with demonstration of 2-D imaging. Even if the principle of such detection technique is less sensitive than the measuring of optical power modulation, the use of voltage-based imaging simplify the microscope architecture because the light source and detector are parts of the VCSEL itself. In addition, the procedure aiming the derivative extraction permits a fine control of vertical distance from the output facet of VCSEL and the sample to be measured. The proposed approach opens the possibility to perform microscopy tasks in a hand-held miniature device with much improved effective-space usage and without an external detector. The association of voltage-base detection with micromachining technology, full integration of microlenses, scanning actuators and microcantilevers with flip-chip assembled lights sources offers now an ideal platform for the miniaturisation of highly sensitive arrays of MEMS scanning microscopes, bringing down the barrier of high cost of commercially available systems. As described here (Fig. 1), we plan to use the proposed detection system as an active detection for confocal microscopy. The microlens and scanner configuration will be a part of a microscope that is 500 to 1,000 times smaller than anything in its class. Major challenge will include realisation array-type integration of multifunctional SCOMOCs on top of microfluidic network. This version of COMOC will be applied for DNA molecule recognition not requiring the fluorescence effects.

The proposed technique can be also used as a distance controller in atomic force microscopy (AFM) where the basic design will consist of VCSELs bonded by flip-chip above an AFM cantilevers. The back side of each cantilever will be illuminated by a VCSEL and back reflected light inducing the optical feedback. In tapping mode, the cantilever will oscillate, modulating the optical feedback. The feedback induced voltage change will be measured to control the distance from VCSEL to cantilever during the scan of the sample.

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