STSM report – Aleksandar Danicic

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STSM Grantee: Aleksandar Danicic
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Home Institution: Vinca Institute of Nuclear Sciences, University of Belgrade, Serbia
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STSM purpose: Joint studies of multispectral imaging technologies for skin cancer detectionIntroduction

VCSEL arrays in self-interferometry arrangement have the potential to be low cost imaging tool for blood perfusion[1] .

The goal of the Action BM1205 is to develop an ultra-compact sensing technology based on the self-mixing interferometer that uses Vertical-Cavity Surface-Emitting Laser (VCSEL) arrays both for the emission and the detection of light. This technique has high sensitivity, high signal to noise ratio, high spatial resolution, simple optical design, low power consumption (portable system), potentially low cost and the significant advantage of possible implementation in massive two-dimensional arrays.

Self-mixing interferometry, on which this objective is based, is an acknowledged new technique for detection of small displacements, change in the refractive index of materials, and particle flow.

The self-mixing phenomenon occurs when the laser beam is partially reflected from an external target and injected back into the laser cavity. The reflected light interferes or 'mixes' with the light inside the laser cavity and produces variations to the threshold gain, emitted power, lasing spectrum and the laser terminal voltage. This phenomenon allows the laser to be used as an interferometric sensor incorporating the light source and the interferometer in one device thus significantly reducing the cost and the complexity of the sensing system.

The homodyne (coherent) detection nature of this sensing scheme inherently provides very high sensitivity (at the quantum noise limit) and consequently suffers minimal crosstalk between the channels in a free-space multichannel implementation.

Due to its short cavity length of the order of the wavelength, VCSELs operate in a single longitudinal mode, which avoids signal distortions due to mode beatings, have low power consumption and the circular output beam allows simpler optics than for side-emitting lasers.

The design of VCSEL devices and arrays has not been expressly pursued for this proposal.

Experimental work and commercial products to date have relied on pre-existing devices sourced from manufacturers for communications applications. As such, the performance of any sensor system based on VCSEL devices is ultimately limited.

As part of this technical objective, the modelling of the self-mixing effect and related device physics will be required to expand the current single-beam technology to 2D and possibly 3D imaging (depth sectioning) based on two-dimensional VCSEL arrays.

[1] http://skin-laser-imaging.org/wp-content/uploads/2013/10/MoU-BM1205.pdf

Review of state of the art of the VCSELs presented at VCSEL day 2014

To the best of our knowledge the most recent publication on this subject is ref [2]. In this paper, a full-field self-mixing sensor system with simultaneous readout from an array of VCSELs for measuring fluid-flow velocities was demonstrated. A small scale prototype of the system, based on the 1×12 VCSEL array was implemented. Due to the fact that VCSELS' construction offers advantages compared to in-plane lasers because they emit light normal to the surface of the wafer, these devices can be operated without dicing of the substrate allowing lasers to maintain their precise lithographic alignment. The performance of the system has been validated by imaging the distribution of fluid flow velocity in a custom made channel. The results obtained match closely the simulated velocity distributions of the channel suggest that the image quality improvement due to lithographic alignment of lasers constituting the monolithic array is essential for expanding this concept in the creation of a massively parallel Doppler imaging systems based on two-dimensional VCSEL arrays. The VCSELs in this system are used as both the light source array and the sensor array by sensing the change in junction voltage across each VCSEL. This sensing technique removes the need for the hybrid integrated photodetector array with the VCSEL array, which significantly reduces the complexity of the proposed system. Furthermore, this coherent detection scheme efficiently suppresses the optical crosstalk from the neighbouring lasers. In comparison to the single spot-raster scan system, the acquisition time is significantly shortened as the mechanical scanning process in one axis is replaced by concurrent acquisition at all channels/pixels. Furthermore, the use of a 2D VCSEL array will remove the need for mechanical scanning completely, thus improving acquisition time, temporal resolution and reducing mechanical complexity.

An overview of VCSEL activity at EFPL, LPN is presented in ref [3]. The conclusion of this paper is that long wavelength VCSELs are very well positioned to enable low power consumption modules for future optical systems, especially those using advanced photonic technology. In particular, it is demonstrated that the wafer-fusion approach will contribute significantly to the progress of industrial fabrication of VCSELs emitting in the 1310 nm band for high speed WDM and other applications (for skin cancer diagnostic, for example). As stated in ref [2] the use of a 2D VCSEL array will remove the need for mechanical scanning completely. Taking into account that with demonstrated wafer fused longwavelength VCSELs and the concept of high accuracy and fast integration into silicon photonics integrated circuit [4,5], one can expect the possibility to have the necessary electronic circuitry for extraction of the data on the same silicon "mother board".
EPFL and Beam Express have reported at *VCSEL days* a further improvement in VCSEL performances [6]. This particular VCSEL application of blood flow imaging was the focus of attention during *VCSEL days 2014.*

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[2] Yah Leng Lim et all, Self-mixing flow sensor using a monolithic VCSEL array with parallel readout. Optics Express, vol 18, N11, 11720, (2010),
[3] V.Iakovlev et all. Progress and challenges in industrial fabrication of wafer-fused VCSELs emitting in the 1310 nm band for high speed wavelength division multiplexing applications, Proc. SPIE 8639, Vertical-Cavity Surface-Emitting Lasers XVII, 863904 (March 13, 2013); doi:10.1117/12.2003759.
[4] http://www.fab2asm.eu/consortium/beamexpress-sa.html.
[5] Ref 4.
[6] Ref 5, Iakovlev VCSEL day 2014

The possible arrangement for 3D imaging (depth sectioning).

One of the possible arrangements of VCSELs for 3D imaging (depth sectioning) is presented in Figure 1. As one can see, for the monitoring of the 3D imaging (depth sectioning) it is necessary to have at least 2 VCSELs for one "pixel" in the image, so a depth scanning using 2D VCSEL arrays presents a real challenge and we do not have identified yet a prototype of such array in literature.

Philipp Gerlach from PHILIPS Technologie GmbH ULM Photonics has presented VCSELs for Oxygen Sensing by TDLAS. In the discussion we have asked him about his opinion on VCSELs for blood perfusion imaging. He has indicated that Philips have "Twin-Eye" Product[7].

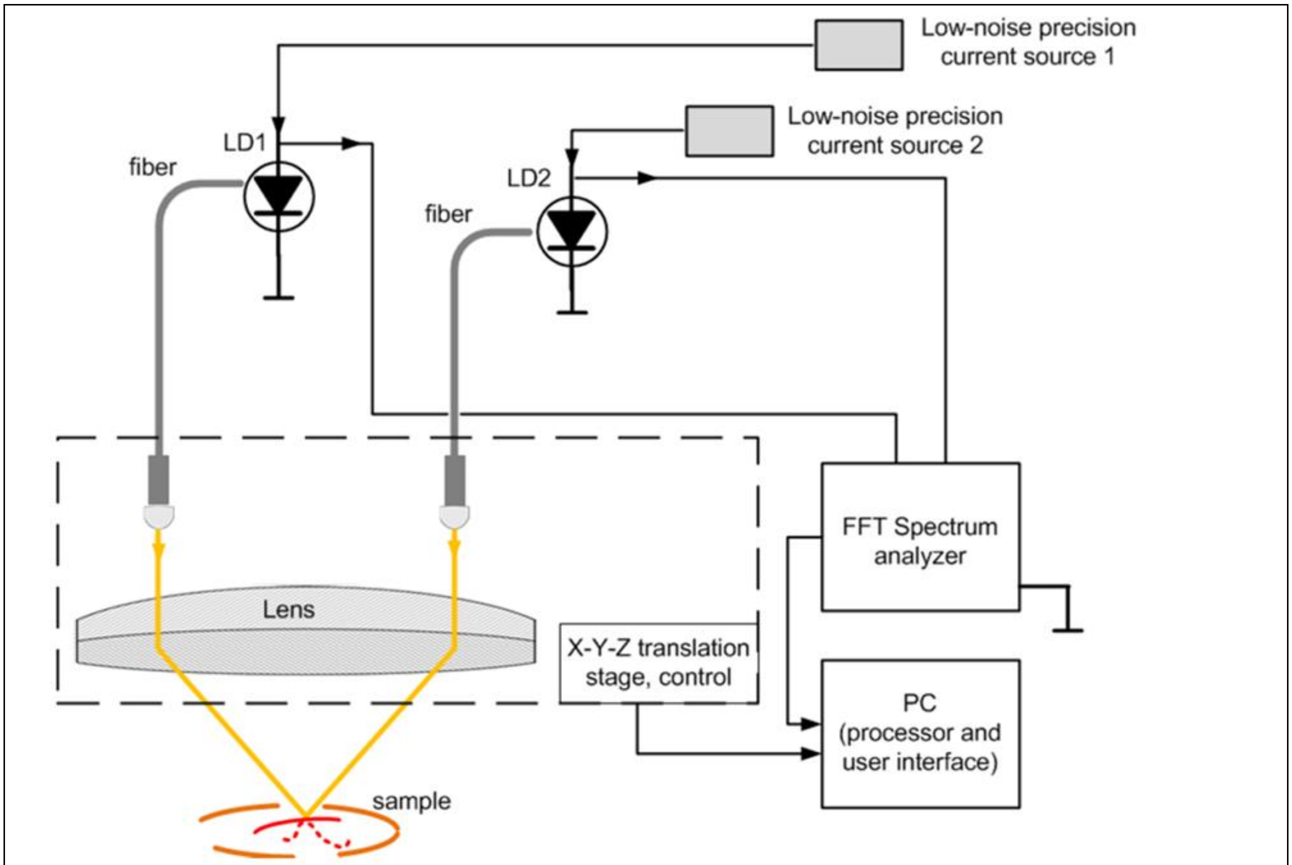

Figure 1

It is a new generation of highly integrated, ultra-small position/velocity sensors. In comparison to other optical sensors, such as LED- and CCD-based devices, this sensor has high resolution, consumes less power and can detect the movement of virtually any physical surface.

Philips Twin-Eye product exploits the effect of self-mixing, as described above. This interference effect, which depends on the frequency difference between the emitted and reflected radiation caused by motion of the target, results in power fluctuations in the laser that are detected by a photo-diode integrated into the sensor. The resolution is similar to that in far more expensive laser Doppler

[7] http://link.springer.com/book/10.1007%2F978-3-642-24986-0

interferometers. By modulating the wavelength of the laser, one can detect the direction in which the target surface is moving, as well as its speed.
Probably one of the best features of the Philips Twin-Eye sensor is its small form factor of less than $0.2cm^3$. It consists of two VCSELs that are able to measure the velocity in x- and y-direction, as well as the height above the surface. There is also an integrated photodiode that measures fluctuations in laser power, injecting the photocurrent into an application-specific integrated circuit, which converts the signal into a digital signal, applies the fast Fourier transformation so the undulation frequency (and therefore the speed relative to the scattering surface) can be determined.
The top surface of the system is a lens made of material resistant to hand and wave soldering. This lens has one outer sphere, but two inner ones, so that VCSELs could be placed off-axis to the inner spheres such that the two beams exit the lens with an angle of 90° with respect to each other and 30° with respect to the surface normal. These lenses project two orthogonal laser beams for X-Y position sensing. Working together, they can also simultaneously detect the Z-axis. The focal point is designed a few millimetres above the lens, making the sensor sensitive only to surfaces in its vicinity. These low-power sensors have the potential to measure movements of less than 1 µm and velocities of several meters per second. As mentioned above, 2D array of these devices can be used for complete monitoring of blood flow, having additional information of all three axes.

Competing approaches for monitoring of blood perfusion

During this STSM we have discussed the potential competitors of the concept described in ref [1,2].
Let us see first if we have competitors in building Laser Doppler Blood Flow Imaging, the main "task" that was supposed to be performed using VCSELs. As we have seen above (ref [2]), one can use laser arrays, but it turns out that using only one laser that will illuminate region of interest one can get images of blood flow [[8]]. The authors of ref [8] are claiming that a 64 × 64 pixel fully integrated CMOS sensor for blood flow imaging is demonstrated. The sensor efficiently integrates analog and digital processing electronics on a single chip, which provides advantages over the existing blood flow imaging systems. We have to note that similar electronics may be needed in case of using the approach proposed in ref [1,2].

Other applications of VCSELs for the goals of BM1205

We do know that OCT [[9],[10]], and we do know that in INSA it was demonstrated a new concept of tunable VCSELs [[11]]. A 1.55µm emitting tunable vertical cavity surface emitting laser (VCSEL) is fabricated, using an intracavity nematic liquid crystal layer. Half cavity VCSEL are realized on InP(001), based on quantum

[8] Ref 6. Diwei He et all, Laser Doppler Blood Flow Imaging Using a CMOS Imaging Sensor with On-Chip Signal Processing, Sensors 2013, 13, 12632-12647; doi:10.3390/s130912632.
[9] V. Jayaraman, et all, OCT Imaging up to 760 kHz Axial Scan Rate Using Single- Mode 1310nm MEMS-Tunable VCSELs with >100nm Tuning Range Lasers and Electro-Optics (CLEO), 2011 Conference.
[10] V. Jayaraman et all, High-sweep-rate 1310 nm MEMS-VCSEL, with 150 nm continuous tuning range, ELECTRONICS LETTERS 5th July 2012 Vol. 48 No. 14
[11] O. Castany et all, Demonstration of a 34 nm monolithic continuously tunable VCSEL at 1.55 µm combined with liquid crystal, 23rd International Conference on Indium Phosphide and Related Materials – IPRM 2011, May 22-26, 2011, Berlin, Germany

wells associated with broadband dielectric mirror, followed by the insertion of a 3µm thick liquid crystal layer in the cavity. Room temperature laser emission is obtained in the 1.5µm wavelength range. Single mode emission with a continuously tuning range of 34 nm is demonstrated by applying a voltage on the liquid crystal layer as low as 2.4 V. Output tunable VCSEL peak emission is polarized along the liquid crystal extraordinary axis. Considering that the full liquid crystal index variation for voltage close to 10 V results in a wavelength tuning as high as 100 nm, these preliminary results demonstrate the interest of nematic liquid crystal in achieving polarization stabilized widely tunable and monolithic VCSELs.
During the STSM at INSA we have identified the motivation to combine expertize of wafer fusion fabrication approach with concept of tuning wavelength using an intracavity nematic liquid crystal layer. It is planned to join resources of LPN in EPFL and at INSA for preparing a proposal for Horizon 2020.

Terahertz generation using VECSELs

During STSM at INSA we have visited the lab demonstrator of a VECSEL emiting 2 wavelength that makes possible terahertz generation. The tissue characterization at THz frequencies of BM 1205 may be interested. In ref [[12]] a continuous wave, single-frequency terahertz (THz) source emitting 1.9THz is demonstrated. The linewidth is less than 100 kHz and the generated THz output power exceeds 100µW. The THz source is based on parametric difference frequency generation within a nonlinear crystal located in an optical enhancement cavity.
Theoretical simulations [[13]] demonstrate the capability of the dual-wavelength VECSEL to efficiently generate the DF far-infrared radiation by means of the intracavity nonlinear frequency conversion. Recently [[14]] EPFL reported results on the design, fabrication and characterization of electrically pumped vertical external cavity surface emitting lasers (EPVECSELs) emitting at 1470nm. They demonstrate 6.2mW of CW output power, which represents the highest power value reported so far for EPVECSELs in the 14XX nm and 15XX nm wavelength bands.

[12] Justin R. Paul et all. Narrow linewidth single-frequency terahertz source based on difference frequency generation of vertical-external-cavity source-emitting lasers in an external resonance cavity
[13] Yuri A. Morozov et all. Intracavity Nonlinear Frequency Down-Conversion in a Continuous-Wave Operation Regime of a Dual-Wavelength Vertical-External-Cavity Surface-Emitting Laser. IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 19, NO. 5, SEPTEMBER/OCTOBER 2013
[14] Ref 12. A. Caliman et all. 14XX nm-wavelength electrically-pumped VECSELs fabricated by wafer fusion, OPTICS EXPRESS, June 2013 | Vol. 21, No. 11 | DOI:10.1364/OE.21.013668.