# Towards fully integrated, low cost Optical Coherent Tomography systems

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*We present here the current achievements in making an all-in-one OCT system solution based on Si integrated photonic circuits and MEMS technology carried out within the Biopsypen project. The monolithic integration of a photonic circuit, a mirror, a collimating lens and a photodetector with an actuator system provides intrinsic alignment of the components and excludes time consuming packaging procedures. Placing all components in one chip allows wafer scale fabrication process leading to low cost handheld medical devices.*

## Dermatological background

A skin cancer, besides being the most common skin problem among Caucasian population, is epidemically rising 3- 8 % per year, putting future generations at higher health problem risk [1]. An early detection has been proved to have a key role in increasing the number of successful medical treatments and lowering its medical cost at the same time [2]. A standard medical biopsy implies surgical tissue removal by a trained medical specialist. Except being harmful and slow, it gives only a temporary disease condition and it is not suitable for periodical monitoring of the skin changes.

To follow live morphological changes in time of moles and lesions, a non-invasive and high-resolution imaging technique is needed. Among currently used techniques such as high-frequency ultrasound, confocal microscopy, optical coherence tomography (OCT), micromagnetic resonance imaging and multiphoton tomography, only OCT has good both lateral resolution of around 10 µm and imaging depth of several millimeters [3]. One of the first demonstrated OCT applications in dermatology used 1.3 µm wavelength [4] which is nowadays also a standard operating light.

There are several commercially available dermatological OCT scanners. However, all of them are bulky on-site systems made of several discrete components and with a high price (~100k€). Even more, due to their misalignment sensitivity they require often maintenances thus making cost of ownership is also high. Unfortunately, all listed limitations are big drawbacks for OCT application in everyday dermatological diagnostics.

## Motivation for integrated MOEMS device

To bring OCT systems in wide use among dermatologists, first both initial and ownership costs should be much lower. Further, portability of the devices will enable inspection of patients anyway in the world. Therefore, the size of the whole systems must be reduced without performances loss. Miniaturization of all system components have partially helped to reduce system footprint. However, time consuming and expensive alignment and packaging procedures remain unsolved.

Using integrated optics, both size and costs can be significantly reduced while still providing a good image quality. Monolithic integration also solves the problem of alignment. Further, integrated optics technology provides significant fabrication scalability, especially in silicon based systems. Several recent studies showed promising results of integrated photonics usage in OCT. Integration was focused on replacing interferometer made of discrete components such as fibers and beam splitters with photonic integrated circuit (PIC) [5-7]. However, they did not focus of light beam movement which is one of the key feature of any scanner.

To generate image in more than single points, light movement is needed. Implementation of MEMS technology in OCT scanner is another approach towards miniaturization. MEMS micro mirrors are widely used wherever lighting manipulation is needed, especially for handheld OCT probes [8]. Even if MEMS technology significantly reduced the size of OCT systems, alignment and packaging remains unsolved with this approach.

Clearly, to make a transition of OCT scanners to commercial application, novel devices need to be developed. Two, novel solutions for self-aligned integrated MEMS based OCT imaging solution is presented in Fig. 1. The system given in Fig. 1a provides *x* direction scanning by tilting the lens around torsional hinge using MEMS actuator system. For *y* direction scanning, which is given in Fig. 1b, actuators need rotate the lens by deflecting supportive hinge. To simplify the illustration, photonic circuit is presented with a simple waveguide. A measurement arm of the interferometer, i.e. a waveguide ends up with a 45 ° mirror which scatters lite down to a Si collimating lens. Since both deflecting and torsional hinges are carrying the waveguide, hinge deformation should ensure that no extra optical loses are induced.

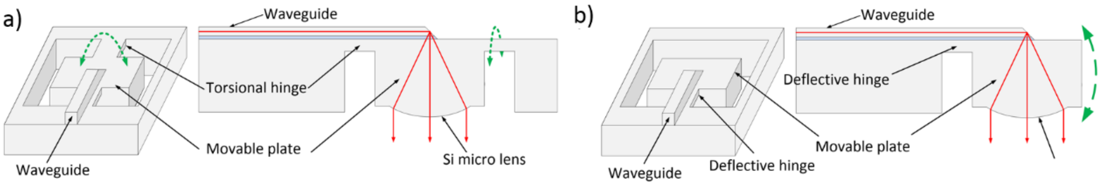

Figure 1. New concept for integrated self-aligned OCT system for (a) *x* directional scanning (b) *y* directional scanning.

## Current achievements within Biopsypen project

Integration of all OCT components can be separated in several steps. First, all components should be developed separately. Next step is the integration of the photonic components together. Finally, the MEMS actuator system should be built on an Si photonic platform.

For detection of light (1.3 um), crystalline Ge grown on Si substrate is used. Design and properties of the developed integrated photodetector is presented in [9]. In Fig. 2a shows a SEM image of a detector while in Fig. 2b shows its dark current characteristics. With a dark current level below 0.1 nA, this detector is promising for sensor application. However, to make it more suitable for OCT systems, further development should be focused for improvement of its responsivity.

To collimate the light, Si micro lenses are made using photoresist thermal reflow fabrication process given in [10]. Based on a transfer function presented in [10], lenses of 150 µm in diameter and radius of curvature of 526 µm, which give focal length of

740 µm. This value is a bit higher than used wafer thickness and should be tuned to 700 µm to get perfect collimation of the light. A white light interferometer image of Si micro lens is shown in Fig. 2c while its cross section is given in Fig. 2d.

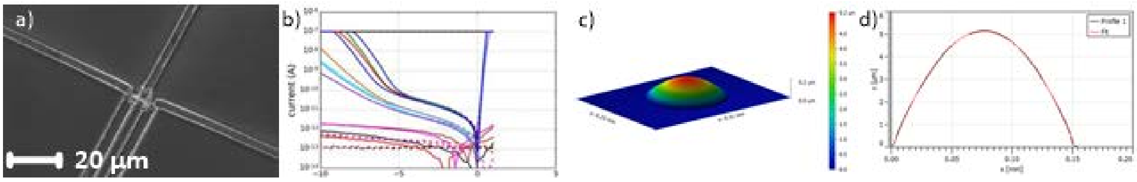

Figure 2. Ge photodetector presented in [9]: (a) SEM image of the detector and (b) dark current response. Developed Si micro lens for integrated OCT system: (a) 3D profile (b) Cross section profile.

To scatter the light from the waveguide towards Si micro lens, waveguides are first etched in two-step etching process and then cut using TMAH based solution to form 45° facet in <110> plane of crystalline. Test structures for waveguide fabrication showed total optical losses of around 3 dB which is slightly higher than 2.1 dB loses on the same structure made by than commercially available process described in [11]. Fabricated mirror introduced additional 1 dB of losses which is probably caused by non-optimum etching process. In Fig. 3 are given SEM images of fabricated waveguide and the waveguide ending with 45° mirror. Further integration of waveguide, mirror and the lens did not introduce any additional optical losses. Since the lens is physically on the other side of the chip it is not possible to present here the integration of all photonic components.

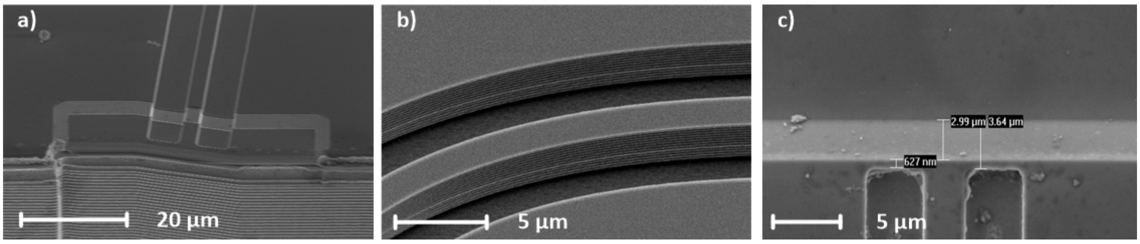

Figure 3. SEM image of waveguide (a) entry facet (b) S-bend (c) 45° ending mirror facet.

Finally, after integration of all photonic components, MEMS actuator system which is presented in [12] is built on fabricated photonic circuit. An image of packaged OCT chip is presented in Fig. 4a. Close look at fabricated MEMS actuators and waveguides for both *x* and *y* scanning are given in optical images presented in Fig. 4b and Fig. 4c respectively.

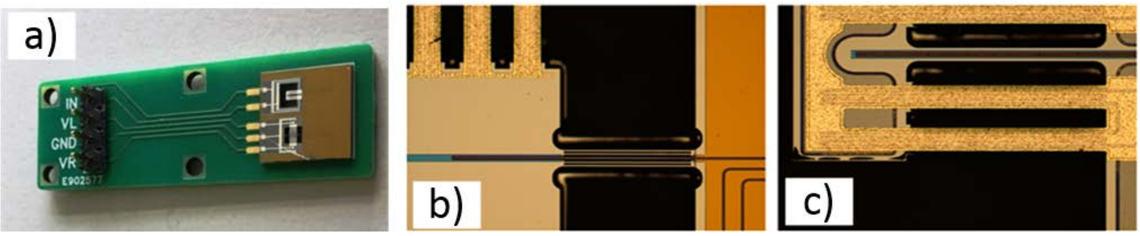

Figure 4. (a) Photo of packaged OCT chip; Optical image of actuator system for (b) *x* and for (c) *y* direction scanning.

The integrated chip is tested using a 1.3 µm super luminescent diode and a CCD camera with a 20 µm pixel size. In Fig. 5a is presented a CCD camera image of the beam from the colimiting lens when the MEMS system is not actuated while in Fig. 5b shows a CCD image when the actuators moved the beam. The measured scanning range is 1.6 mm while intensity calculations showed no additional losses while actuating?

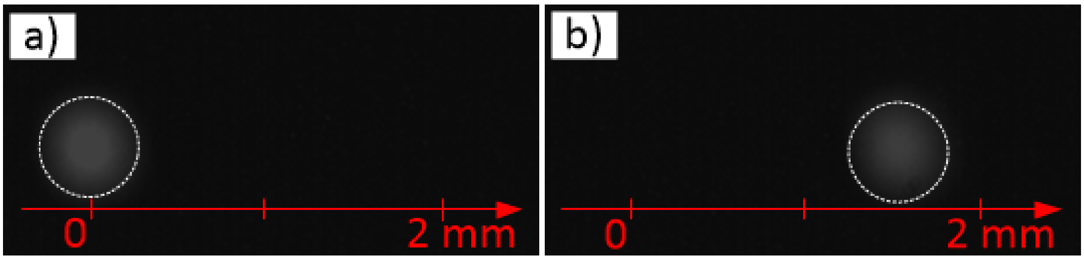

Figure 4. CCD image of the beam in (a) non- actuated state (b) actuated state of the MEMS system.

## Conclusion and future work

The presented research is a clear guideline towards full integrated OCT on chip imaging solution. Next step in building such device is the incorporation of Ge photodetectors and optical modulators to the passive photonic circuit with MEMS actuators and finally the integration of an hybrid integrated light source. Finally, combining *x* and *y* scanners into a 2D scanning system will result in complete 3D imaging OCT chip.

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## References

[1] F. Erdmann et al., “International trends in the incidence of malignant melanoma 1953–2008—are recent generations at higher or lower risk?”, International Journal of Cancer, Vol. 132, Iss. 2, 385-400, 2013.
[2] D.S. Rigel and J.A. Carucci, “Malignant Melanoma: Prevention, Early Detection, and Treatment in the 21st Century”, CA: A Cancer Journal for Clinicians, Vol. 50, No. 4, 215-236, 2000.
[3] T. Gambichler, V. Jaedicke and S. Terras, “Optical coherence tomography in dermatology: technical and clinical aspects”, Archives of Dermatological Research, Vol. 303, Iss. 7, 457-473, 2011.
[4] J.M. Schmitt, M.J. Yadlowsky and R.F. Bonner, “Subsurface imaging of living skin with optical coherence microscopy”, Dermatology, Vol. 191, No. 2, 93-98, 1995.
[5] G. Yurtsever et al., “Photonic integrated Mach-Zehnder interferometer with an on-chip reference arm for optical coherence tomography”, Biomedical Optics Express Vol. 5, Iss. 4, 1050-1061, 2014.
[6] B.I. Akca et al., “Toward Spectral-Domain Optical Coherence Tomography on a Chip”, Journal of Selected Topics in Quantum Electronics, Vol. 18, No. 3 1223- 1233, 2012.
[7] Y. Hunag et al., “Wide-field high-speed space-division multiplexing optical coherence tomography using an integrated photonic device”, Biomedical Optic Express, Vol. 8, No. 8, 3856-3867, 2017.
[8] J. Sun and H. Xie, “MEMS-Based Endoscopic Optical Coherence Tomography”, International Journal of Optics, Vol. 2011, Article ID 825629, 2011.
[9] G. Pandraud, S. Milosavljevic, A. Sammak, M. Cherchi, A. Jovic and P. M. Sarro, “Integrated SiGe Detectors for Si Photonic Sensor Platforms”, Proceedings, Vol/ 1. Iss. 4, , 559(1-5), 2017,
[10] A. Jovic et al., “Fabrication process of Si microlenses for OCT systems”, Proc. SPIE 9888, Micro-Optics, 98880C, 2016.
[11] K. Solehmainen, et al., “Dry-Etched Silicon-on-Insulator Waveguides With Low Propagation and Fiber- Coupling Losses”, Journal of Lightwave Technology, Vol. 23, No. 11, pp 3875-3880, 2005.
[12] A. Jovic et al., “Two novel MEMS actuator systems for self-aligned integrated 3D optical coherent tomography scanners” 2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS), Las Vegas, NV, 797-800, 2017.