Mirau micro-interferometer for swept-source optical coherence tomography endomicroscopy

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***Abstract*— We focus on the design and technology of Mirau micro-interferometer, which is a key part of MOEMS endomicroscopic probe, operating with Swept-Source Optical Coherence Tomography detection.**

Keywords—component; Integrated glass lens, MOEMS Mirau micro-interferometer, SS-OCT endomicroscope.

I. INTRODUCTION

The early detection of stomach cancer allows to increase significantly the treatment efficiency and survival rate of patient. Biopsy followed by histological examination is nowadays the gold standard for clinicians. However, this procedure is invasive, painful for patient and time consuming. Research is being conducted towards the development of fast and non-invasive methods for early cancer detection. One of the most attractive methods combine endomicroscopy and a Swept-Source Optical Coherence Tomography (SS-OCT). The SS-OCT permits real-time 3D optical biopsy of biological tissue with high resolution (~5µm) and relatively big penetration depth (~1.5mm). The technology of micro-opto-electro-mechanical systems (MOEMS) has unique ability to produce millimeter-sized OCT probes, consisting of well-aligned passive or active components to perform necessary optical functions (focusing, scanning etc.) [1]. Further miniaturization of SS-OCT system is possible by integrating its core component: a miniature interferometer, into OCT probe.

This paper presents a concept of the SS-OCT endomicroscope for early detection of stomach cancer, using an integrated and pigtailed Mirau micro-interferometer. Here, we describe the design and technology of the vertically integrated Mirau micro-interferometer and focus on the optical characterization of a selected key components: silicon base with integrated glass lens, fabricated by thermal glass reflow.

II. DESIGN.

The SS-OCT endomicroscope contains a swept-source, an optical fiber-based circuit, a MOEMS probe and a detection block (Fig. 1). The main component of the endomicroscope, the MOEMS probe, includes an optical input-output circuit, based on GRIN lens collimator, and a common path Mirau micro-interferometer for both focusing of the optical beam on tissues and generating interferences, which is necessary to create a single-point tomogram (A-scan). The Mirau micro-interferometer is fabricated by wafel-level vertical stacking and bonding of silicon-glass components: silicon base, glass lens, reference mirror, separator and beam splitter. The MOEMS probe is connected to a continuum robotic arm, which is placed on the extremity of the endomicroscope and allows the 3D scanning of stomach tissue.

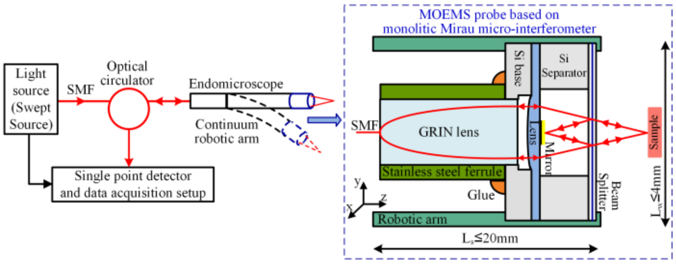

Fig. 1. Scheme of the SS-OCT endomicroscope and construction of MOEMS probe based on Mirau micro-interferometer.

III. FABRICATION

The technological process of the Mirau micro-interferometer is presented in Fig. 2. The hybrid components of Mirau micro-interferometer are fabricated separately and assembled by anodic bonding. In the first step, the silicon base is fabricated on 4 inch, (100)-oriented and 500-µm-thick wafer. This part is used as a mechanical support of whole Mirau micro-interferometer and allows the passive alignment of GRIN lens along the optical axis of the glass lens. The Si base has two cavities: a lens cavity with 300 µm depth (top side of wafer) and a GRIN lens assembly port with 100 µm depth (bottom site). The silicon cavities are fabricated by two subsequent photolithography steps and deep reactive ion etching (DRIE) as shown in Fig. 2a-b. A thin membrane (100 µm) placed between cavities is necessary to keep vacuum in lens cavity during subsequent fabrication of glass lens. According to this method, the silicon base wafer is anodically bonded in vacuum to 500-µm-thick Borofloat®33 glass wafer (Fig. 2c). The structure is then heated in furnace. Due to the vacuum created in the cavity, and hence high pressure difference between lens cavity and environment, the glass flows into cavity (Fig. 2d). After reflow process, glass wafer is polishing to obtain plano-convex lens. Next, the silicon membrane is removed by DRIE etch to release the glass lens (Fig. 2e). The next step is the deposition of a reference micro-mirror (Cr/Au) on the polished glass wafer using e-beam evaporation (Fig. 2f). A silicon separator is then connected to the silicon-glass structure by anodic bonding process (Fig. 2g). The separator thickness is selected to ensure the position of

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planar beam splitter in the middle of focal length of the reflowed glass lens.

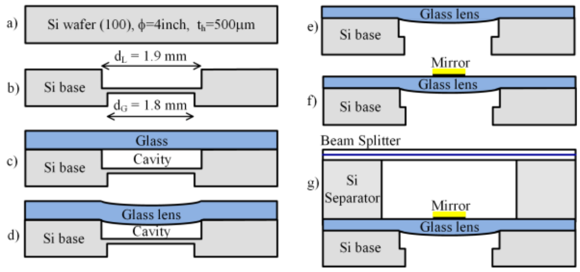

Fig. 2. The main technological process steps of Mirau micro-interferometer.

IV. EXPERIMENTAL RESULTS

The most important issues to ensure proper operation of the MOEMS probe are: accurate positioning of each building components (GRIN lens, glass lens, mirror, separator, beam splitter) during vertical integration, and also appropriate profile of the focusing glass lens after reflow. The profile of the lens has an impact on: optical properties (focal length f_l, shape of light beam in focal plane, imaging resolution) and on geometrical dimension of the MOEMS probe (distance between lens and beam splitter, working distance of the probe). The profile of the lens depends on the following technological parameters of glass reflow: time t_r, temperature T_r, pressure P_r and diameter of silicon cavity d_L. Therefore, it is important to calibrate technological parameters of glass reflow, which in turn allows to formation of a glass lens with required focal length f_L for endomicroscope probe application: in this case f_L = 10.6 mm. The glass lens presented below was reflowed at temperature T_r=650°C for time t_r=100 min. The sag of the lens S_L = 94.9 µm was measured after dicing through lens center by Scanning Electron Microscope. The cross section of the lens is presented in Fig. 3 a. Silicon base of Mirau micro-interferometer with integrated glass lens after release is presented in Fig. 3b.

a) b)

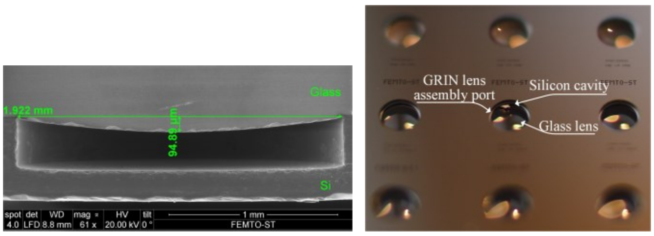

Fig. 3. Cross section of reflowed lens into cavity before releasing a), Silicon base with integrated glass lens b).

The lens surface curvature was measured using Microsystem Analyzer MSA-500 from Polytec (Fig. 4a). Measured radius of curvature of the lens is equal to R_L=4.95mm. The cross section of lens surface curvature and matched theoretical circle (radius R_L) are presented in Fig. 4b

a) b)

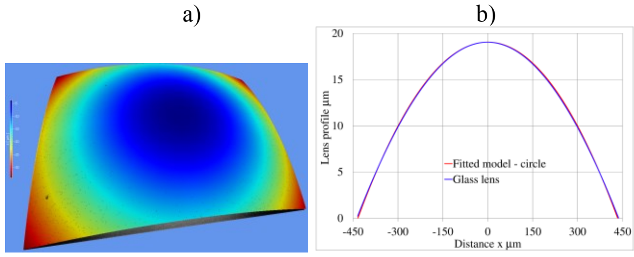

Fig. 4. Geometrical properties of reflowed lens: a) surface, b) profile.

The optical quality of the reflowed glass lens was measured by method based on the 3D Intensity Point Spread Function, operating in transmission mode [2]. Registered in-focus distribution of light intensity in the direction transverse to the optical axis is presented in Fig. 5a. Distribution of the light intensity in center of an Airy disk is presented in Fig. 5b.

a) b)

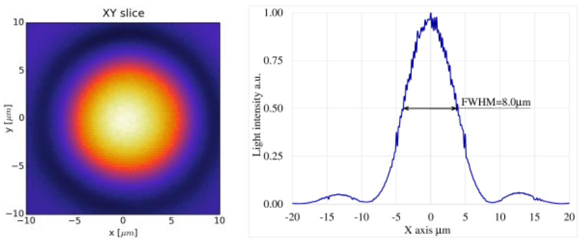

Fig. 5. The Airy disk in focal plane: a) light distribution, b) cross section of light intensity.

V. CONCLUSION

We present a new construction of MOEMS-based SS-OCT probe with integrated Mirau micro-interferometer for endomicroscopy applications. The glass lens has been successfully integrated to a silicon base of Mirau micro-interferometer. The main advantages of glass reflow into silicon cavity is a non-contact process, resulting high surface quality. The glass lens is characterized symmetrical and near to spherical shape. The MOEMS probe thanks to small external dimension (max. 4mm x 4mm x 20mm) can be connected with robotic arm and placed at the end of endomicroscopy. Presented technology of MOEMS probe is suitable for mass production (230 structures can be fabricated on 4 inch wafers).

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