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Chip based common-path optical coherence tomography system with an on-chip microlens

Abstract

We demonstrate an integrated optical probe including an on-chip microlens for a common-path swept-source optical coherence tomography system. This common-path design uses the end facet of the silicon oxynitride waveguide as the reference plane, thus eliminating the need of a space-consuming and dispersive on-chip loop reference arm, thereby obviating the need for dispersion compensation. The on-chip micro-ball lens eliminates the need of external optical elements for coupling the light between the chip and the sample. The use of this lens leads to a signal enhancement up to 37 dB compared to the chip without a lens. The light source, the common-path arm and the detector are connected by a symmetric Y junction having a wavelength independent splitting ratio (50/50) over a much larger bandwidth than can be obtained with a directional coupler. The signal-to-noise ratio of the system was measured to be 71 dB with 2.6 mW of power on a mirror sample at a distance of 0.3 mm from the waveguide end facet. Cross-sectional OCT images of a layered optical phantom sample are demonstrated with our system.

This chapter has been published in:

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C.1 Introduction

Optical coherence tomography (OCT) [1] is an optical imaging technique which provides three-dimensional images with micrometer-resolution. OCT imaging of biological tissue has many clinical applications [137, 138]. More recently, OCT has also been increasingly used in industrial applications [139, 140, 141, 142, 143]. The state-of-the-art OCT systems are based on Fourier-domain OCT (FD-OCT) [144], which provides a sensitivity advantage over time-domain OCT (TD-OCT) [115]. FD-OCT is performed as either spectral-domain OCT (SD-OCT) with a broadband light source and a spectrometer or swept-source OCT (SS-OCT) with a narrow-bandwidth frequency-swept light source [137]. FD-OCT systems provide a one-dimensional depth image (known as an A-scan) with a Fourier transform of the measured spectrum. The cross-sectional images (known as B-scans) are commonly measured by scanning the beam over the sample (such as using a galvanometer scanner) [144].

Currently, most of the OCT systems are based on discrete free-space optical components and fibers. The development in integrated optical circuit technology provides the opportunity to develop chip-based OCT systems having the potential for considerable size and cost reduction. Recently, several chip-based FD-OCT systems have been demonstrated. Akca et al. demonstrated a SD-OCT system with a $2 \times 2$ splitter and an integrated spectrometer based on silicon oxynitride (SiON) waveguides where the reference arm was not integrated on the chip [122]. Nguyen et al. demonstrated a SS-OCT system with a Si$_3$N$_4$ waveguide based interferometer and reference arm [79]. Nguyen et al. also demonstrated focusing with chip based Fizeau OCT, similar to the work performed here [112]. Yurtsever et al. demonstrated two different OCT systems [124, 145]. Both systems have a sufficiently long on-chip reference arm to accommodate a galvanometer scanner in the sample arm to obtain B-scans.

In systems with an on-chip reference arm, the dispersion difference between the reference arm and the sample path needs to be compensated using methods that may reduce the attainable axial resolution [145]. The on-chip reference arm has also relatively large dimensions in many OCT chips, especially in low-contrast waveguide technology where the minimum bending radius is the limiting factor for miniaturization. Another common practical challenge in chip based systems is the design and fabrication of a broad-bandwidth 50/50 coupler to be used in the interferometer, see e.g. [146]. Directional couplers are wavelength-dependent devices of which the coupling ratio is strongly dependent on fabrication accuracy, as reported in [79]. Both deficiencies decrease the efficiency of the OCT system. In all of these chip-based OCT studies, external lenses are needed for the optical chip-to-sample coupling. These external elements can be much larger than the chip itself.

In this study we demonstrate a chip-based common-path SS-OCT system that addresses the problems of current designs. Firstly, by using a common-path OCT system we avoid the need of a separate reference arm. Some advantages of common-path OCT compared to dual-arm OCT are a greater ease of alignment, a smaller sensitivity to vibration and a better stability. These have been demonstrated in several free-space-based or fiber-based OCT systems [147, 148, 149, 150]. On our chip we exploit the back reflection from the end facet of the waveguide to act as
the reference, thus obviating the need for a separate reference arm. This leads to a significantly smaller footprint of each OCT system which could be interesting for chip-based parallel OCT. This solution not only saves space on the chip, but also eliminates the decrease of axial resolution caused by dispersion [115]. Secondly, the three ports (the light source, the detector, and the common-path arm) of the chip are connected by a symmetric Y junction. Such junctions are intrinsically wavelength independent and their design and fabrication are less critical than for a directional coupler. Thirdly, a directly integrated micro ball lens [151] is positioned at a short distance from the waveguide facet for efficient coupling of the light between the chip and the sample. This micro-ball lens is the key component enabling the common-path configuration. The lens significantly reduces the divergence angle of the light exiting from the waveguide, thus improving the lateral resolution and the chip-sample coupling compared to the case without a lens. Our SS-OCT has a maximum optical depth range of 5.1 mm (measured from the end facet of the waveguide, limited by the laser source and detector-determined spectrum resolution), of which the lens occupies only the first 0.2 mm, thereby leaving sufficient room for the sample.

The introduction of a lens causes additional reflections at the lens surface, which act as additional parasitic reference planes that reduce the image quality. This artifact has also been observed in a fiber-based common-path OCT system with a 500 μm diameter ball lens [150]. We demonstrate the recovery of the image quality by using a deconvolution algorithm which is more generally applicable to other OCT systems suffering from the effects of multiple reference planes.

C.2 Experimental set-up

The key components of the integrated optical circuit are a Y junction (200 μm long, 7 μm wide) and a polymer micro-ball lens (100 μm in diameter). The circuit was fabricated on a silicon substrate with SiON waveguide technology which was developed in the Integrated Optical MicroSystems group at the University of Twente [152]. The waveguide core is a 600 nm thick, 2 μm wide SiON channel embedded in a SiO2 layer. The refractive index of the SiON and SiO2 parts are 1.55 and 1.45, respectively, at λ = 1300 nm. The integration of the polymer micro-ball lens with the SiON waveguide chip is based on photolithography and thermal reflow of a photoresist polymer [151].

The schematic layout of the SS-OCT system is shown in Fig. C.1(a). Light emitted from the swept laser (Axsun Technologies, USA, 1312 nm center wavelength, 92 nm optical bandwidth, 20.9 mW output power, 50 kHz repetition rate) travels through an optical isolator (OI) and is coupled to the chip through a fiber array unit (FAU) with a 250 μm pitch. The splitting ratio of the Y junction has been measured to be between 48/52 and 52/48 in the wavelength range of 1170 nm to 1650 nm by a separate setup. The wavelength range is limited at the short wavelength side by the waveguide becoming multi-modal and at the long wavelength side by the available InGaAs detector. The in-coupled light propagates through the Y junction with approximately 50% efficiency. The waveguide end facet, which back-reflects part of the light, acts as a reference plane as shown in Figs. C.1(b) and Fig. C.1(c). Due to the etching process, this facet is angled at 86 degrees (θ) with respect to
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Figure C.1: Schematic of the SS-OCT experimental setup. (a) Light emitted by the swept laser source travels through an optical isolator (OI) and a fiber array unit (FAU) to the chip. The blue lines indicate optical fibers and the yellow lines represent the waveguides on the chip. (b) Microscope image of the end part of the chip showing the channel waveguide and the micro-ball lens. (c) Schematic of the side view of the structure in (b). The end facet is angled at 86 degrees ($\theta$) with respect to the Si substrate plane.

the substrate plane, as shown in Fig. C.1(c). Thus, only 60% (simulated with a beam propagation method [153]) of the Fresnel-reflected light (3.5%) couples to a guided waveguide mode, resulting in a calculated effective power reflection of 2%, which was experimentally verified. The light that is transmitted through the facet travels through the lens onto the sample. For the experiments reported here, we chose a micro-ball-lens arrangement ($65 \pm 0.5 \mu m$ facet-to-lens-center distance, lens radius of $49 \pm 0.5 \mu m$) providing the best possible collimated beam (1.6 degrees half divergence angle, 15.3 $\mu m$ beam waist at 0.3 mm optical path length, corresponding to an expected FWHM lateral resolution of 18 $\mu m$, 29 $\mu m$, 57 $\mu m$ and 150 $\mu m$ at 0.3 mm, 1 mm, 2 mm, and 5 mm optical path length, respectively) that has been reported in our earlier paper [151] (the beam divergence experiments, in an earlier paper, are repeated at a wavelength of 1.3 $\mu m$). Part of the light back reflected from the sample is coupled into the waveguide through the lens and interferes with the light that is reflected by the end facet. This interference signal propagates through the Y junction where 50% enters into the detection branch. The output signal from the chip is coupled to a detector (Thorlabs PDB 450C, USA; only one port of this balanced photodetector is used) through the same FAU. More details about the used light source and detector configurations can be found in Ref. [59]. OCT images are generated by scanning the sample in front of the chip with a linear translation stage (Zaber T-LS28-M).

C.3 Results and discussion

As the presence of the integrated lens has been shown to provide a considerable reduction of beam divergence [151], a substantial increase of the OCT signal is expected. This improvement is quantitatively demonstrated in Sec. C.3.1. In Sec. C.3.2 we show cross-sectional images of an optical phantom sample, which were obtained
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<table>
<thead>
<tr>
<th></th>
<th>Reflected reference power $P_R$ ($\mu$W)</th>
<th>Reflected sample power $P_S$ ($\mu$W)</th>
<th>Power incident on the sample $P_I$ (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without micro-ball lens</td>
<td>12.0 ± 0.5</td>
<td>2.8 ± 0.5</td>
<td>2.9 ± 0.1</td>
</tr>
<tr>
<td>With micro-ball lens</td>
<td>14.5 ± 0.5</td>
<td>$(2.9 \pm 0.1)10^2$</td>
<td>2.6 ± 0.1</td>
</tr>
</tbody>
</table>

Table C.1: Measured reflected reference power, reflected sample power and power incident on the sample with and without a micro-ball lens. The mirror was placed at 100 $\mu$m from the waveguide facet.

with our integrated probe. Some ghost images were noticed which are caused by closely spaced (less than the coherence length of a spectral channel) multiple reference reflections from the waveguide end facet and the lens surface. A deconvolution based method is demonstrated that largely removes these ghost images. The mathematical details of this method, which is based on a model of a multiple reference Fourier-domain OCT system is described in Ref. [154].

C.3.1 Signal enhancement with a micro-ball lens

The optical power levels were measured at several positions in the optical setup without and with a microlens (Table C.1). These optical power levels are important to quantitatively understand the signal enhancement realized with the micro-ball lens. The laser power ($9 \pm 0.2$ mW before coupling to the chip) was the same for all measurements in Table C.1. A mirror sample was located as close as possible to the chip, which is approximately 0.1 mm distance, resulting in 0.3 mm and 0.1 mm optical path length from the sample to the waveguide facet in the case with and without a lens, respectively. The reflected reference power $P_R$ and reflected sample power $P_S$ were both measured at the detector location as shown in Fig. C.1(a).

The power incident on the sample $P_I$ is measured by placing a power meter at the position of the mirror sample. The signal-to-noise ratio of the system was measured to be 71 dB with 2.6 mW of power on a mirror sample at a distance of 0.3 mm from the waveguide end facet.

The results in Table C.1 show that $P_R$ and $P_I$ are similar in both systems. The slightly larger $P_R$ and slightly smaller $P_I$ in the situation with a micro-ball lens are due to reflections from the surfaces of the lens. Despite the larger optical path length between sample and waveguide facet $P_S$ is approximately 100 times larger when compared to the case without the lens. $P_R$ and $P_I$ are kept the same as in Table C.1 for all the OCT measurements with the chip system in this study. $P_S$ decreases rapidly in case of no lens, such that it cannot be measured directly (with the current setup) at larger optical path lengths but can only be calculated from the OCT measurements.

In order to study the OCT signal enhancement with the lens, the A-scan results of a mirror sample measured with and without the lens are shown in Fig. C.2(a). A peak is clearly visible at a position that corresponds to the optical path length difference between the mirror sample and the end-facet of the waveguide. For this measurement, the sample has been located at approximately 0.33 mm and 0.36 mm
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from the waveguide facet in the respective cases with and without lens; the small offset was introduced to distinguish both peaks in the same graph. This means that in the case without the lens $P_S$ at the sample is different from the value listed in Table C.1. The signal peak magnitude as measured for the chip with the micro-ball lens is a factor of 28 larger than the one measured without a lens.

The OCT signal roll-off (measured as the peak magnitude in the A-scan as a function of optical path length) with and without a micro-ball lens is compared in Fig. C.2(b). For these measurements the mirror sample was positioned at different distances from the waveguide facet, with the same light source and detector settings in all cases. The presence of the micro ball lens enhances the signal strength by up to 37 dB depending on the optical path length. In the same Figure, the calculated expected signal roll-off is presented, following Eq. (2) in Ref. [155]. For comparison, the calculated signal is normalized to the largest signal measured with a micro-ball lens. The calculated signal roll-off is based on the finite spectral resolution of the system, assuming a constant chip-sample coupling efficiency over the whole optical path length range. The values used in this calculation are 5.1 mm maximum optical path length and the ratio 0.73 of the spectral resolution to the sampling interval which is approximated by the detector duty cycle (0.73).

From Fig. C.2(b) it follows that the micro-ball lens extends the 6 dB roll-off range from $0.2 \pm 0.1$ mm to $1.7 \pm 0.1$ mm. This 6 dB roll-off range is commonly used as a characteristic parameter to indicate the signal decreasing speed of an OCT system. Since we could not measure the sample signal at exactly zero optical path length in our common-path configuration, the 6 dB signal roll-off is referred to the closest point (first point) measured in each system. The faster signal roll-off in the experiment, compared to the calculated one (which assumes a hypothetical 0 degree divergence beam), is most likely caused by the decrease of the chip sample coupling efficiency due to the beam divergence.

C.3.2 Multiple reference planes and phantom imaging

Close inspection of Fig. C.2(a) shows the appearance of relatively strong shoulders on the main peak for the case when the micro-ball lens is used. This is caused by Fresnel reflections that take place, not only at the end facet of the waveguide (the intended reference plane), but also from the front and back surfaces of the micro-ball lens. These lens surfaces, therefore, act as two additional reference planes in this common-path OCT system. Next, we will demonstrate that by using a deconvolution technique the artifacts in the A-scan caused by the lens can be eliminated. We model the measured signal as:

$$i(z) = G * H_{PSF},$$  \hspace{1cm} (C.1)

where $*$ denotes convolution and $G$ and $H_{PSF}$ denote the sample reflectivity and the point spread function (PSF) of the OCT system in the axial direction, respectively [156]. The PSF is composed of the coherence gate depending on the source bandwidth and center wavelength, and a function describing the dependence on the reflectivities and relative positions of the (multiple) reference planes. This PSF can be characterized by measuring the response of a mirror. In case of a multiple references like in our chip system, this PSF is a multi-peak function resulting in ghost images for every additional reference plane that may overlap with the image that
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Figure C.2: Characterization of the chip-based OCT system. (a) A-scan results of a mirror sample measured with and without a micro-ball lens. The signal measured without the lens is multiplied by 28 to obtain equal peak magnitude for the cases with and without lens to enable easy comparison. The insets show a zoom in to the main signal peak and the noise floor, respectively. (b) Signal roll-off measured with and with out a micro-ball lens. The peak position of each A-scan is marked with a red dot for the case with a lens and a black square for the case without lens. The peak magnitude is given in dB units, where 0 dB corresponds to the value 1 of the arbitrary units used in (a). The dashed black curve is a calculated signal roll-off based on the finite spectral resolution of the system. The red dashed lines indicate the 6 dB roll-off optical path length for each curve.

originates from the primary reference plane. A commonly used imaging processing technique, deconvolution, can be used to suppress or remove these unwanted ghost images [156].

Here, we investigate the applicability of the deconvolution technique for suppressing the ghost images. To this end, the PSF of our chip system is measured with a mirror sample, since \( G \) is a delta function in this case. A zoomed-in view of an A-scan result of a mirror sample is shown by the black curve in Fig. C.3(a), which is the PSF of our system. The effect of the two additional references is clearly visible as two additional peaks (peak 2 and 3) in Fig. C.3(a). The peaks numbered 1, 2, and 3 in Fig. C.3(a) are the interference of the mirror-waveguide-facet, mirror-lens-surface (close to the waveguide) and mirror-lens-surface (far from the waveguide), respectively. Next, this PSF is used in the deconvolution of A-scans from any sample measured with this chip system. An example of a deconvolution result is shown by the red curve in Fig. C.3(a) which shows a strong suppression of the peaks caused by reflections from the lens’ surfaces.

In theory, the measurement of \( H_{\text{PSF}} \) is not sensitive to the position of the mirror sample with respect to the reference planes. Several PSF measurements using different mirror position have been performed and no significant differences were observed in the results.

Finally, we apply our OCT system to image an optical phantom. The optical phantom that is used consists of three scattering layers separated by two transparent layers. The scattering layer is silicone elastomer-based which includes scattering by
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Adding TiO$_2$.[90] This layered sample is placed on a glass slide which is mounted on a translation stage to obtain cross-sectional OCT images. Two zoomed-in cross-sectional imagines are shown in Fig. C.3(b) and Fig. C.3(c). Each A-scan in the cross-sectional image is averaged over 30 measurements. The image after deconvolution shows a clear improvement in the contrast. This is due to the suppression of the ghost images of the scattering layers.

The full range of a deconvolved cross-sectional image is shown in Fig. C.3(d). All three scattering layers of the optical phantom can be clearly seen. The image in Fig. C.3(e) is a deconvolved cross-sectional image of the phantom measured at a larger distance from the chip. The image of the phantom becomes dimmer with increasing optical path length. Scattering layers are still clearly visible at an optical path length of 2.6 mm. Scattering (the glass holder and the sample were placed under angle to avoid specular reflection) from the rear side of the glass holder is even visible up to 4.2 mm.

Many different deconvolution algorithms exist for image processing. The deconvolution result may be different depending on the noise in the measurement and the algorithm used.[157] Since the described experiment is intended as a proof of concept that the artifacts arising from the multiple reference planes can be suppressed with a deconvolution approach, we did not perform a systematic study of different deconvolution algorithms. A further study on the selection of the deconvolution algorithms may be needed to find the optimal algorithm for this particular system.

The cross-sectional images demonstrated here were obtained by translating the sample with a mechanical stage. Since the micro-ball lens is integrated and the optical chip is a small low-mass device, an alternative implementation might mount the fiber-connected chip directly on a scanner to obtain two- or three-dimensional images.

C.4 Conclusions and outlook

In this study, we have demonstrated a chip-based common-path SS-OCT system with an integrated micro-ball lens. The common-path design eliminates the space-consuming and dispersive on-chip loop reference arm. Therefore, no dispersion compensation is needed to achieve the light-source-limited axial resolution. The three-port configuration (light source, common-path arm, and detector) enables the use of a wavelength-independent 50/50 Y junction which is much less sensitive to fabrication errors compared to a directional coupler. The drawbacks of this common-path configuration is that it cannot use a balanced detector, which leads to around 3-4 dB lower sensitivity compared to a traditional dual-arm OCT.[150] The use of an on-chip micro-ball lens eliminates the need for external optical elements for coupling the light between the chip and the sample. Such a micro-ball lens enables a very short distance of a few hundred μm between the sample and the reference plane, which is an important requirement for common-path OCT. The use of this micro-ball lens leads to a signal enhancement up to 37 dB compared to the chip without a lens, for a mirror sample. Multiple ghost images caused by additional reference planes (originating from the lens surface) could be largely suppressed using a decon-
Figure C.3: (a) A zoomed-in view of an A-scan result of a mirror sample. This plot shows the effect of multiple references on a mirror sample (black curve) and its deconvolved solution (red curve). (b) and (c) Zoomed in cross-sectional images of a phantom sample before and after deconvolution. (d) and (e) The deconvolved phantom images at different distances from the chip.

Deconvolution scheme. Finally, cross-sectional imaging of a layered optical phantom, with suppressed ghost image, has been demonstrated.

The minimum footprint of this design could, in principle, be as small as 400 μm by 100 μm, which may enable the fabrication of a chip-based parallel OCT system with multiple independent detection channels. The minimum length of 400 μm is determined from the 200 μm long Y junction plus the 100 μm diameter micro-ball lens, plus some spacing. (However, in order to facilitate testing of the device, our prototype was equipped with several cm long straight access waveguides.) The minimum width of 100 μm is determined from the diameter of the lens.

We believe that, by integrating a micro-ball lens onto the chip and using a common-path configuration, we have moved a significant step forward in the development of on-chip SS-OCT systems.