PECVD SiN photonic integrated circuit for swept source OCT at 840 nm

(Student Paper)

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ABSTRACT

Optical coherence tomography (OCT) is an imaging technique widely used for retinal diagnostics, typically operating in the wavelength region around 840 nm. Current state of the art systems use a combination of bulk and/or fiber optical components, which limits their utilization due to high cost and large dimensions. With photonic integrated circuits (PICs) both aspects can be reduced allowing for a more widespread use, especially for point of care applications. In this paper, we present the design of a prototype PIC for a swept source (SS) OCT system operating in the 840 nm wavelength region with a bandwidth of up to 100 nm. Due to the operation wavelength silicon nitride (SiN) is used as the waveguiding material. The SiN fabrication is done with a low-temperature plasma enhanced chemical vapor deposition (PECVD) process to ensure CMOS-compatibility. This enables the subsequent monolithic co-integration of opto-electronic and electronic components for on-chip signal detection and analogue to digital conversion. With the fabricated SiN waveguide chip, we show for the first time a PIC based SS-OCT system capable of in-vivo retinal imaging.

Keywords: photonic integrated circuit, optical coherence tomography, silicon nitride, PECVD

1 INTRODUCTION

Optical coherence tomography is a non-invasive interferometric technique used for cross sectional imaging [1]. The OCT image is created by interfering light reflected at different positions in a sample with light from a reference optical path, both originating from a common light source. In contrast to conventional microscopy, the axial resolution provided by OCT is independent of the numerical aperture, which makes it especially useful for retinal imaging due to the limited opening of the pupil. While OCT is already an established method in ophthalmology for retinal diagnostics, current state-of-the-art systems are expensive and bulky. This limits the widespread use in particular for point of care applications, which require cheap, light-weight and compact probes. Photonic integrated circuits (PICs) hold the promise of providing the same functionality as bulk/fiber optical systems with much smaller dimensions and unit manufacturing costs. Further, PICs can be monolithically co-integrated with opto-electronic and electronic components, further reducing the cost and size. Additionally, this would allow novel OCT designs that are challenging to implement with bulk/fiber optical components, e.g. functional multiplexing as demonstrated by Wang et al. with an integrated receiver [2].

There are two imaging modalities in OCT which can provide the cross sectional information of the sample, time domain and Fourier domain with the latter having an inherent sensitivity advantage [3]. In Fourier domain OCT the sample cross section is encoded in the spectral response of the interference and accessed with an inverse Fourier transformation. This spectral response can either be obtained with a broadband light source and a spectrometer for spectral domain (SD) OCT or with a wavelength swept light source and a photodiode recording different wavelengths at different time steps for swept source (SS) OCT. Similar performance to state-of-the-art systems is easier to achieve with a PIC based SS-OCT system, which does not require the implementation of a spectrometer. In the following section, the design of a PIC based SS-OCT system intended for retinal diagnostic is described, which includes the full functionality of a conventional optical OCT system.

2 DESIGN OF A PIC FOR SWEPT SOURCE OCT

Light probing the retina has to pass through the vitreous body, mainly consisting of water. Therefore, light with wavelengths above 1100 nm is unsuitable for this application due to the high absorption in water at these wavelengths. Consequently, the well established SOI waveguide platform cannot be used because silicon is not transparent for wavelengths below 1100 nm. OCT systems for retinal diagnostics operate in the wavelength regions around 840 nm and 1050 nm. The wavelength region around 840 nm is chosen for the PIC design in this work. This has the advantage of better axial resolution, which is proportional to $\lambda_0^2/\Delta\lambda$ with λ_0 being the central wavelength and $\Delta\lambda$ the wavelength bandwidth. To allow low loss propagation of light with a wavelength

This research has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 688173 (OCTCHIP).

of 840 nm silicon nitride (SiN) as core material and silicon dioxide (SiO2) as cladding material are chosen for the waveguide platform. Low-temperature plasma enhanced chemical vapor deposition (PECVD) is used to fabricate these waveguide layers because it opens up the highly attractive possibility of a monolithic back-end-of-line co-integration of SiN waveguides on CMOS opto-electronic chips. Low pressure chemical vapor deposition (LPCVD) would result in lower propagation losses but render this co-integration impossible.

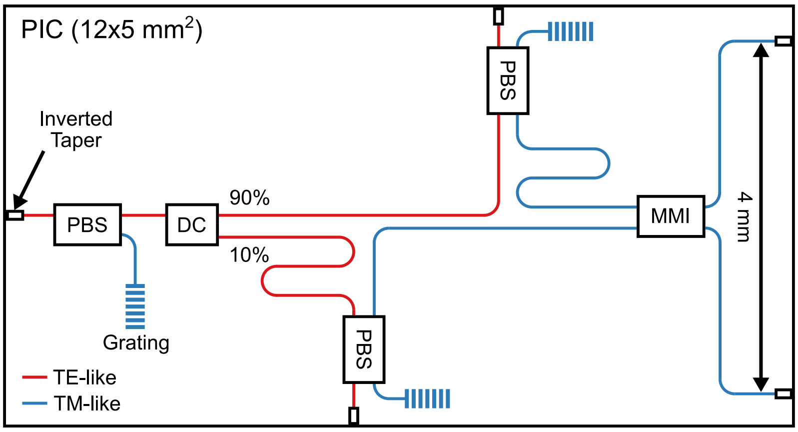

Figure 1. Schematic of the PIC design for SS-OCT. The input is on the west side and the outputs towards the balanced photodiodes on the east side. The light is coupled from the input single mode (SM) fiber to the PIC with a low-loss inverted taper. A polarization beam splitter (PBS) suppresses the orthogonal polarization and allows optimizing the input polarization by using the light emission of the grating as feedback signal. A directional coupler (DC) splits the optical power into the sample and the reference path. Before emission towards the sample and the reference mirror another PBS is passed. This allows redirecting the reflected light towards the detector by introducing a 90 degree rotation of the polarization before reentering the PIC. The returning light is brought to interference with light from the reference path at the multimode interferometer (MMI). The optical signals of both MMI output ports are guided to the east side facet of the chip.

A schematic of the PIC based SS-OCT system can be seen in Fig. 1. Typically, in OCT setups the light returning from the sample and reference mirror is diverted to the detector either by means of an optical power splitter or by an fiber optical circulator. In the optical power splitter approach, a significant portion of the source light is sacrificed to maximize the amount of reflected sample light returning to the detector. In many cases, a 90/10 splitter is used such that only 10% of the source light hits the sample while 90% of the reflected light is redirected to the detector. This power loss can be avoided by using a fiber optical circulator. However, it is difficult to implement the functionality of an optical circulator as a waveguide component in a photonic integrated circuit. To avoid excessive loss of optical power we therefore exploit the polarization characteristic of light. By rotating the polarization of the light returning from the sample by 90 degrees with respect to the light illuminating the sample, an almost lossless splitting of the forward and returning sample light paths can be achieved on chip. The 90 degree polarization rotation can be realized by means of a polarization controller acting as quarter wave plate in the off-chip sample path between chip and sample. An on-chip polarization beam splitter (PBS) acts as a nearly lossless optical path separating element.

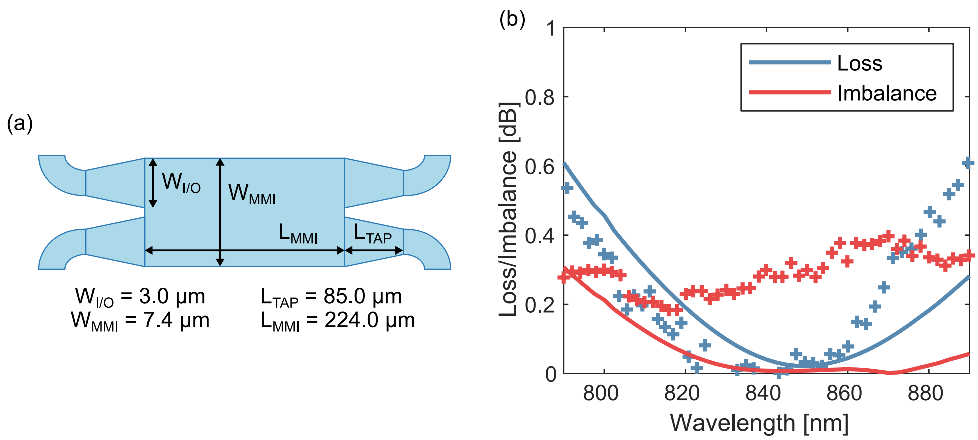

Figure 2. (a) The MMI design used as interferometer. (b) Simulation (lines) and measurement results (crosses) for the loss and imbalance of the fabricated device for TM-like polarization.

To implement the PIC design we use SiN wire waveguides with a core dimension of $700 \times 160\,\text{nm}^2$ surrounded by a SiO2 cladding. The thickness of the SiO2 bottom cladding is 3 µm to avoid coupling to the silicon substrate. This waveguide cross section only supports the fundamental TE-like and TM-like polarization modes for the relevant wavelength range. Measurements of the propagation losses for these PECVD SiN waveguides in the wavelength range of 790 nm to 890 nm show values below 1 dB and 0.5 dB for TE-like and TM-like polarization, respectively [4]. Light was coupled to and from the chip by means of optical fibers. Inverted tapers were designed to better match the mode field of the optical fibers for maximizing the coupling efficiency. Coupling losses below 1.4 dB in the full wavelength range have been achieved by using high-NA fibers in combination with index matching fluid [4]. For this PIC we use the design of the broadband 90/10 directional coupler (DC) for TE-like polarization shown in our previous work [5]. Measurements of the PBS show that in the operational wavelength range the polarization extinction ratio can be kept above 10 dB [6]. The multimode interferometer (MMI) design was optimized for TM-like polarization. The simulation as well as measurement results can be seen in Fig. 2.

The PIC was fabricated at ams AG using PECVD, deep UV lithography, and reactive ion etching [7]. With the fabricated PIC in-vivo measurements were carried out at the Medical University of Vienna. Figure 3 shows the in-vivo optical coherence tomogram of a human retina obtained with the above described SiN waveguide PIC based SS-OCT system. These first measurements demonstrate that losses in the PIC can be kept sufficiently low to perform in-vivo retina OCT measurements without exceeding a power limit of 0.75 mW for the single beam entering the human eye.

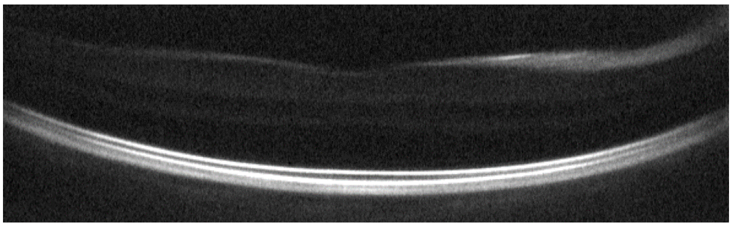

Figure 3. In-vivo optical coherence tomogram of a human retina obtained with the fabricated PIC.

3 CONCLUSIONS

In conclusion, we have shown the design of a PIC based SS-OCT system operating at 840 nm. The first measurements using the fabricated PIC show that in-vivo measurements of the human retina can be achieved even with the limited amount of sample light in accordance with laser light safety regulations. The use of a CMOS-compatible PECVD SiN waveguide layer deposition process opens up the possibility for the co-integration of photodiodes and read-out electronics, which would significantly increase the PIC functionality.

ACKNOWLEDGMENT

This research has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 688173 (OCTCHIP).

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