

Design of a Photonic Integrated Device with an on-Chip k-Clock and Tunable Reference Arm for Swept-Source Optical Coherence Tomography

Ivan V. Stepanov*, Evgeniy A. Talynev, Anton A. Ivanov, Ruslan V. Kutluyarov, and Elizaveta P. Grakhova

Ufa University of Science and Technology, 32 Zaki Validi str., Ufa 450076, Russia

*e-mail: stepanov.iv@ugatu.su

Abstract. The paper presents a photonic integrated circuit (PIC) design that offers a high degree of integration of building blocks required to implement a swept-source optical coherence tomography (SS-OCT) system. The device includes an interferometer, sample arm, k-clock, and a tunable reference path integrated on a single chip implemented based on the silicon nitride fabrication platform. The PIC elements are optimized to perform low losses and minimal dispersion around a central operation wavelength of 1310 nm, which is critical for applications such as OCT. The device was simulated using Ansys Lumerical software. Simulation results show that the proposed PIC provides precise control of the scanning depth with a resolution of 0.725 nm/mV. Also, the frequency of the OCT signal does not exceed 17 GHz for scanning distances below 5 mm. © 2023 Journal of Biomedical Photonics & Engineering.

Keywords: optical coherence tomography; photonic integrated circuits; swept-source OCT; integrated k-clock; tunable reference path.

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1 Introduction

Photonics opens prospects in the medical diagnostics especially in the non-invasive visualization methods. Thus, optical coherence tomography (OCT) has found wide application in scientific medical research and clinical practice due to the possibility of non-contact and highly sensitive visualization of the structure of tissues and organs and their pathological changes. High scanning speed virtually eliminates motion artifacts, and precision allows for an objective quantitative assessment of microstructural changes at the level of cell layers. Thereby, OCT has proven itself well in ophthalmology [1–3], oncology [4–6], neurosurgery [7, 8], urology [9, 10], gynecology [11], and other fields of medicine [12–14].

The potential advantages of integrated photonics, such as mechanical stability, miniaturization, the ability to integrate many components on a single chip, and low cost, are of great interest in OCT [15]. In addition, the possibility of implementing new form factors of diagnostic probes based on photonic integrated circuits

(PIC) can significantly expand the opportunities of OCT [16], for example, for intraoperative studies, in which an objective assessment of tumor boundaries plays an essential role.

Full integration of the optical and optoelectronic parts of the OCT device is an intricate problem that attracts many researchers around the world. Most of the effort is on Fourier-domain OCT techniques, including spectral-domain OCT (SD-OCT) [17] and swept-source OCT (SS-OCT) [18], because they demonstrate superior scan speeds and axial imaging resolution. For published solutions, the integration of individual system elements on the PIC, such as interferometers [19, 20], arrayed waveguide gratings [17, 21], reference arm [22], or even combinations of several components [18, 23, 24], has been reported. However, total integration has yet to be achieved, even though researchers report the feasibility of an integrated radiation source [23, 25]. To date, experiments with PIC for OCT use an external source.

The main disadvantages of PIC-based OCT systems are high losses and dispersion compared to the fiber

implementation, which negatively affects the signal-to-noise ratio, and hence the imaging resolution. At the same time, a significant part of the losses is associated with interconnections between integral and discrete parts [15]. To reduce these losses, solutions for optimizing devices for coupling and decoupling light on PIC are presented [18, 26]. However, the high integration of elements on a chip is again a much more reliable and robust solution. For example, in Ref. [25], a multi-channel SS-OCT scheme is proposed, simultaneously performing measurements at several points of the sample, increasing the measurement speed by a factor of several. Such scaling in large systems is impossible due to the complexity of configuration, maintenance, and the need for many additional components.

Thus, this paper proposes one more step towards a fully integrated SS-OCT system. To this end, in addition to the conventional interference scheme and the sample arm, we propose implementing two key components of SS-OCT on the PIC to improve the system's performance: an integrated k-clock and an adjustable reference arm.

The SS-OCT systems suffer from a drift of the light source sweep over time [27], which happens due to the phase instability of the laser [28]. Therefore, the system includes an optical clock (k-clock) to strictly synchronize the swept-source sweep and the digital signal processing cycle to prevent visualization errors. Moreover, the integrated k-clock provides more minor time delays and losses than discrete devices because of smaller dimensions and the number of interconnections and eliminates the need for additional signal post-processing for phase calibration [29]. In the research, the k-clock is implemented with a tunable unbalanced Mach-Zender Interferometer and balanced photodetectors.

Fixed optical delay lines that are used in conventional SS-OCT systems as reference arm cannot provide to adjust the visualization depth, which is essential for some applications. In turn, Bragg gratings [30], microresonators [31], and photonic crystals [32] used to implement the optical delay tuning on the chip are significantly limited in bandwidth. For wideband

operation, researchers offer different methods such as thermo-optical effect [22], microelectromechanical systems [33] that can be utilized in wideband operations. Thus, Ref. [22] demonstrates the possibility of increasing the scanning depth of the OCT system by 0.6 mm due to the use of a silicon PIC containing only a tunable reference arm based on platinum microheaters and a thermo-optic effect. Nevertheless, implementing long delay lines while keeping a low loss and small footprint remains challenging. In the research, the adjustment of the optical delay in the reference arm is realized in a small footprint with a gold heater 5 μm wide.

The paper is organized as follows. Section 2 describes the SS-OCT system concept with an integrated k-clock and tunable reference arm. Section 3 depicts issues of the PIC components design and simulation. Section 4 shows the results PIC performance analysis. The outlook for the system implementation is presented in Section 5, while the conclusion is given in Section 6.

2 The Concept of PIC with an Advanced Level of Components Integration for Application in SS-OCT

The scheme for SS-OCT with the proposed photonic integrated device is presented in Fig. 1. The design was carried out for a silicon nitride platform (Si_3N_4) that provides minimal loss compared with other semiconductor platforms for PIC fabrication. In this case, the drawback of such a solution is the absence of integrated photodiodes [34]. This problem can be subsequently solved with heterogeneous integration. However, in the research, we utilized discrete photodiodes connected to the PIC through edge couplers.

The device is operating as follows. The light from the narrowband sweeping laser (in the range from 1260 to 1360 nm) is coupled to the PIC through the edge coupler (EC). A 95/5 multimode interference coupler (MMI) divides the input light between the OCT interference scheme and the integrated k-clock segment.

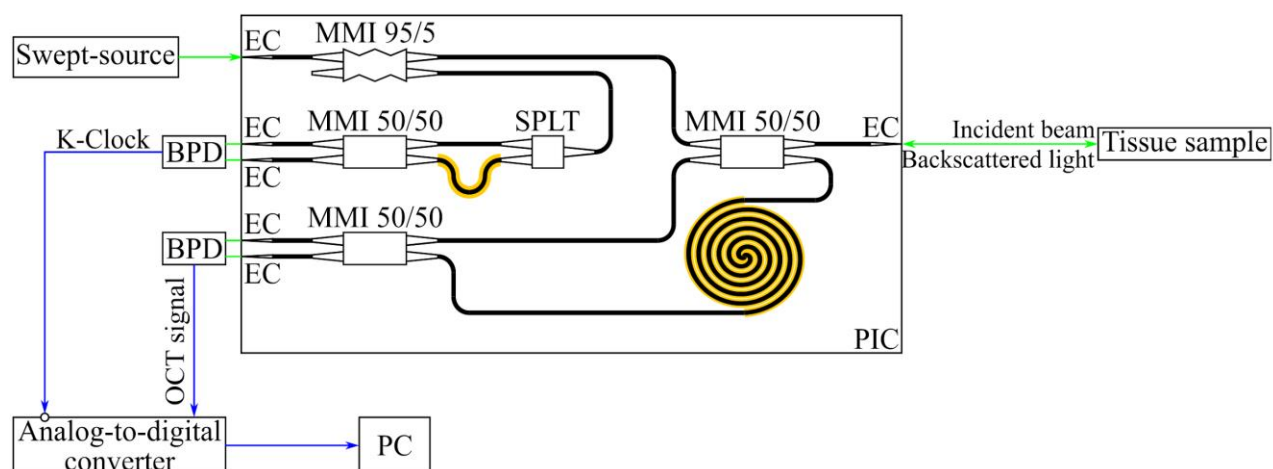


Fig. 1 PIC-based SS-OCT system scheme: EC – edge coupler, MMI – multimode interference coupler, SPLT – splitter, BPD – balanced photodiode, PIC – photonic integrated circuit, PC – personal computer. Blue lines represent electrical signals and green – optical. Thick black lines show waveguides inside the PIC, yellow – heaters.

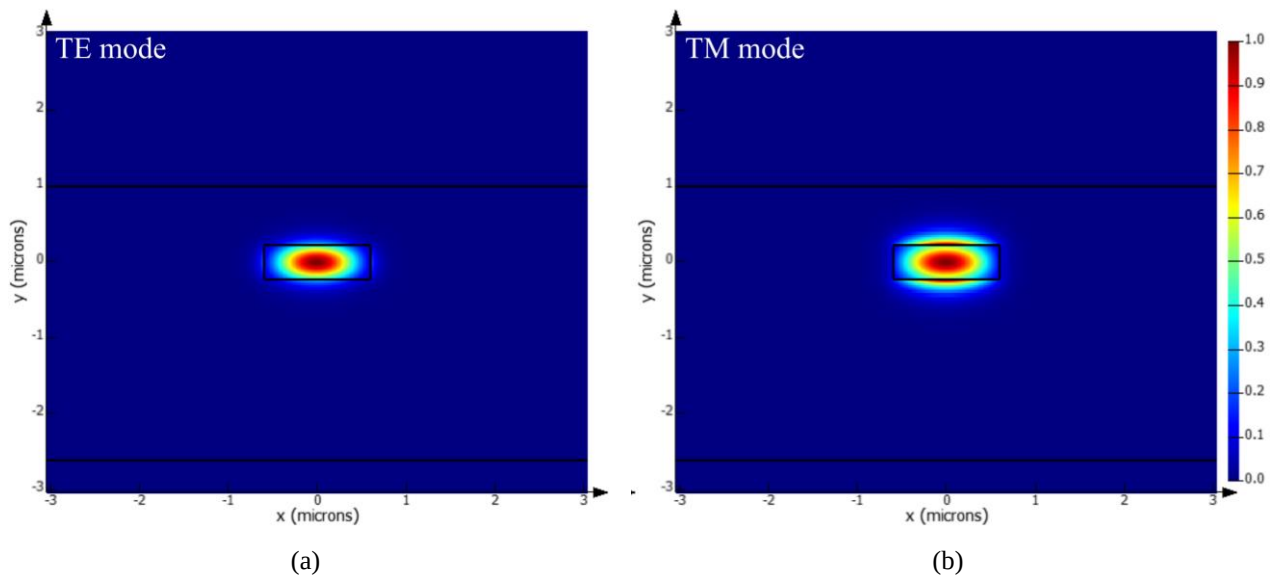


Fig. 2 TE- (a) and TM-mode (b) field intensity in the waveguide cross-section.

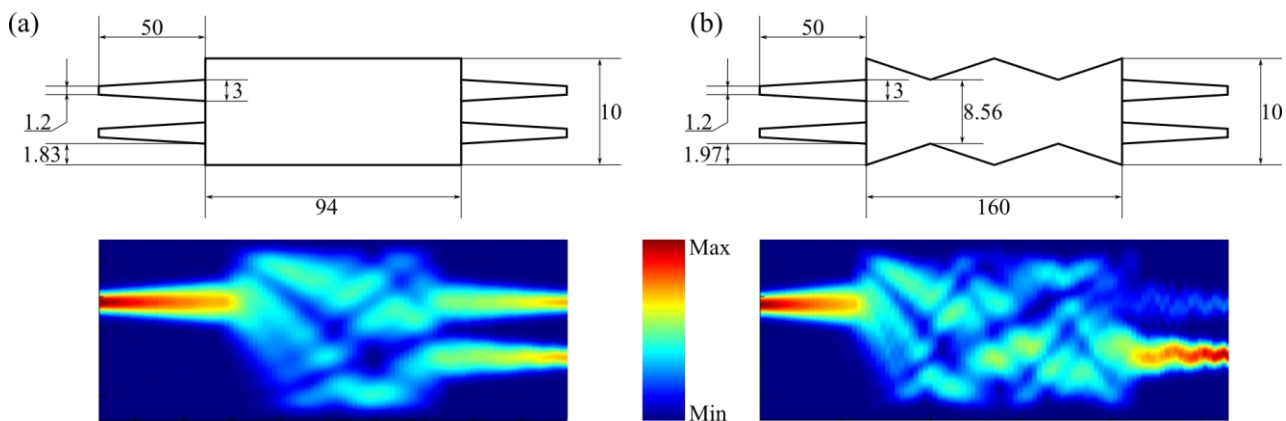


Fig. 3 Dimensions of the multimode interference couplers (top) with different coupling ratios and field distributions (bottom): (a) 50/50, (b) 95/5. All dimensions are given in μm .

In the OCT part, light is divided equally by 50/50 MMI between the sample arm and reference arm. In the first, through the EC, incident light illuminates the test sample, backscatters in the tissue, and is collected back to the PIC through the same waveguide. At the same time, the second half of the optical power passes through the reference arm (tunable delay line) to interfere with backscattered light after the second 50/50 MMI.

Simultaneously 5% of the optical power in the k-clock arm goes to the unbalanced Mach-Zehnder interferometer (MZI). The length difference of the MZI's arms is calculated to provide a 3 dB transmission at the starting wavelength of the laser sweep. This condition offers zero amplitude at the balanced photodiode (BPD) output with a frequency corresponding to the period of the laser. When such a signal from the BPD output is connected to the inverted input of the analog-to-digital converter (ADC) board, the required signal is generated to launch the digital processing cycle of the received OCT signal. To reduce the influence of possible manufacturing errors on the transmission characteristics

and to adjust the k-clock signal period, the MMI's long arm could be upgraded with the heaters.

The delay line length is calculated to provide a zero delay point located as close to the PIC fringe as possible to reduce the attenuation of the already low-power backscattered light when propagating in free space and, respectively, to increase the visualization depth. Zero delay point corresponds to the equal optical path at the reference and sample arms. The operation of the tunable reference arm will be described in the next chapter.

The applied MMIs in the scheme can be replaced with wideband directional couplers (DC). However, DC's characteristics are more sensitive to fabrication errors [35].

3 PIC Components Design and Simulation

PIC design contains the following elements: waveguides, MMIs with coupling coefficients 95/5 and 50/50, splitter (MMI with one input and two outputs), and heaters for tunable elements. Simulation of the components was performed in the ANSYS Lumerical software.

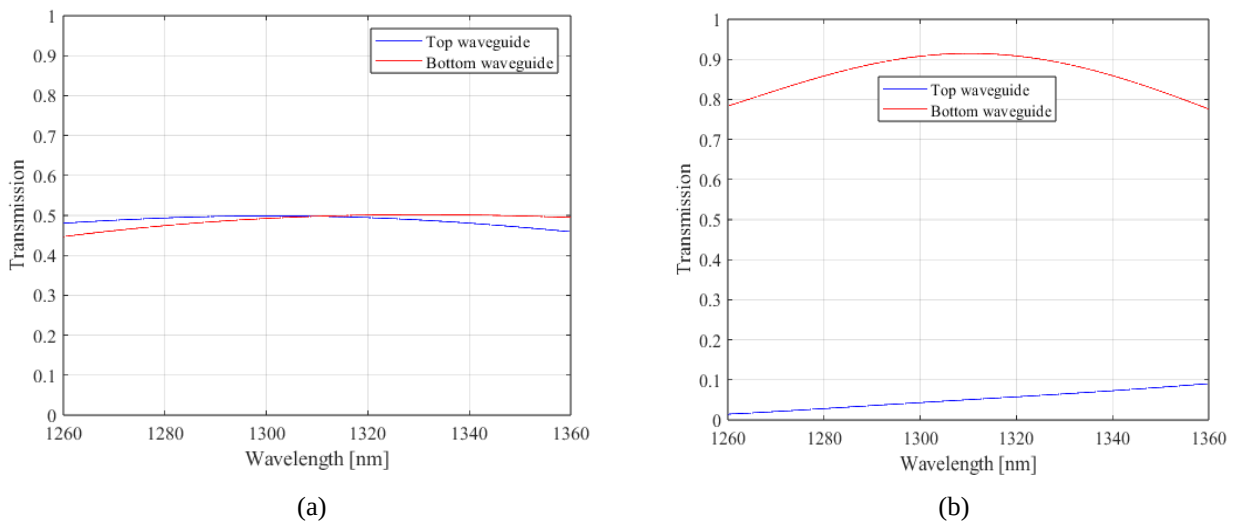


Fig. 4 Transmission spectra of the 50/50 MMI (a) and 95/5 MMI (b).

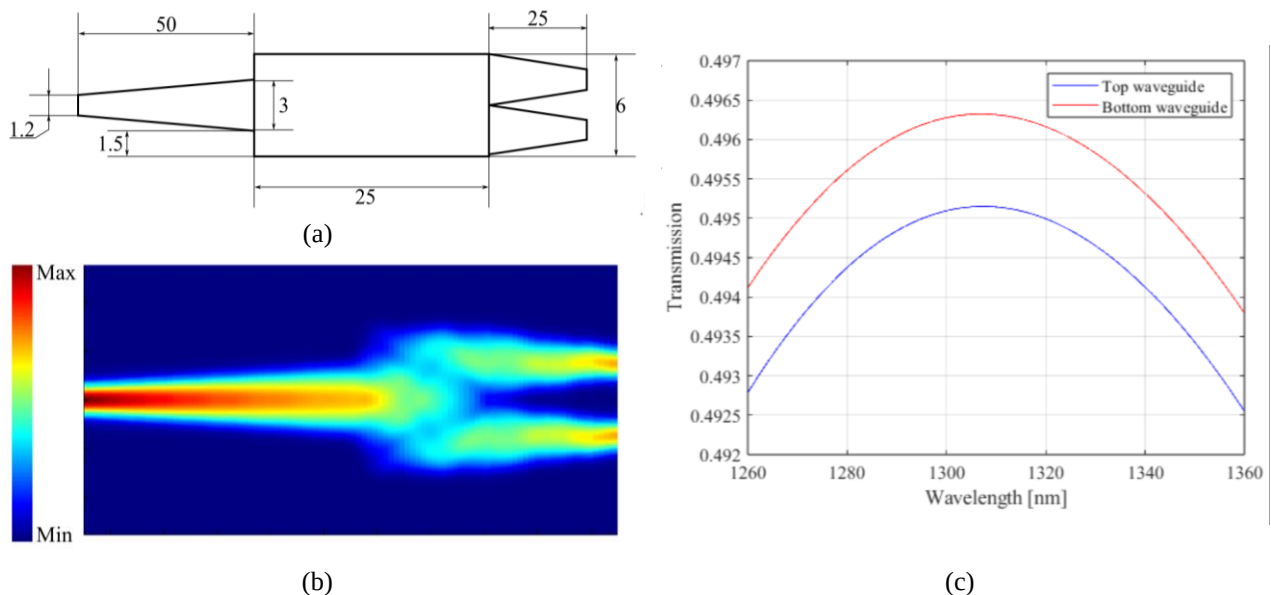


Fig. 5 Dimensions (a), field distribution (b), and transmission spectra (c) of the splitter MMI.

As mentioned earlier, the proposed PIC is developed for the Si_3N_4 (silicon nitride) platform, which provides minimal loss and higher system sensitivity. The waveguide's dimensions equal 1200×450 nm were chosen to keep single-mode operation and close to zero dispersion around 1300 nm. The waveguide simulation was performed using the finite difference Eigenmode method in the Lumerical MODE software. The TE- and TM-mode field distributions in the waveguide cross-section are presented in Fig. 2.

Dimensions of the 50/50 and 95/5 MMIs were calculated by the approach presented in Refs. [36, 37], respectively. The components we further simulated in a Lumerical MODE software, but the Eigenmode expansion method was used in this case. We optimized the geometry of MMI using the same software to achieve the desired operation mode. The final MMIs dimensions with field distributions are presented in Fig. 3. Transmission spectra of the MMIs are provided in

Fig. 4. The transmission spectra of 50/50 MMI has a shift of 20 nm between the output waveguides; however, it could be compensated during MZI design. Particle swarm optimization can be applied to flatten the proposed MMIs' transmission spectra. Nevertheless, proposed MMI structures are the most robust to fabrication errors.

Compared to discrete directional couplers, the MMI on PIC offer less flat transmission spectra. However, integrated components are much smaller than discrete [38–41].

Instead of using a conventional waveguide splitter, we applied MMI with one input and two outputs since it is easier to fabricate and is more tolerant of manufacturing errors. The 1×2 MMI length was calculated according to Ref. [36]. The MMI's optimized dimensions, field distribution, and transmission spectra are presented in Fig. 5.

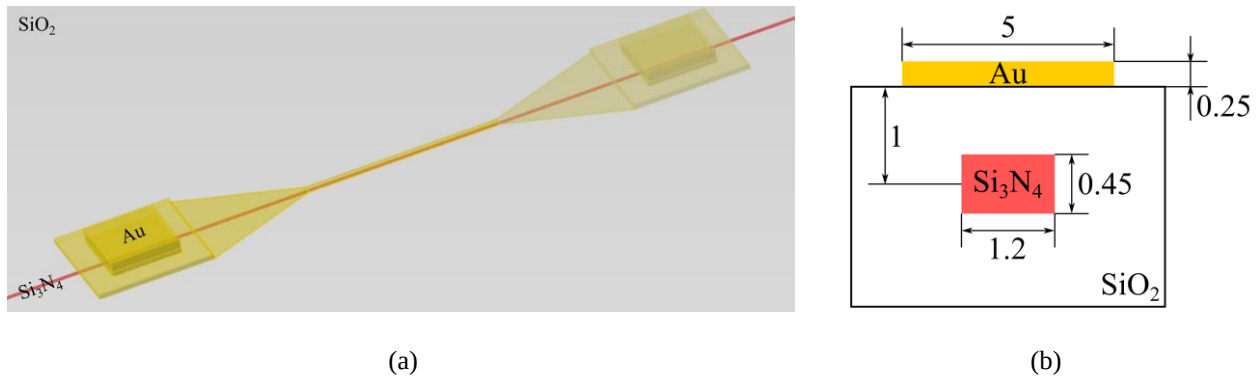


Fig. 6 Simulation model of the heater in Lumerical DEVICE (a) and heater cross-section (b). All dimensions are in μm.

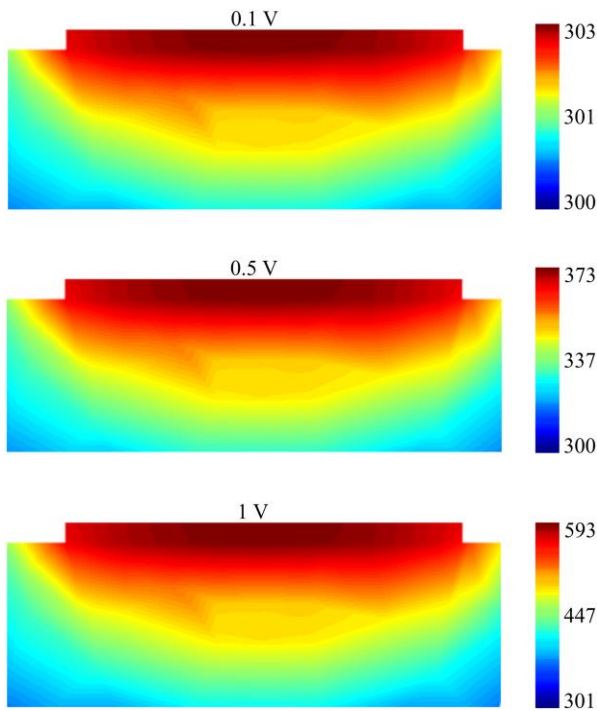


Fig. 7 Heat dissipation profile simulation in Lumerical DEVICE for different voltages. All temperatures are in Kelvins [K].

The electric heater simulation was performed using the finite element method in the Lumerical DEVICE package. A three-dimensional view of the model is presented in Fig. 6. First, we obtained the device temperature dependence from the applied voltage and next exported it to the Lumerical MODE to calculate effective index variation. Corresponding heat dissipation profiles for different used voltage ratings are provided in Fig. 7. The waveguide temperature dependence on the applied to the heater voltage is depicted in Fig. 8. Corresponding effective index dependence on the applied to the heater voltage is depicted in Fig. 9.

In the simulation, the heater length equals 100 μm, and this assumption was made to decrease computational requirements. The heater is represented by a gold microstrip line with dimensions of 5×0.25 μm and is deposited on the glass layer with 1 μm thickness.

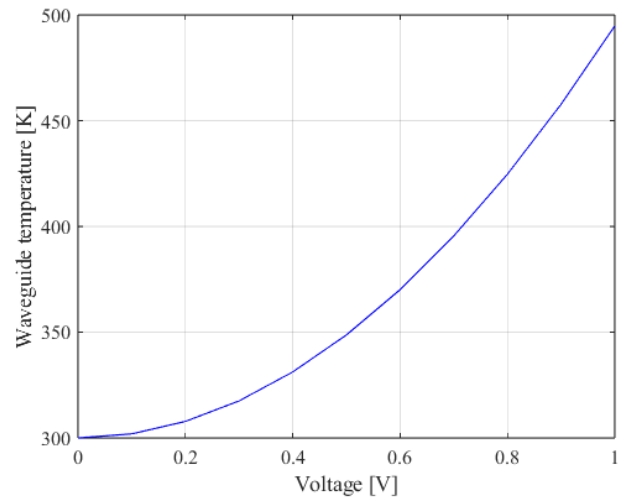


Fig. 8 Waveguide temperature dependence from applied to the heater voltage.

The waveguide temperature deviation range is 200 K with a maximum achieved value of 500 K for a 1 V applied voltage.

That corresponds to the waveguide fundamental TE mode effective index change by $4.5 \cdot 10^{-3}$ (Fig. 9). Such results are within tolerance for silicon photonics [42, 43], which means that heating does not significantly affect the mode propagating in the waveguide, which ensures minimum losses.

Waveguide temperature shift leads to the relative change in the optical path length. This change can be calculated as follows [22]:

$$\Delta l_{OPL} = \varepsilon \cdot \Delta T \cdot l_0,$$

where ε is the thermo-optical coefficient of the Si₃N₄ that equals $2.45 \cdot 10^{-5}$ RIU/°C, ΔT is the temperature shift, and l_0 is the length of the waveguide. The waveguide length variation due to temperature change is depicted in Fig. 10.

Thus, for the heater voltage up to 1 V, the relative change in the optical path length reaches 100 μm.

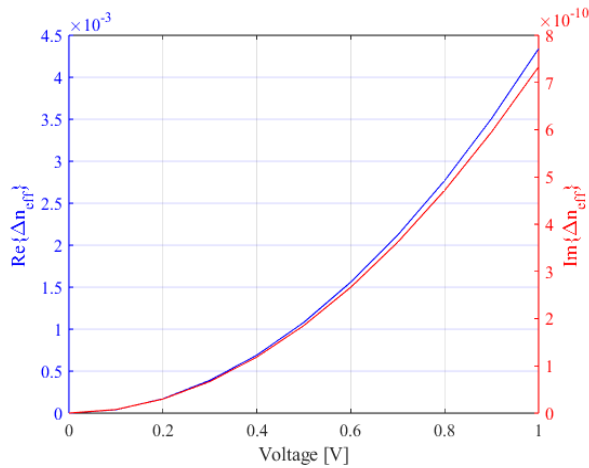


Fig. 9 Waveguide effective index dependence from applied to the heater voltage.

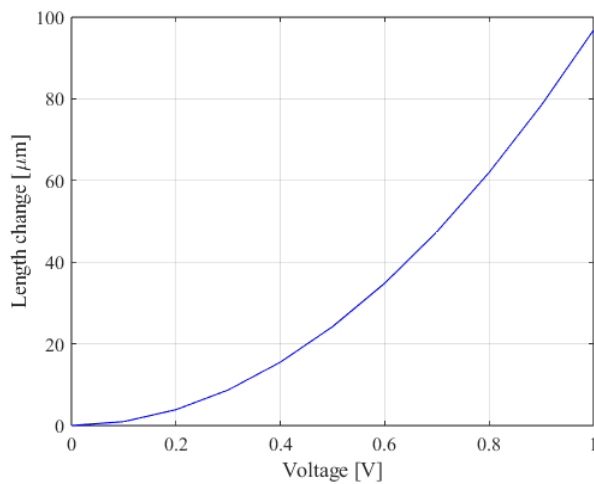


Fig. 10 The optical path tuning range vs the applied voltage to the heater.

4 Simulation Results of the Photonic Integrated Device Performance

The PIC simulation model based on the topology presented in Fig.1 and designed components was performed in Lumerical INTERCONNECT using scattering matrices apparatus. Commercial SS-OCT systems have a sweep rate of 100 kHz [29], corresponding to the sweeping period of 10 μ s. Since the zero delay point calculation is based on the operating wavelength band and waveguide lengths and does not depend on the laser sweeping period, the latter was set to 10 ns for a reasonable simulation time.

The first simulation step was k-clock characterization to ensure an equal transmission coefficient at the desired wavelength. Obtained transmission spectra of the integrated k-clock are depicted in Fig. 11. It is worth noting that this MZI is designed for the calculated MMI transmission spectra.

As can be seen from Fig. 11, the free spectral range (FSR) of the k-clock's MZI is equal to 100 nm. It is necessary to prevent the ADC's false start within the

swept-source period. For example, if the wavelength sweep of the source is equal to 50 nm, then the FSR value should be higher than 50 nm.

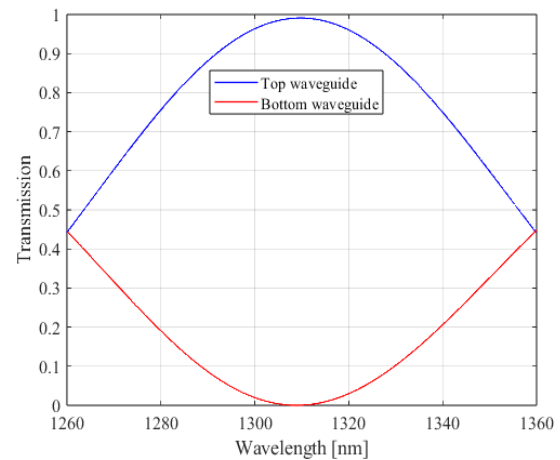
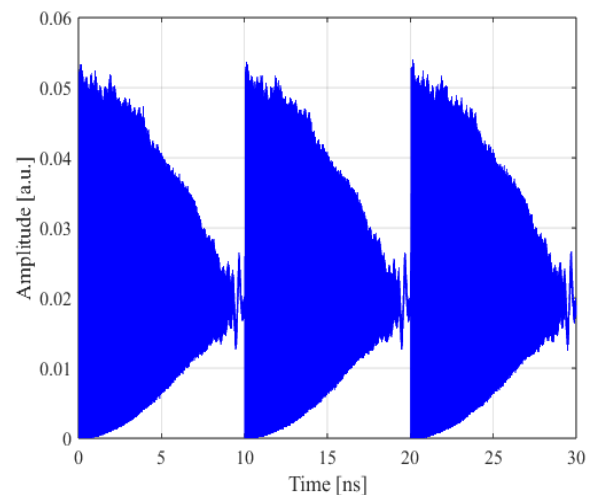
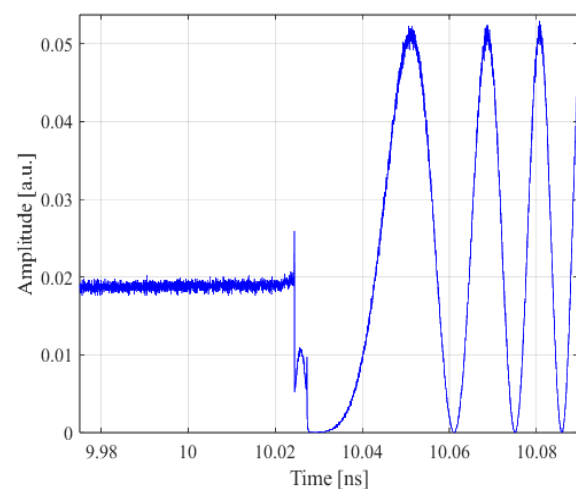


Fig. 11 The integrated k-clock transmission spectra.



(a)



(b)

Fig. 12 The electrical clock signal in the time domain at the output of BPD (a) and its transition between the first and the second sweeping period of the laser (b).

The following simulation step is the PIC operation in three periods of the swept-source. The main goal of this stage is to get the dependence of the electrical signal frequency at the output of the OCT arm from the distance to the optical inhomogeneity in the test tissue sample, in which the incident beam is backscattered. We applied an optical mirror with a 0.99 reflection coefficient to imitate such a layer in a tissue sample. This mirror is connected with an interference scheme through the edge coupler and air volume.

The k-clock operation in the time domain for three sweeping periods of the laser is shown in Fig. 12.

Ripples on the timing diagram arise from the 95/5 MMI transmission coefficient irregularity. These amplitude deviations have almost no effect on the trigger work, and the time delay of the trigger is about 0.03 ns.

The output signal frequency dependence vs a distance between the chip fridge and backscattering layer in the tissue sample for different voltages applied to the heater is presented in Fig. 13. Zero delay point shift between 0 V and 1 V is 0.047 mm. The maximum zero delay point shift is 0.063 mm. The reference path tuning time is about 1 μ s [44].

From the Gaussian interpolation, we obtained a trend line that shown in Fig. 14. We calculated a delay line tuning resolution of about 0.725 nm/mV by this trend.

5 Discussion

The achieved scanning depth variation is lower than was demonstrated in Ref. [22, 33]. However, these solutions do not provide the full potential of integrated photonics. First, the presented devices provide integration of only one system/s component on the PIC, leading to an additional loss at the connections. Also, our reference arm can be implemented as Archimedes' spiral with a total footprint of about $800 \times 800 \mu\text{m}$ for the Si_3N_4 platform. This value is comparable to the device footprint presented in Ref. [33] (about $300 \times 600 \mu\text{m}$) and much lower than that shown in Ref. [22] (8 mm^2). It is worth noting that the tuning range of the scanning depth can be increased by using different waveguide materials with higher thermal coefficients (for example, silicon) or with true-time delay device integration [45]. Also, a longer reference path can be utilized in thermal tuning [22].

Another approach to expand the tunability of the reference path is effective index contrast between two states increasing. Phase change materials can provide a more effective index difference between distinct states [46]. For example, the effective index change for $\text{Ge}_2\text{Sb}_2\text{Te}_5$ deposited on the Si_3N_4 waveguide reaches 0.1 [47] for other states in the second transparency window when thermo-optical effect leads to the effective index change of order of 10^{-3} (as shown in Fig. 9).

To further improve system performance, a fast Fourier transform can be implemented in the optical domain on the PIC [48], removing the high-performance digital signal processors and significantly reducing the SS-OCT system's cost.

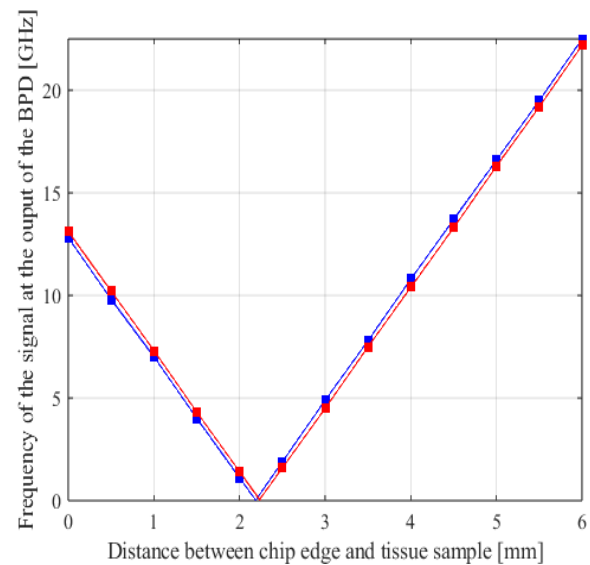


Fig. 13 BPD's output signal frequency dependence on the distance to the backscattering layer in the tissue sample for two voltages applied to heater – 0 V (blue line) and 1 V (red line).

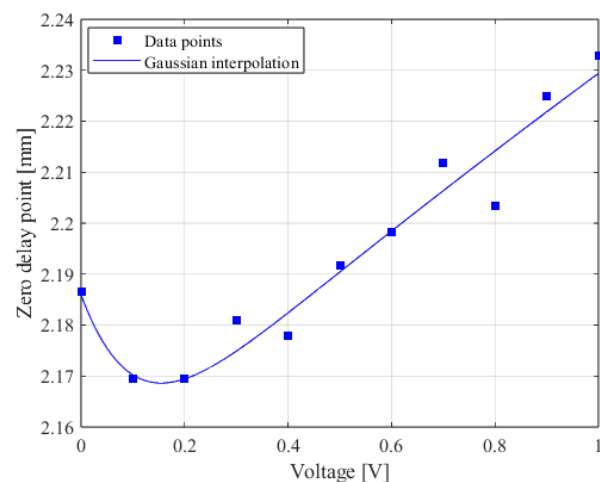


Fig. 14 Zero delay point dependence from applied to the heater voltage.

Another possible optimization of the proposed device can be implemented by replacing the Mach-Zehnder interferometer in the k-clock arm with a microring resonator with an FSR value above 100 nm [49]. This replacement provides for further reducing the footprint of the device.

6 Conclusion

In the paper, we presented a PIC design for the SS-OCT with a high integration degree of the system's components. The proposed PIC is developed for the Si_3N_4 platform. Although, the PIC topology is compatible with different fabrication platforms after the corresponding redesign and optimization of the components.

Simulation results in the Lumerical software show that OCT electrical signal frequency does not exceed 17 GHz for scanning depths up to 5 mm. This frequency fits the 3 dB bandwidth of the most integrated and discrete high-speed photodiodes [34]. The integrated k-clock shows a minor start time error equal to 0.03 ns that can be compensated with proper heating. An integrated tunable reference path controls the zero delay point position from 2.17 to 2.23 mm. With a voltage resolution of 1 mV, our tunable reference path provides a scanning depth change resolution of about 0.725 nm.

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Disclosures

The authors declare that they have no conflict of interest.

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