Performance of microheaters for tunable on-chip interferometer

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Abstract. Mach-Zehnder interferometer (MZI) is a valuable practical tool in many optical science areas. In particular, high-contrast MZI are required for experimental realization of displacement-based quantum receivers that can discriminate weak coherent states of light with the minimum error rate. In this work we study phase modulators of tunable on-chip interferometer on silicon nitride (Si₃N₄) platform for telecom wavelength (1550 nm) consisting of several MZI. Phase modulators on one of the arms of MZI consists of microheaters and waveguide. Microheaters heat waveguides changing its refractive index due to thermo-optical effect providing a phase shift. We measure the bandwidth of phase modulators and study their operation in pulse mode.

1. Introduction

High-contrast interferometry is an important prerequisite for experimental demonstration of novel methods for quantum measurements, communications, and control [1-5]. Although the recent progress in realization of ultra-sensitive quantum receivers was achieved with the optical fibers [6-9], the use of integrated optical circuits offers potentially much higher contrast. Photonic integrated circuits based on silicon nitride (Si₃N₄) have many advantages over fiber and free space realizations because of a small footprint of the device itself, less susceptibility to heat and phase fluctuations and higher stability.

One of the technical problems is how to obtain the desired phase shift with the integrated Mach-Zehnder interferometer (MZI). In this work, we use a microheater as a phase modulator. Microheater’s work is based on the thermo-optical effect, i.e. the refractive index of waveguides material is changing due to the temperature change [10]. We investigate performance of phase modulators and find their main parameters such as effective bandwidth.

2. Device description

The tunable on-chip interferometer on silicon nitride shown in figure 1. Tunable interferometer...
consists of 3 MZI: main interferometer MZI 1 and 2 interferometers MZI 2, MZI 3 on its arms, which are used for attenuation of signal. To control MZI 1 - phase modulators PM1 and PM3 are used, to control MZI 2 and MZI 3 - PM4, PM5 are used respectively. As waveguide material, we used Si$_3$N$_4$ due to its low absorption in infrared (IR) and good mechanical properties [11] and possibility of integration of SNSPD [12] on chip which allows to fabricate more accurate devices. Phase modulator consists of waveguide and microheater. Microheaters are Ti/Au film with thickness of Au 300 nm. They can be divided in two parts: one part lying on waveguide to heat it and another part is contact plates to apply voltage with contact plate width 225 μm. Part on waveguide has significantly smaller width in comparison with leading contact plates, therefore we may neglect resistance and heating of the contact plates. Four of microheaters are used as phase modulators and one of them (PM2) is used to change splitting ratio of beam splitter dividing optical power between output ports 1 and 2. Interferometer (except contact plates) is covered by layer of SiO$_2$ of thickness 300 nm to exclude contact of microheaters with atmosphere and prevent burn down at high temperatures. We used FGC (Focusing Grating Couplers) for telecom wavelength with grating period 1.088μm and fill factor 70% (in design). FGC 3 is used to input light, and FGC 1 and FGC 2 are used to output light from the interferometer.

**Figure 1.** Optical micrograph of interferometer. PM 1, PM 3, PM 4, PM 5 - phase modulators; PM2 - microheater to control splitting ratio of beam splitter for output ports 1 and 2; MZI 1 - main Mach-Zehnder interferometer; MZI 2, MZI 3 - interferometers for attenuation of the signal in the arms of MZI 1; FGC 1, FGC 2 - focusing grating couplers for output optical power; FGC 3 - focusing grating coupler for input optical power.

### 3. Bandwidth of microheaters
To measure bandwidth of phase modulators we used experimental setup shown on Figure 2. We used lock-in amplifier with internal sinusoidal signal generator. Sinusoidal signal was applied to one of the microheater, radiation of 1596 nm from the laser was introduced to interferometer through fiber array and FGC. Simultaneously optical power from output port 1 was measured by InGaAs detector with bandwidth 2 GHz. Sinusoidal voltage of constant amplitude heats microheater which leads to the phase shift in arms of interferometer. Output optical power also has sinusoidal form and measured by detector.
Figure 2. Experimental setup for bandwidth investigation. Laser 1596 nm - New Focus TLB-6600; Lock-in amplifier - Stanford Research System RS830; Detector 2GHz - Hamamatsu G9801; Blue line corresponds to optical fiber; Green line corresponds to electric wires.

The results can be seen on the graph on Figure 3. Obtained curve has flat region, which means phase modulators able to work in this frequency range. Curve goes down after some frequency, that means that phase modulators are not able to work on frequencies higher than some characteristic frequency.

Figure 3. Frequency response curve. Red line corresponds to fitting curve. Characteristic frequency is shown on the graph, but the performance will be twice bigger because heat process is independent on sign of applied voltage.

As characteristic frequency can be taken such a frequency that output amplitude is twice smaller than amplitude in flat region, which corresponds to -3 dB. This frequency can be obtained by fitting frequency response curve by equation 1.

\[
U(f) = U \left(1 + \left(\frac{f}{f_{3dB}}\right)^2\right)^{-0.5}
\]  

(1)

A value of 40 kHz for characteristic frequency was obtained after fitting. But as the sinusoidal signal was used, the performance will be twice bigger, because we take into account periods of heat which are independent on voltage sign. Therefore final performance is 80 kHz.
4. Optimal pulse mode for microheater operation.

Performance value of 80 kHz was obtained, but in practice it is often necessary to get a phase difference of 0 or π during some period of time for some switching speed. Therefore we define optimal impulse regime as maximum switching speed between 0 and π. There are 2 restrictions on maximum switching speed. Firstly, thermo-optical effect based phase modulators are relatively slow because of inertia of thermal processes connected with specific heat and heat conductivity of waveguides and microheaters. Switching speed defined not only by speed of heating of waveguides, but also by their speed of cooling. Those parameters are defined by design of structure. Second restriction connected with maximum voltage, which can be applied to microheater. After constant voltage applied, microheater is heating itself and heats waveguide leading to phase shift due to thermo-optical effect. Work region for bias voltage 4-8 V [13]. If constant voltage is high or applied for a long time it leads to burn out of microheaters. Therefore it is better to use impulse regime, periodically apply constant voltage for the short period of time. In other time waveguides and microheaters are cooling down for initial temperature because of heat dissipation into the substrate. To find optimal regime of phase shift experimental setup shown in Figure 4 was used. Radiation of 1596 nm from laser introduced into interferometer through fiber array and focusing grating couplers. Rectangular electrical signal from delay generator was applied to microheater PM4, heating up the waveguide and modulating phase shift. The electrical signal had an amplitude of 7 V and a duration of 500 ms. At the output of the chip, the interfered light was detected by an InGaAs detector with a 5 GHz bandwidth.

![Figure 4](image_url)

Figure 4. Scheme of the experimental setup for investigation of microheaters in pulse mode. Laser 1596 nm - Venturi Tunable Laser TLB-6600; Delay generator - Highland Technology P400 Digital Delay Generator; Oscilloscope - Rohde & Schwarz RTO 1012; Detector 5GHz - ThorLabs DET08CFC/M; Blue line corresponds to optical fiber; Green line corresponds to electric wires.

Figure 5 represents the response from the detector. The absence of voltage on the microheater corresponds to an arbitrary interference result. At a voltage of 7 V, we get destructive interference, which corresponds to a phase difference of 0 in the interferometer. However, the time of establishing destructive interference is long and is approximately 400 μs. For 100 μs after that, the interference is stable. Further, after the voltage is turned off, the microheater is cooled due to the heat leaving the substrate and returns to its original state. The maximum repetition rate of rectangular pulses is 4 Hz. As the repetition rate increases, the chip overheats, because the microheater and the waveguide do not have time to cool down and the interference result becomes unstable. The same thing happens if you increase the time of applying voltage to the microheater. Accordingly, to obtain constructive interference, the amplitude of the displacement voltage changes by 10.2 V, which corresponds to the phase difference π. Thus, we found the optimal pulse mode for microheaters: a rectangular pulse signal with a repetition frequency of 4 Hz and a pulse duration of 500 μs with amplitudes of 7 V and
10.2 V for the phase shift of 0 and $\pi$, respectively. The relaxation time for heating is 400 µs. The time with a stable phase is 100 µs.

Figure 5. (a) Detector response for destructive interference for pulse with amplitude 7 V. (b) Detector response curve for constructive interference for pulse with amplitude 10.2 V. Blue curve corresponds to rectangular bias voltage applied to microheater. Red curve corresponds to detector response to optical power from output port 1. Enlarged graphs for stable interference regions provided at the right.

5. Conclusion
The output frequency response curve was obtained. After fitting bandwidth value 80 kHz was obtained. Optimal pulse mode for the microheaters was found. Detector response curves for rectangular voltage were obtained and analyzed. These results have potential for using this tunable on-chip interferometer as a part of quantum receiver of weak coherent signals.

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