Study of microheater’s phase modulation for on-chip Kennedy receiver

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Abstract. In this work we describe phase modulators for several Mach-Zehnder interferometers (MZI) on silicon nitride platform for telecom wavelength (1550 nm). We obtained current-voltage and phase-voltage curves for these modulators. MZI are needed for experimental realisation of various quantum receivers that can distinguish weak coherent states of light with extremely low error. Thermo-optical (TO) modulation is ensured by microheaters on one of the arms of MZI, which enables the change of the refractive index of the material with temperature. This approach allows to apply the necessary voltage to the golden microheaters to obtain the required phase change. For the on-chip microheaters we demonstrate the dependence of the phase shift on the voltage applied to our on-chip microheaters.

1. Introduction
Mach-Zehnder interferometers with microheater phase modulators are one of the main parts in the experimental realization of highly sensitive quantum receivers that can distinguish weak coherent states of light [1]. The receiver performs optical displacement of the unknown signal to find out the actual signal state [2,3,4]. Such receivers were already demonstrated using free-space and in fiberoptics components [5,6,7]. On-chip realization of the receivers allows us to get advantages like small footprint, which leads to higher stability of device including temperature fluctuations along the surface, and also it has shorter waveguides which leads to less phase fluctuations. As a waveguide material we used silicon nitride (Si₃N₄) platform, which combines low optical absorption in the infrared (IR) and good mechanical properties [8]. For phase modulation we used thermo-optical (TO) effect, due to dependence of refractive index on the temperature. This change of refractive index leads to difference of optical paths in different arms of interferometer, which give us the required phase shift between them. For realisation of quantum receiver we need the phase shift ranging from 0 to 180 degrees for constructive and destructive interference, respectively.
2. Device design and fabrication

Figure 1 shows an optical image of a fabricated device. There are 5 phase modulators (PM), but one of them (PM4) used as beam splitter to divide power between output port 2 and 3, electrical contacts for applying voltage, optical input (port 1) and outputs (ports 2 and 3). Electrical contacts are connected to the heaters and after applying voltage they start to heat Si₃N₄ waveguides and due to thermo optic effect reflection coefficient changes in one of the arms. Thermo optical coefficient dn/dT for Si₃N₄ at the room temperature equal to (2.51±0.05)*10⁻⁵ K⁻¹ [6]. To collect optical signal we used focusing grating couplers for telecomm wavelength with grating period 1.088μm and fill factor 70% [7] (in design). Grating coupler is special device which is used to focus and collect light into the narrow waveguide using diffraction of the light. It can be seen that scheme consists of 3 MZI to create constructive or destructive interference: main MZI 3 and MZI 1, MZI 2 on its arms. MZI 1 operated by PM2, MZI 2 operated by PM1, MZI 3 operated by PM3 and PM5.

![Figure 1. Optical image of the fabricated device.](image)

We used several stages of nanophotonic fabrication processing on commercially available Si wafers with a 450 nm Si₃N₄ waveguiding and 2600 nm SiO₂ cladding layers. Firstly we apply and develop resist ZAP 520 A in O-xylene, then using electron-beam lithography and dry etching in CHF₃ atmosphere, we fabricated a waveguiding scheme, consisting of several Mach-Zehnder’s interferometers and focusing grating couplers for input/output light from a chip. At the second stage, e-beam deposition of 1μm thick SiO₂ on the top waveguide layer was made. Finally, we used laser lithography to form Ti/Au -contact pads and microheaters of 300 nm width by standard lift-off technique in acetone: firstly we apply layer of resist MMA/PMMA, form a scheme of contact-pads using laser lithography, develop resist and in solution of isopropanol and water (8:1), then goes thermal deposition of 300 nm layer of Ti/Au and lift off of the resist with Ti/Au layer on it. Finally, we get Ti/Au contact-pads.
3. Experimental setup for testing
Using tunable power supply Tektronix PWS2326, operated by program, we apply voltage on each heater separately (other heaters were not connected to any voltage source) and collect data about current using the same power supply, because it can also measure current and voltage. Voltage source was connected to the receiver’s contacts with special 200 μm beryllium bronze pads. Simultaneously we measured the optical power from the receiver’s output port 1 to get power-voltage curve.
We obtain IV curves for heaters with different serial number (PM1, PM2, etc). Thus we have several Kennedy receivers on one structure, it was possible to obtain more than 1 curve for each heater, and get some specific curves for each serial number of microheater. Here (figure 4, a) represented those specific curves for each serial number of heater which can be used as reference for other heaters. It can be seen that those curves are different for different microheaters. This is due to the different size and geometry of electric contacts which determine resistance of contacts and influence on IV curves.

![Figure 4. (a,b). (a) IV curves for all microheaters; (b) Phase-voltage dependence for PM3.](image)

Also we measure the optical transmission on the 1596 nm wavelength (from port 1 to port 2). Using power $P_{\text{min}}/P_{\text{max}}$ (formula 1) values we can translate power into phase shift $\phi$.

$$\phi = \arccos((2P - (P_{\text{max}} + P_{\text{min}}))(P_{\text{max}} - P_{\text{min}})^{-1})$$

This phase-voltage curve (figure 4, b) is for PM3 and other microheaters were not used during measurement. It can be seen that the phase-voltage curve has maximum and minimum points, therefore phase changes at 180 degrees, (which corresponds to the 3V voltage change) which is enough for Kennedy receiver. Also it can be seen that 8V - burnout voltage. This curve can be explained by thermo optical effect, because of the increasing voltage, temperature of waveguide also increases leading to increase on refractive index and increase of optical paths between arms of interferometer. On the graph we see that phase increases and also decreases with applied voltage, but it can be explained just by arccos function properties. Its value must be between 0 and $\pi$ and as it reaches one of them it goes up or down, without going beyond the borders.

4. Conclusion
We fabricated on-chip Kennedy receiver scheme, consisting of several MZIs with microheaters and focusing grating couplers on silicon nitride platform. We studied IV curves of the phase modulators and observe some general properties of them, and found that curves has reproducibility for different heaters. Also we studied phase-voltage curves, which demonstrates, that phase changes from 0 to 180
degrees, which is enough for Kennedy receiver. Our results have a great potential for fabrication on-chip Kennedy receiver.

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