Optimized silicon-nitride Y-branch splitter and directional coupler elements

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Motivation

We present results of numerical optimization, fabrication and measurement of Y-branch spliter and directional couplers (DC) in integrated silicon-nitride photonic structures. Silicon nitride platform enables further miniaturization of the circuits we produce in the lab using femtosecond laser writing technology [1].

Our goal is to develop the integrated photonic technology suitable for linear optical quantum computing [2].

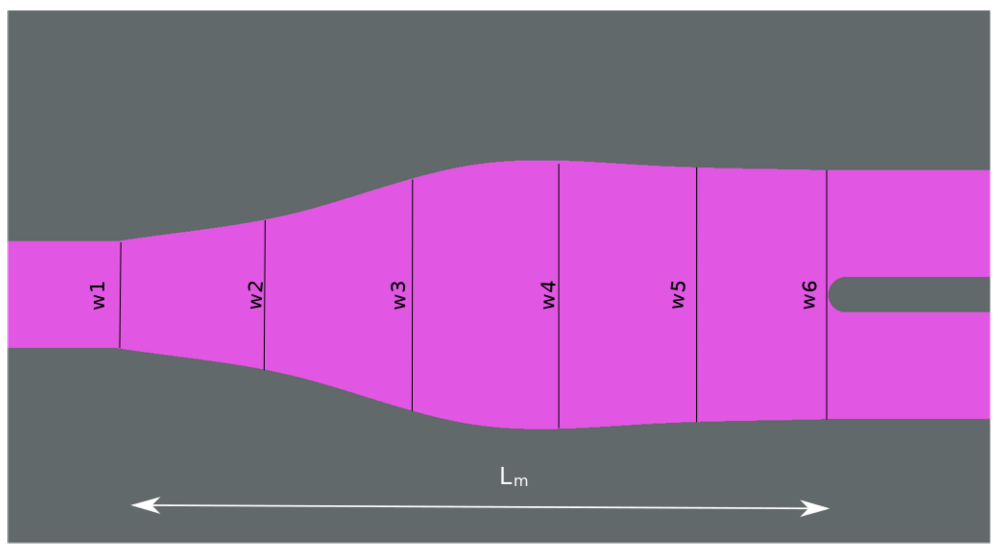
The aim of this research is to optimize the geometry of balanced Y-branch junction for 925 nm wavelength and investigate directional coupler performance.

Y-branch optimization

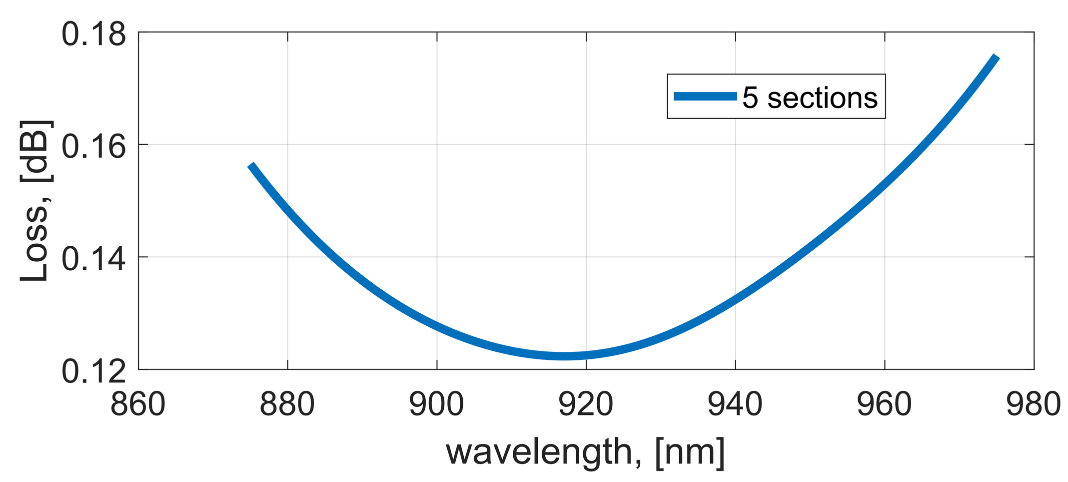
The integrated element design was optimized for 220 nm thick Si_3N_4 wafers and 925 nm wavelength. The optimization of Y-branch spliter was carried out with the use of the particle swarm optimization [3] according [4]. The Fig. 1 a) schematically depicts the design of Y-branch. The taper was first divided into 5 segments of equal length and different width w1, w2, w3 ... w6. The particle swarm method was applied to optimize the number of sections into which the Y-junction was divided, their widths and the length L_m of the splitter. Result of the optimization is presented in following table:

Table: Optimized parameters. Units of the width are in microns, loss in dB.

w1	w2	w3	w4	w5	w6	Lm	Loss @ 925 nm
0.55	0.611	0.86	1.6	1.5	1.3	6	0.13



a)



b)

Figure: 1. a) Schematic view of the layout with 5 section. The branch geometry is defined by the spline interpolation of w1 to w6. b) Loss in Y-branch with 5 section.

Directional coupler

The directional coupler is depicted on the Fig. 2. According to the coupled mode theory the fraction of the power coupled from one waveguide to the other can be expressed as:

$$T_{cross}(L_{int}) = \sin^2\left(\frac{\pi L_{int}\Delta n}{\lambda_0} + C_0\right) = \sin^2(C \times L_{int} + C_0),$$

$$T_{througth}(L_{int}) = \cos^2\left(\frac{\pi L_{int}\Delta n}{\lambda_0} + C_0\right) = \cos^2(C \times L_{int} + C_0),$$

where C_0 corresponds to coupling between bent waveguide sections, provided that the $L_{int} = 0$.

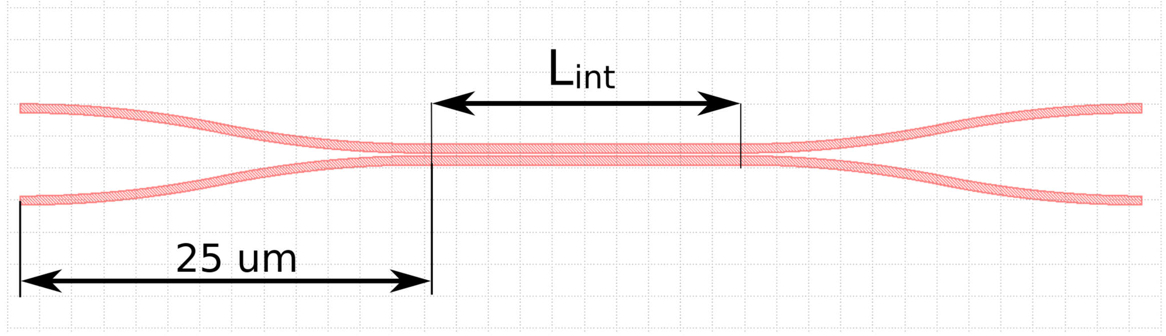
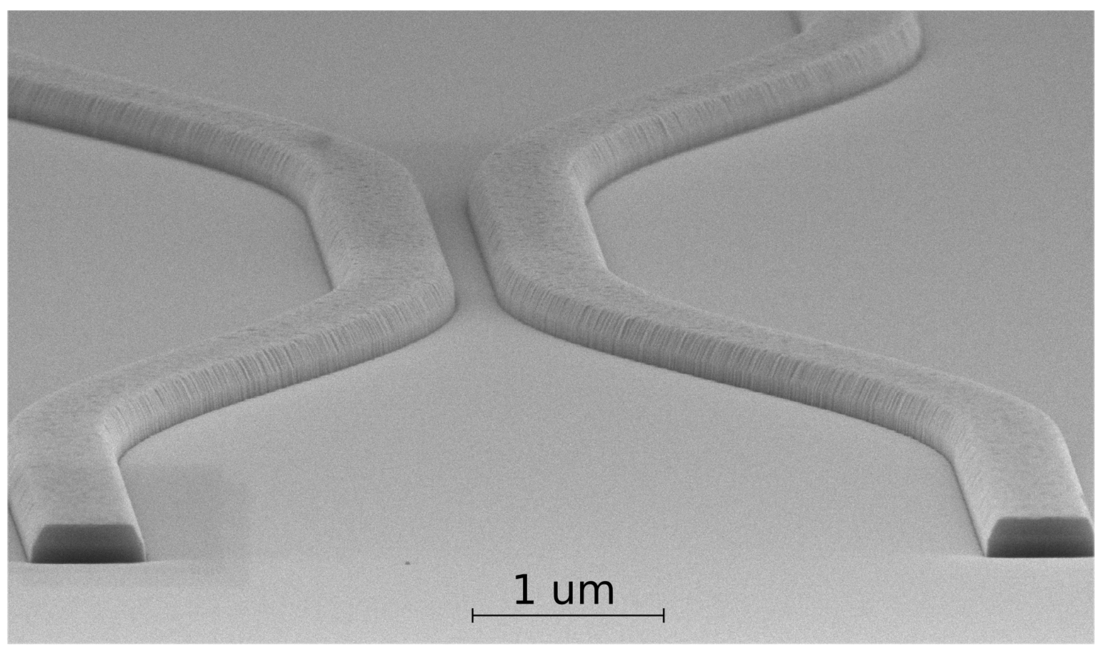


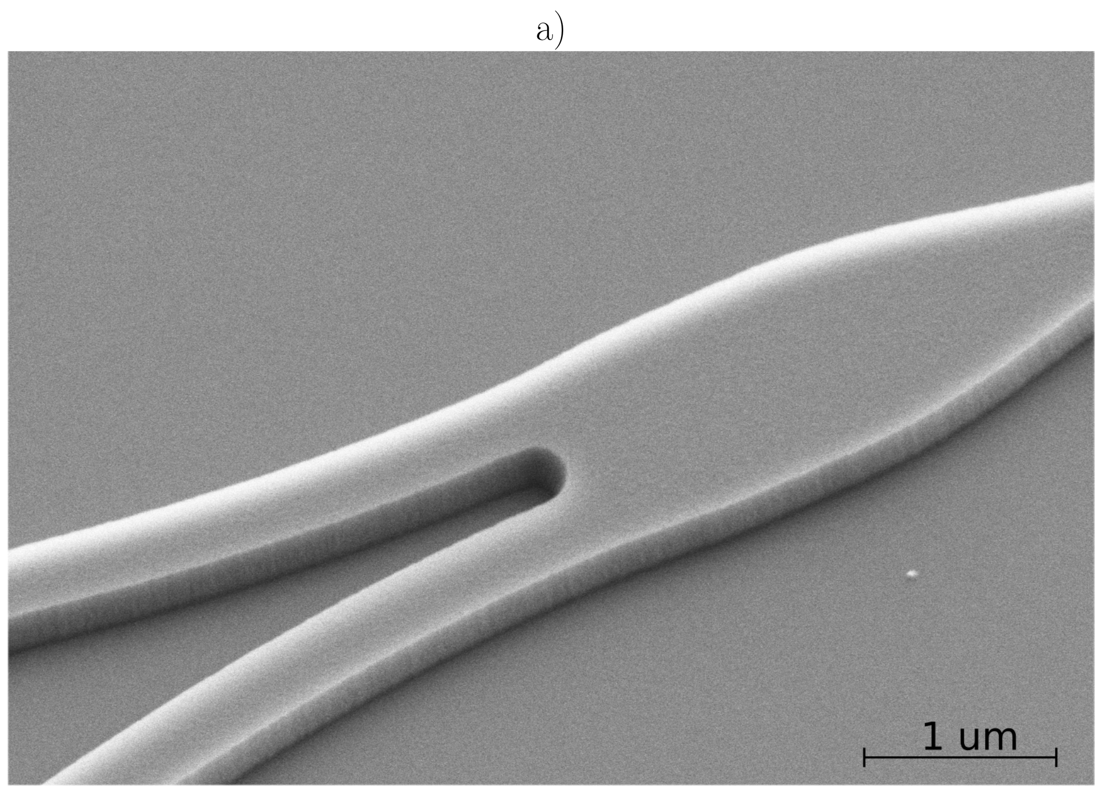
Figure: 2. GDS layout of directional coupler.

Fabrication in BMSTU

All integrated elements (DC, Y-branch splitter and grating couplers Fig.3) were fabricated by ultra-high resolution electron-beam lithography system with 50 kV accelerating voltage. We chose ma-N 2405 negative resist with polymer conductive layer for our design. For 220 nm thick Si_3N_4 the resist layer was estimated as 330 nm and 30 nm of conductive layer to prevent charging of dielectric layers stack during e-beam exposure process. The multiple-pass lithography technique reduces the exposure statistical errors by averaging so the final working fields stitching has a value about 2.5 nm and standard deviation about 12 nm.



a)



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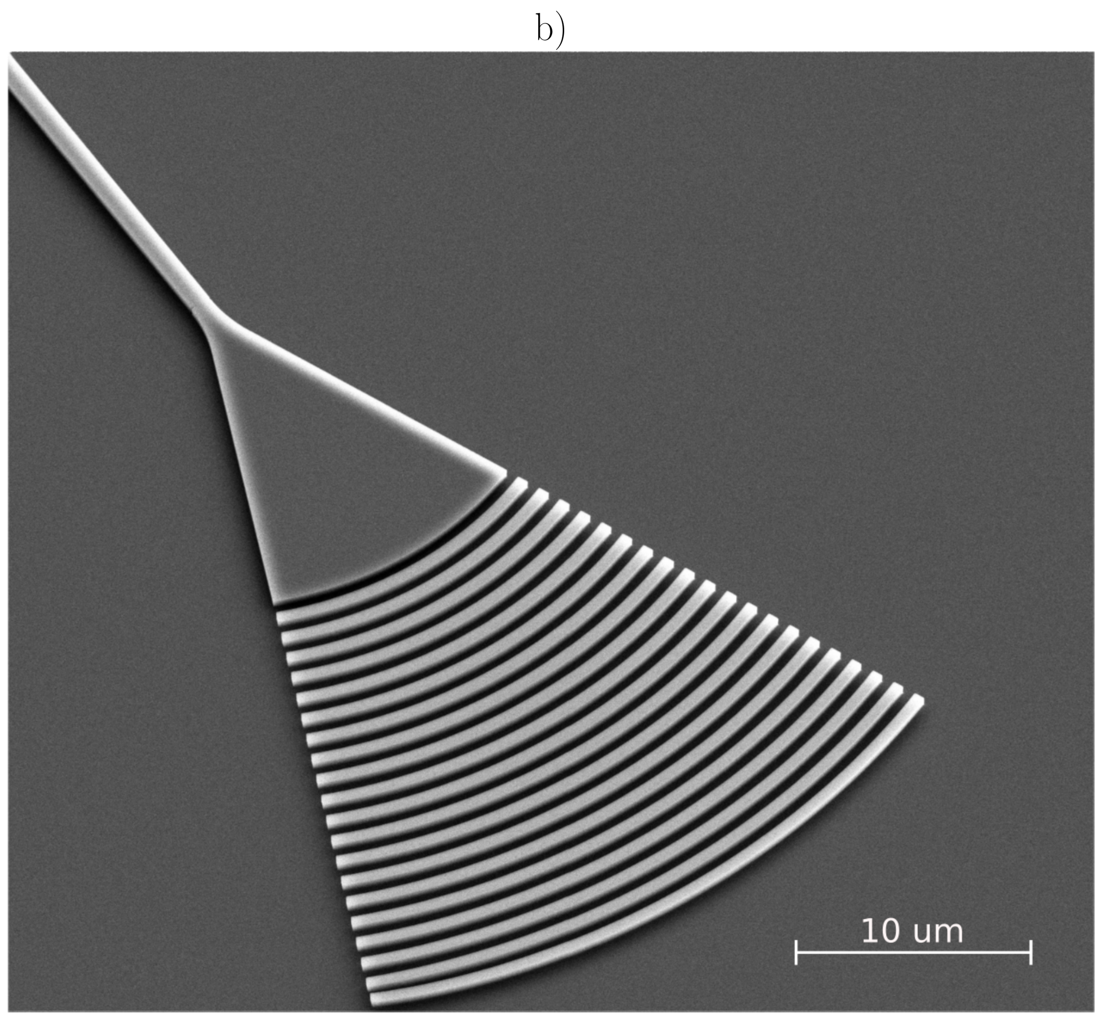


c)

Figure: 3. The SEM image of a) Directional coupler, b) Y-branch and c) grating coupler.

Optical I/O

To couple light into integrated structures, several approaches are used: with grating coupler and edge coupling. Grating coupler were numerically optimized at wavelength 925 nm using the particle swarm method. The optimization was carried out according to three parameters (filling factor, period, fiber position above the grating) and yielded the following results: at $ff = 0.465$ and $period = 606$ nm, the loss is 3.77 dB. In the experiment, losses of about 8 dB per grating were obtained. In some gratings, losses close to 7 dB were observed.

Y-branch. Experimental results

To measure the loss on Y-junctions, a different number of consecutive pairs of dividers were manufactured. Each pair consisted of two dividers interconnected as shown in the Fig. 4.

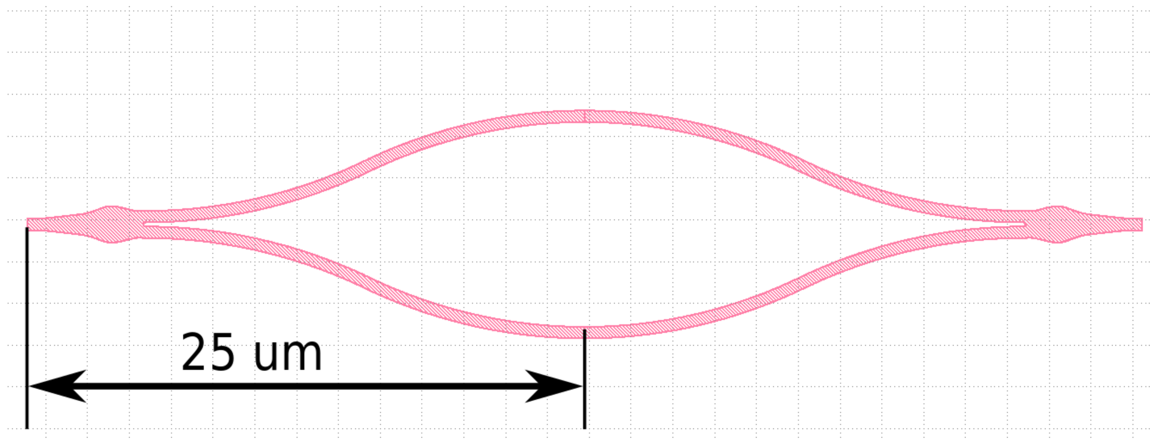


Figure: 4 GDS layout view of pair of spliting y-branches.

The dependence of losses on the number of pairs of Y-dividers is shown in Fig.5. According to data fit the loss per Y-junction is about 0.36 ± 0.14 dB.

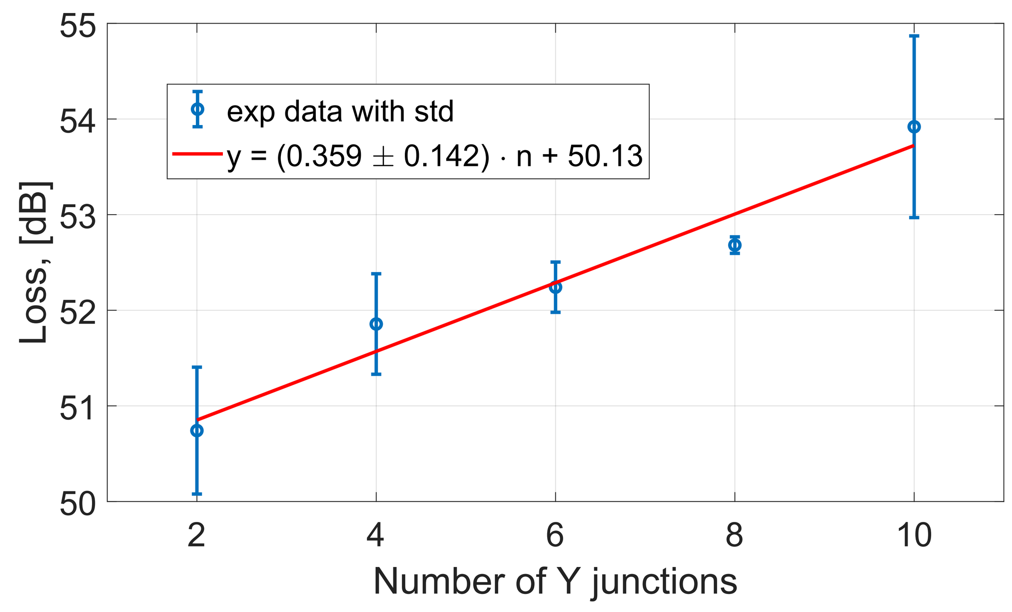
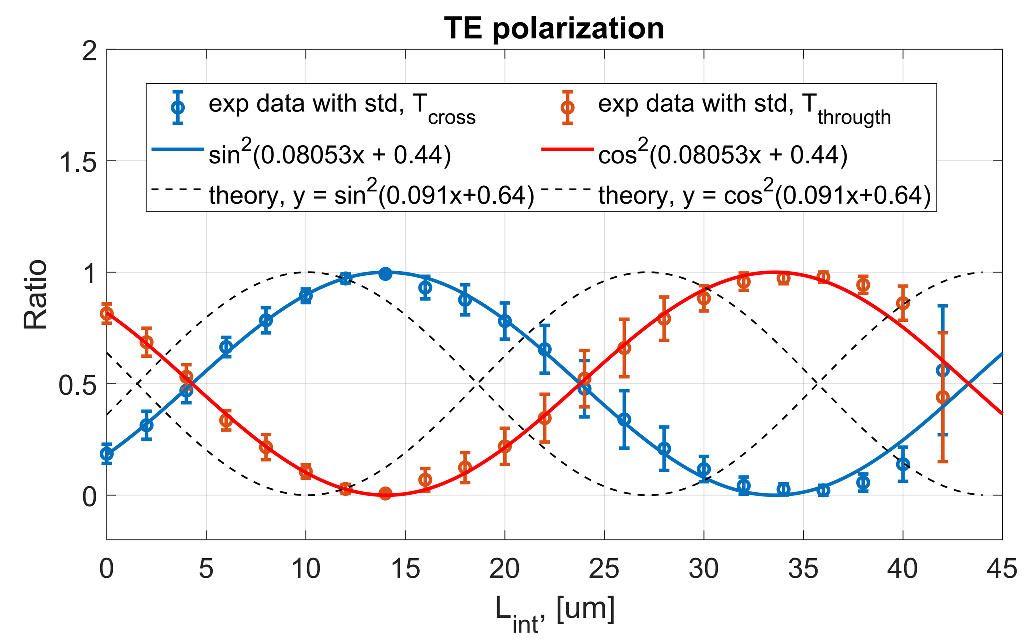


Figure: 5 Dependence of losses on the number of y-branches.

DC. Experimental results

The characteristics of the directional coupler were analyzed for two polarizations in a wide range of interaction lengths (L_{int}) from 0 to 42 μm.



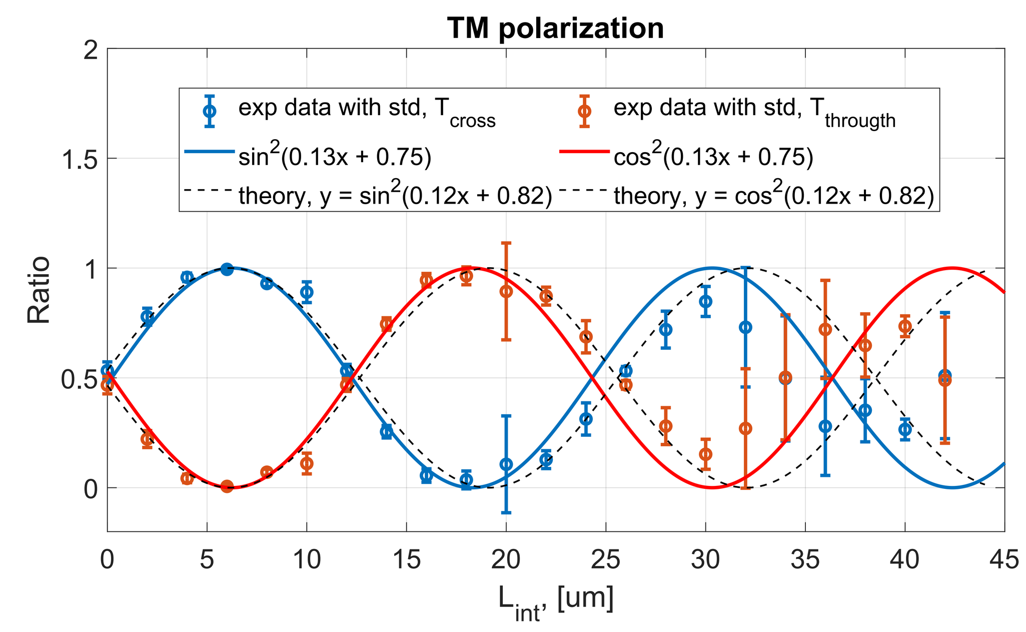


Figure: 6. DC. a) TE polarization b) TM polarization . The graph shows the experimental points and standard deviations corresponding to them. Each experimental point represents an average value of 20 measurements. Solid red and blue lines - results fit. The dashed black lines correspond to numerical calculations in 3D FDTD.

The numerical calculations in 3D FDTD were done as follows: the coefficient C_0 was found corresponding to the case when the interaction length L_{int} was zero . The coupling coefficient C was found from equation $C = \frac{\pi \Delta n}{\lambda_0}$, where $\Delta n = n_1 - n_2$ – difference in index between the 2 coupled modes of 2 waveguides that are separated by a gap of 200 nm.

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1. For the Y-splitter, the optimal geometry was calculated and the series of prototype devices has been fabricated and measured. In the calculations of such an element, the loss is 0.13 dB per splitter,experimentally measured loss 0.36 ± 0.14 dB per splitter.

2. For a directional coupler there are noticeable deviations of the experiment from calculation. This may be due to production uncertainty characteristic of lithographic processes. These uncertainties can lead to small variations in the width of the waveguides and as a consequence to a change in the gap.