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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

NQSTI National Quantum Science and Technology Institute

Spoke 6 Integration

T. H. Dao, F. De Matteis, *A. Salamon*

Silicon On Insulator CNOT gate

February 2025

Outlines

- Introduction
- Workflow
- Results
- Future work

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Introduction

- Goal: the research aims to optimize a Silicon Photonic Integrated Circuit for Linear Optics Quantum Computing. The chosen scheme is the CNOT gate built with SOI technology.
- Collaboration: **T. H. Dao**, F. Amanti, G. Andrini, F. Armani, F. Barbato, V. Bellani, V. Bonaiuto, S. Cammarata, M. Campostrini, S. Cornia, **F. De Matteis**, V. Demontis, G. Di Giuseppe, V.D. Tchernij, S. Donati, A. Fontana, J. Forneris, R. Francini, L. Frontini, G.C. Gazzadi, R. Gunnella, S. Iadanza, A.E. Kaplan, C. Lacava, V. Liberali, L. Martini, F. Marzioni, C. Menozzi, E.N. Hern´andez, E. Pedreschi, P. Piergentili, P. Prosposito, V. Rigato, C. Roncolato, F. Rossella, **A. Salamon**, M. Salvato, F. Sargeni, J. Shojaii, F. Spinella, A. Stabile, A. Toncelli, G. Trucco, V. Vitali.

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UNIVERSITÀ DEGLI STUDI DI SALERNO
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CORNERSTONE

Photonic Integrated Circuit

- PICs, or optical chips, integrate multiple photonic functions for information signals imposed on optical wavelengths.
- Advantages:

-Small stochastic noise level.

-PICs are strongly pursued for classical computing purposes, and the core components necessary are under research. PICs are not only CMOS compatible but also can be built with nothing changed in CMOS fabrication techniques and standards.

Silicon photonics with Silicon-On-Insulator technology

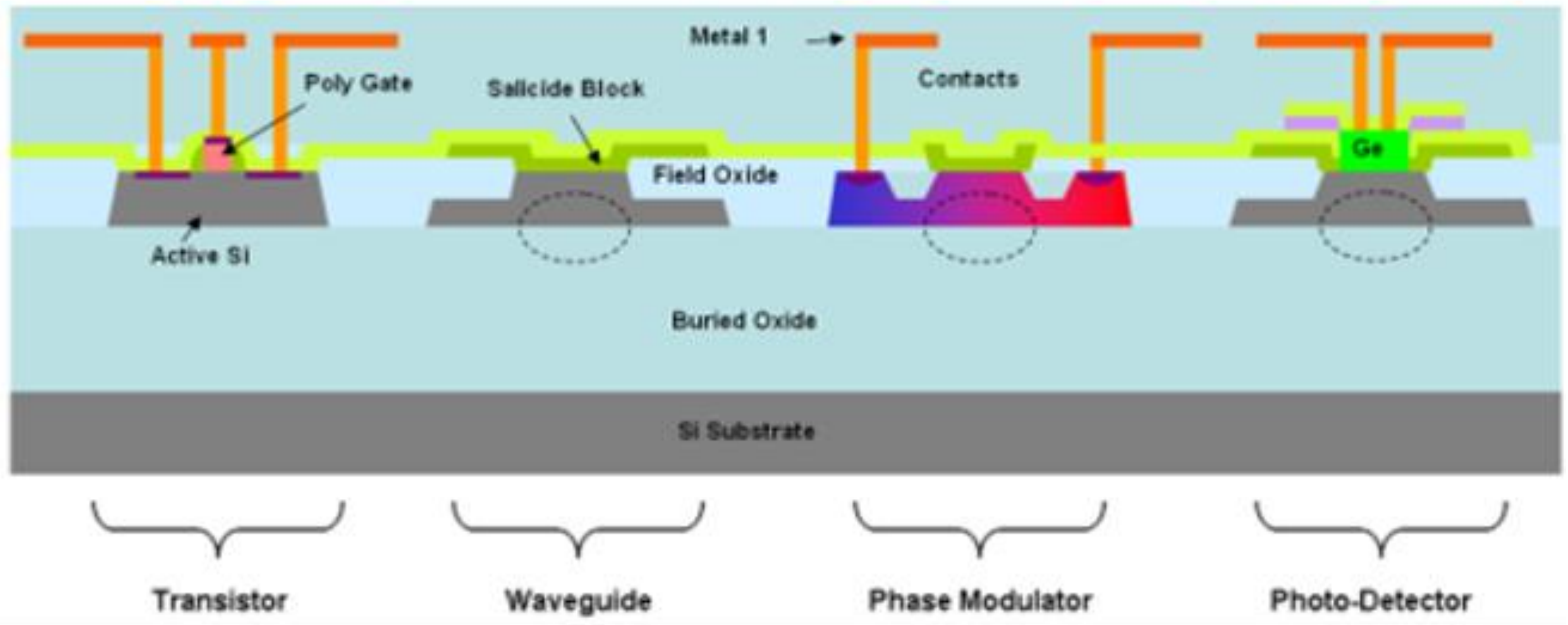
- Silicon photonics: low spectral dispersion, high refractive index

→ easy integration of complex optical system

→ chip-integrated communication systems for world-wide communication networks.

- SOI technology: Silicon optical components are built over a thick oxide layer previously deposited on top of a Si handling wafer.

Silicon On Insulator SOI



Quantum Computing

- 1982: R. P. Feynman proposed building a computer based on the manipulation of wavefunctions in order to simulate nature with quantum computer.
- 1994: P. W. Shor suggested an algorirthm to factorize integers into prime numbers operating on a quantum computer more efficent than the classical analogue.
- 2001: Knill, Laflamme and Milburn demonstrated how it is posible to use linear optics for quantum information processing using beam splitters, phase shifters, single photon sources and detectors.
- 2001-2002: T. C. Ralph, N. K. Langford, T. B. Bell and A. G. White proposed a NOT-controlled linear optical gate based on coincidence.

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Controlled NOT (CNOT) gate

1 qubit: $\alpha_0|0\rangle + \alpha_1|1\rangle, \; |\alpha_0|^2 + |\alpha_1|^2 = 1$

Quantum logic gate for 1 qubit

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad R_\phi = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{pmatrix} \quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

2 qubits: $a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle \qquad |a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$

Controlled NOT (CNOT) gate

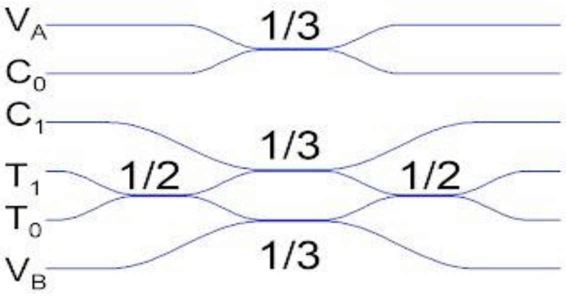
control bit

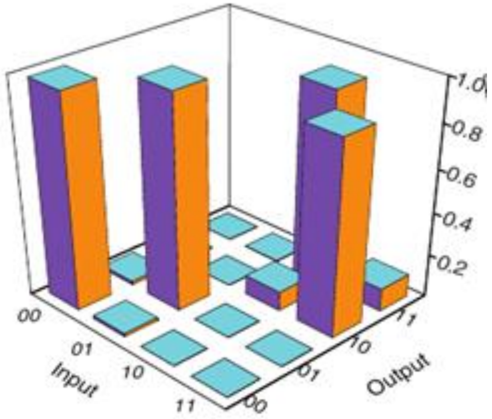
$$\mathrm{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

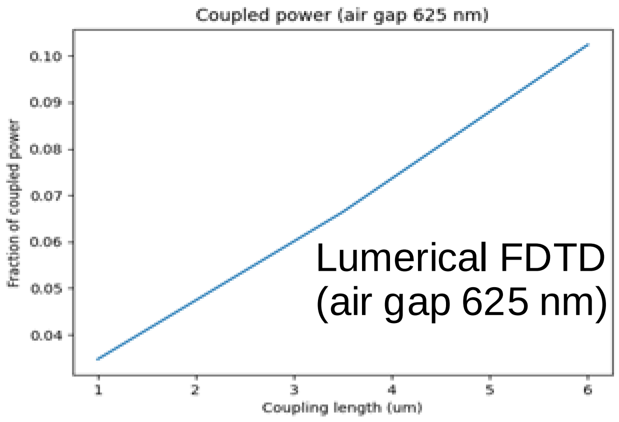
target bit

$$a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle \rightarrow a|00\rangle + b|01\rangle + c|11\rangle + d|10\rangle$$

CNOT-gate with Linear Optics



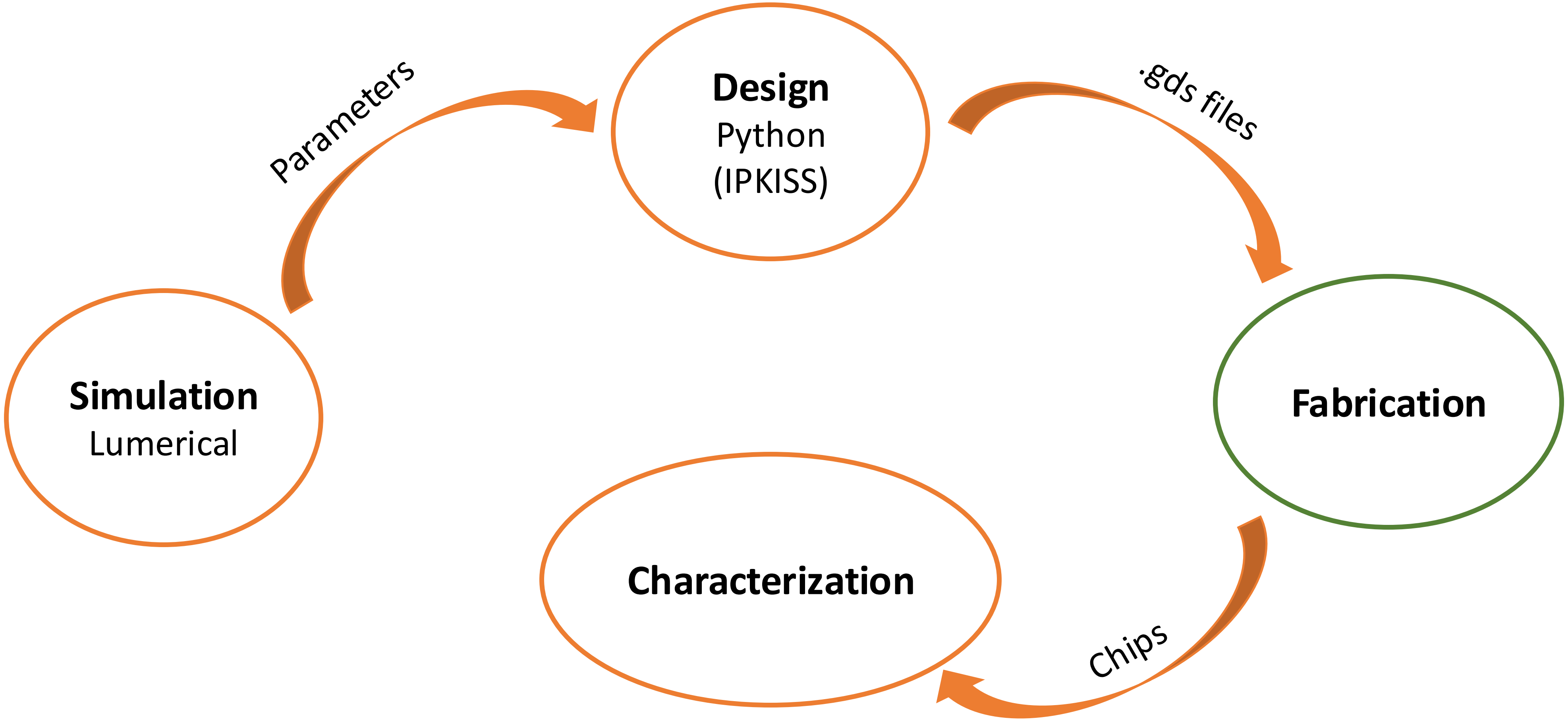




Waveguide coupler used as beam splitter (SR=1/2, SR=1/3)
Coincidence basis (C_0T_0, C_1T_0, C_0T_1, C_1T_1)
Postselected probabilistic gate (P=1/9)

T. C. Ralph et al, Linear optical controlled-NOT gate in the coincidence basis, DOI: 10.1103/PhysRevA.65.062324
A. Politi et al, Silica-on-Silicon Wavegide Quantum Circuits, DOI: 10.1126/science.1155441

Workflow

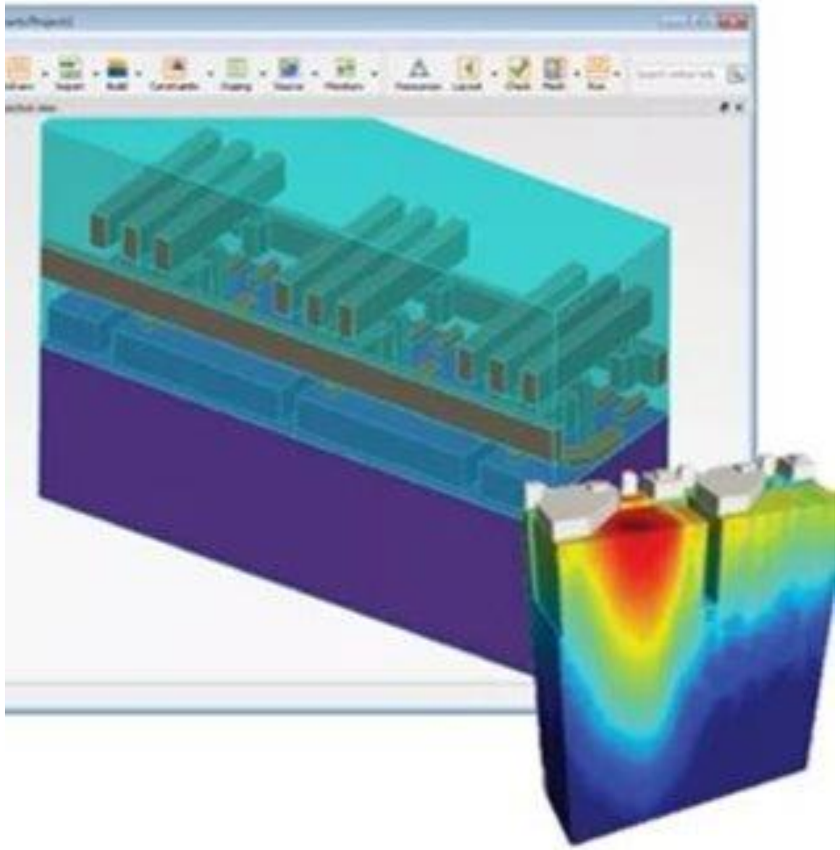

Design
Python
(IPKISS)
.gds files
Fabrication
Chips
Characterization
Simulation
Lumerical
Parameters

Simulation

- Ansys Lumerical Photonics Simulation & Design Software

- Simulating light's interactions for the design of photonic components and systems

- License



Lumerical Solutions Products

Device Suite for photonic multiphysics simulation

- FDTD 3D Electromagnetic Simulator
- MODE Waveguide Simulator
- CHARGE 3D Charge Transport Simulator
- HEAT 3D Heat Transport Simulator
- DGTD 3D Electromagnetic Simulator
- FEEM Waveguide Simulator
- MQW Quantum Well Gain Simulator
- STACK Optical Multilayer Simulator

System Suite for Photonic integrated circuit simulation

- INTERCONNECT Photonic Integrated Circuit Simulator
- CML Compiler Photonic Model Development Kit
- Laser Library Advanced Laser Modeling Extension
- System Library Advanced System Modeling Extension
- Photonic Verilog-A Platform Runtime Library & Utilities for PIC Simulation

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Finite Difference Time Domain (FDTD) solver

- The Finite-Difference Time-Domain (FDTD) method is a powerful tool for modeling nano-scale optical devices. Giving a direct time and space solution for Maxwell's equations without any physical approximation, FDTD offers an unique insight into all types of problems in electromagnetics and photonics. Even the frequency solution can be obtained by exploiting Fourier transforms, from which a full range of useful quantities can be calculated.
- The FDTD method solves Maxwell's equations on a mesh and computes E and H at grid points spaced Δx, Δy, and Δz apart, with E and H interlaced in all three spatial dimensions. FDTD includes the effects of scattering, transmission, reflection, absorption, etc..
- FDTD can simulate any structure where Maxwell's equations describe the necessary physics. Typical applications for this method include: LEDs, solar cells, filters, optical switches, semiconductor-based photonic devices, sensors, nano- and micro-lithography, nonlinear devices, and meta-materials (negative index of refraction).

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Design

- Python is a programming language that lets you work quickly and integrate systems more effectively.
- Luceda Photonics Design Platform, the first-time-right photonic IC design software, automates and integrates all aspects of the photonic design flow in one platform, using one standard language.

Results

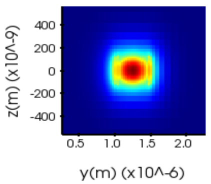
- **Simulation**

- Directional coupler

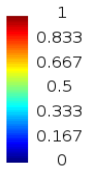
- Bragg grating coupler

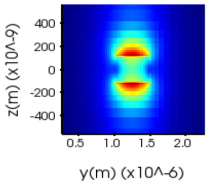
Directional coupler

$$\text{TE polarization fraction (Ey)} = \frac{\int |Ey|^2 dydz}{\int (|Ey|^2 + |Ez|^2) dydz}$$

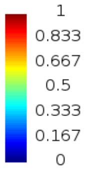


E_TE0



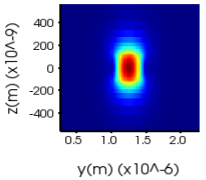


E_TM0

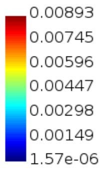


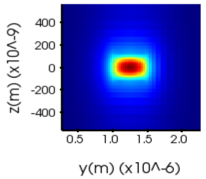
$$\text{waveguide TE fraction} = 1 - \frac{\int |E_\perp|^2 \, dA_{||}}{\int (|E|^2) \, dA_{||}}$$

$$\text{waveguide TM fraction} = 1 - \frac{\int |H_\perp|^2 \, dA_{||}}{\int (|H|^2) \, dA_{||}}$$

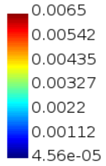


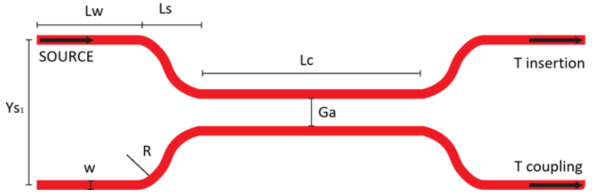
H_TE0

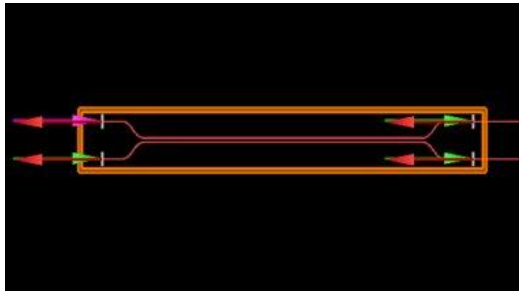




H_TM0







Effective index	Mode	TE polarization fraction (Ey)	Waveguide TE/TM fraction (%)
2.351788	TE0	98	72.67/81.52
1.750815	TM0	4	74.39/88.14

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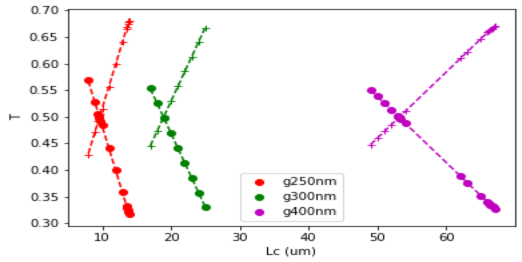
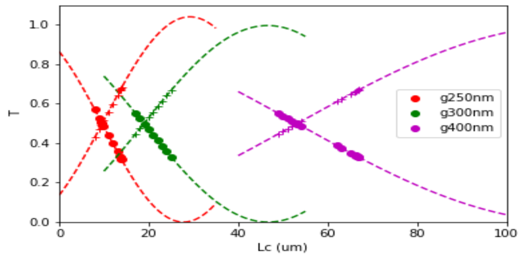
Directional coupler

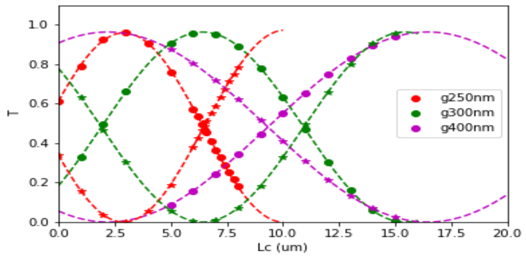
Gap (um)	SR (Ti/Tc)	TE		TM
		Lc_lin (um)	Lc_sin2 (um)	Lc_sin2 (um)
0.25	½-½	9.60724607	9.60654607	6.46486465
0.25	1/3-2/3	13.54303543	13.54443544	7.23227232
0.3	½-½	18.92133921	18.921178922	1.910419
0.3	1/3-2/3	24.89289893	24.9297993	0.93568936
0.4	½-½	53.1299313	53.11673117	9.32949329
0.4	1/3-2/3	66.54066541	66.56886569	7.78887789



TE Linear fit



TE sin^2 fit

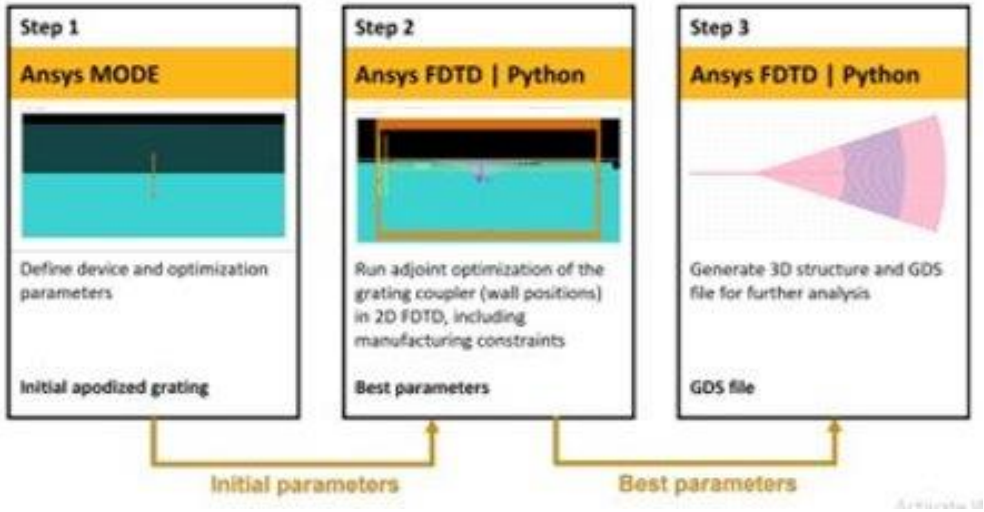


TM sin^2 fit

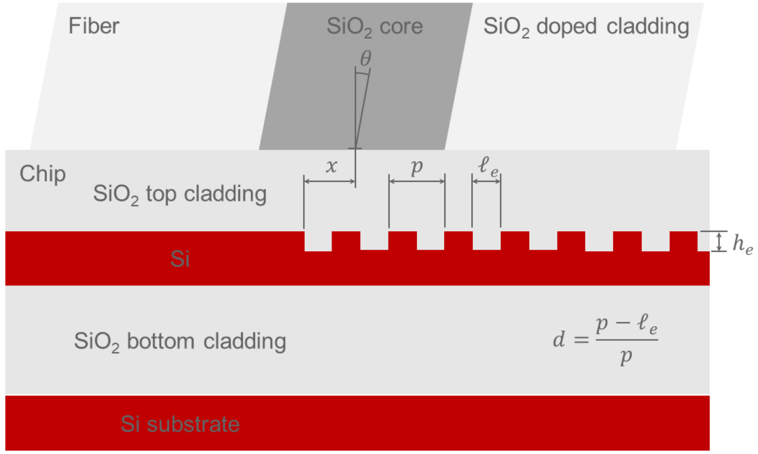
Bragg grating coupler

Apodized fully etched grating coupler:

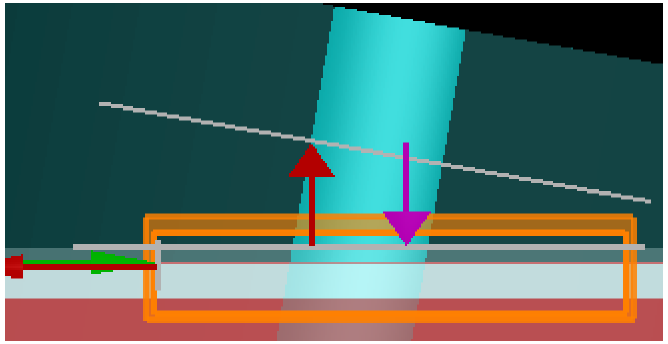
- Etch depth: 220 nm
- Tilt angle theta of the source: 6.8

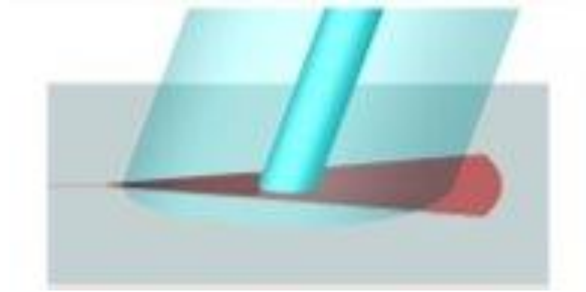


Bragg grating coupler

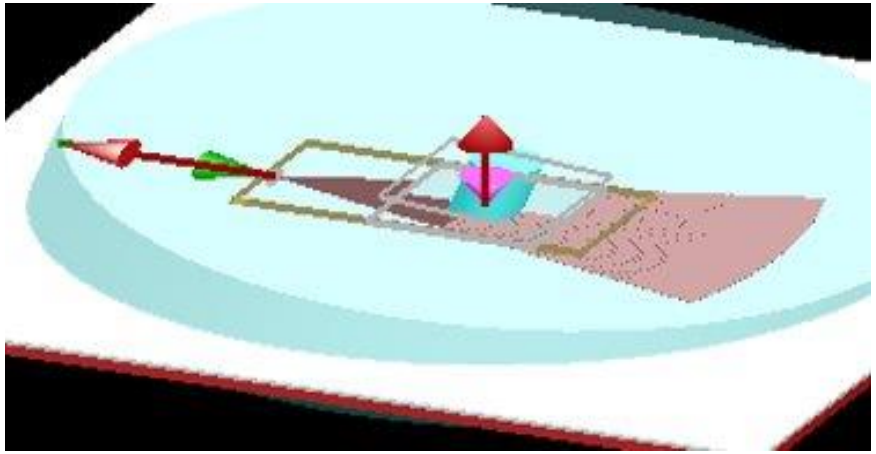


2D





3D



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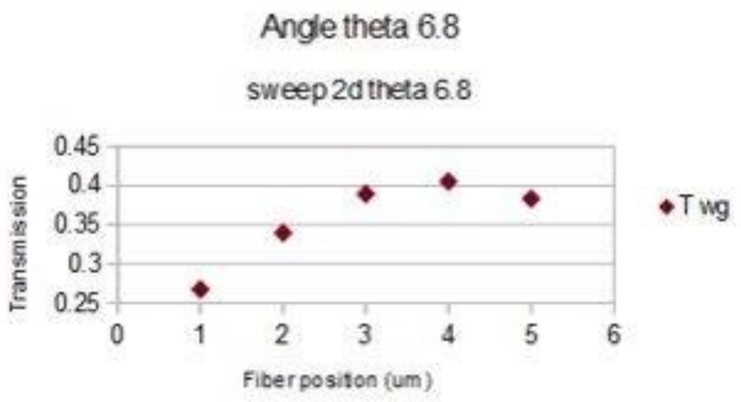
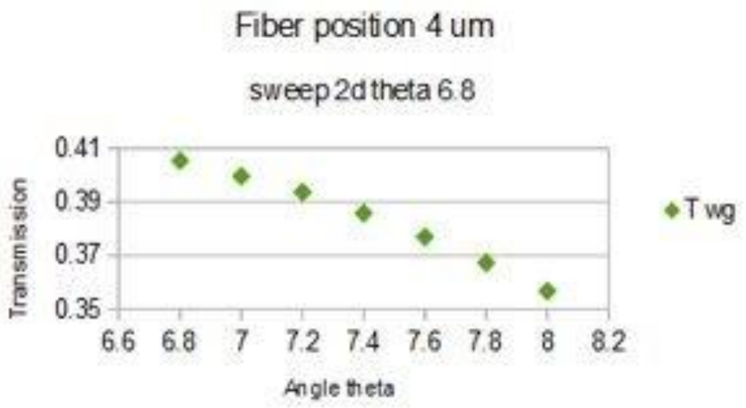
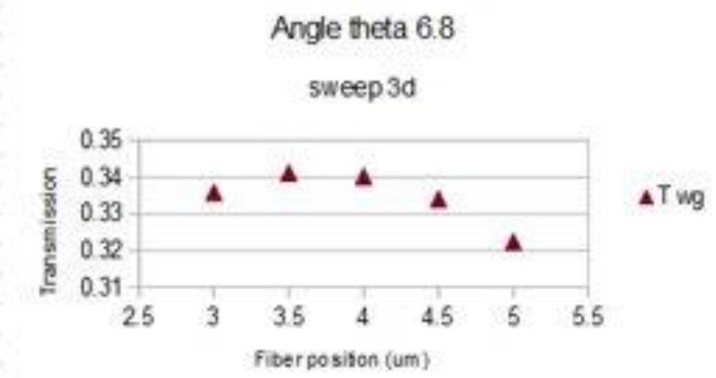
Bragg grating coupler

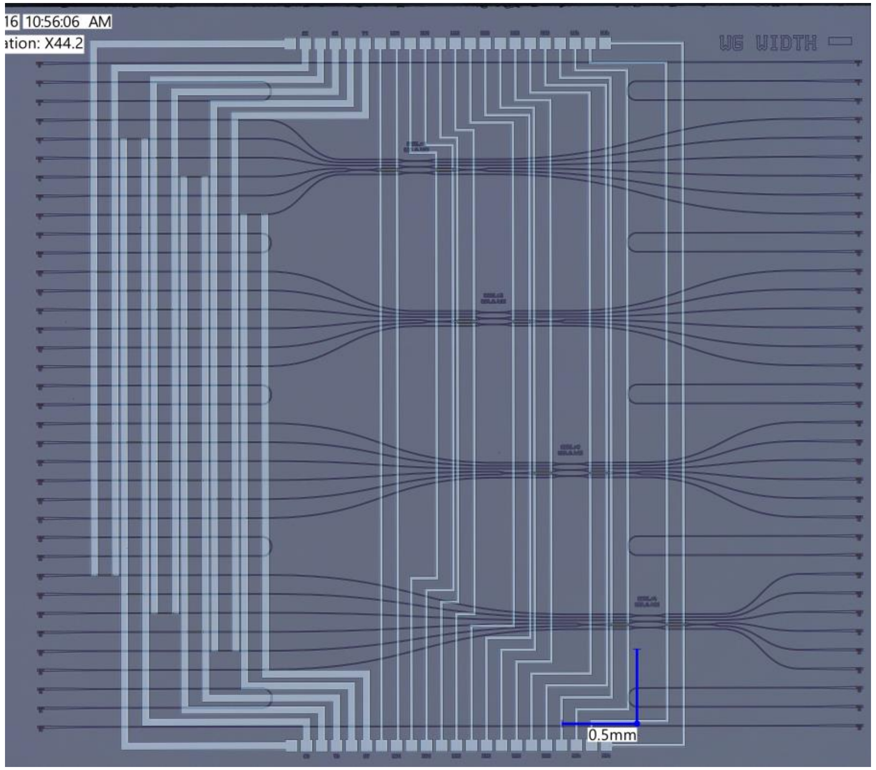


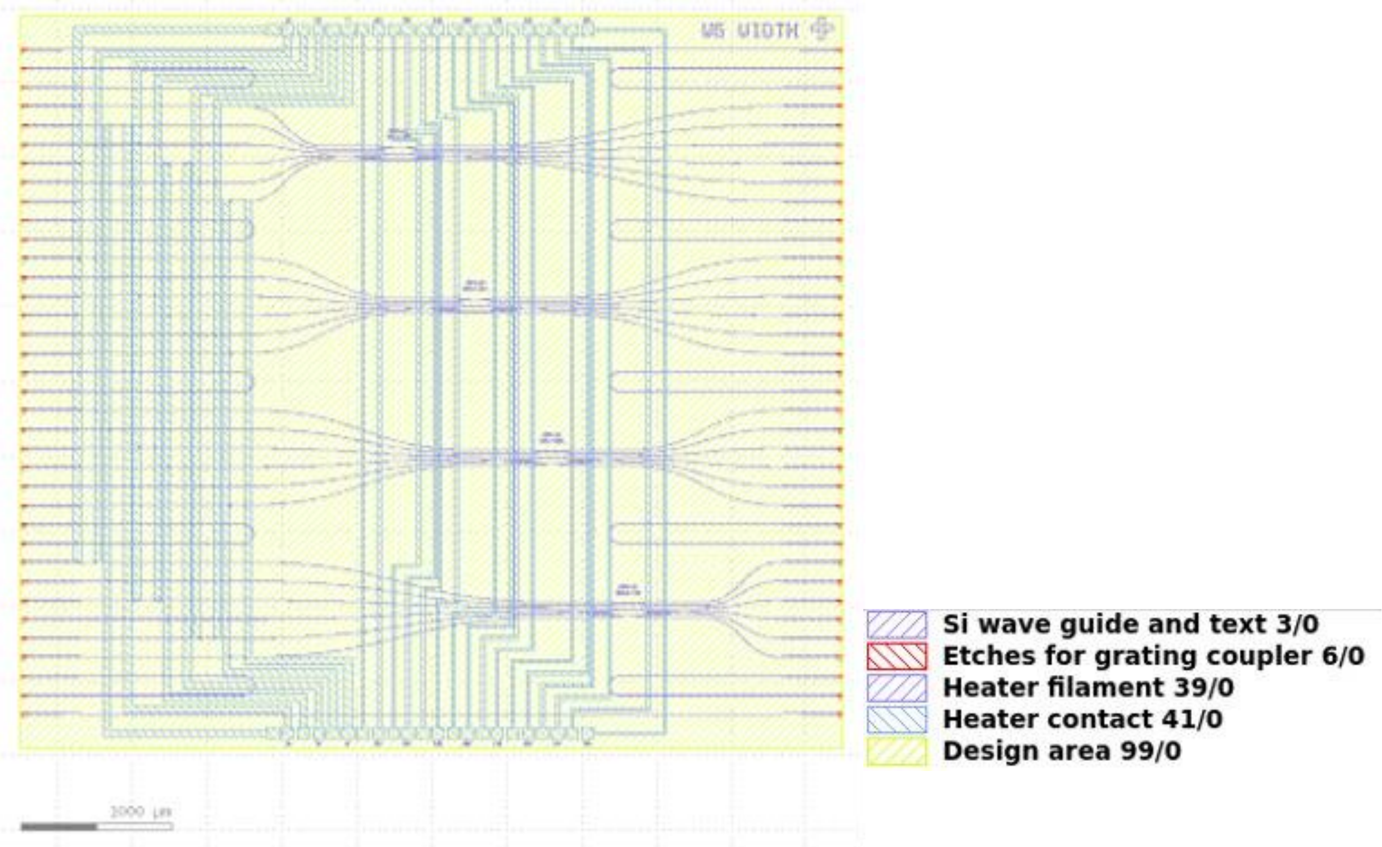




Results

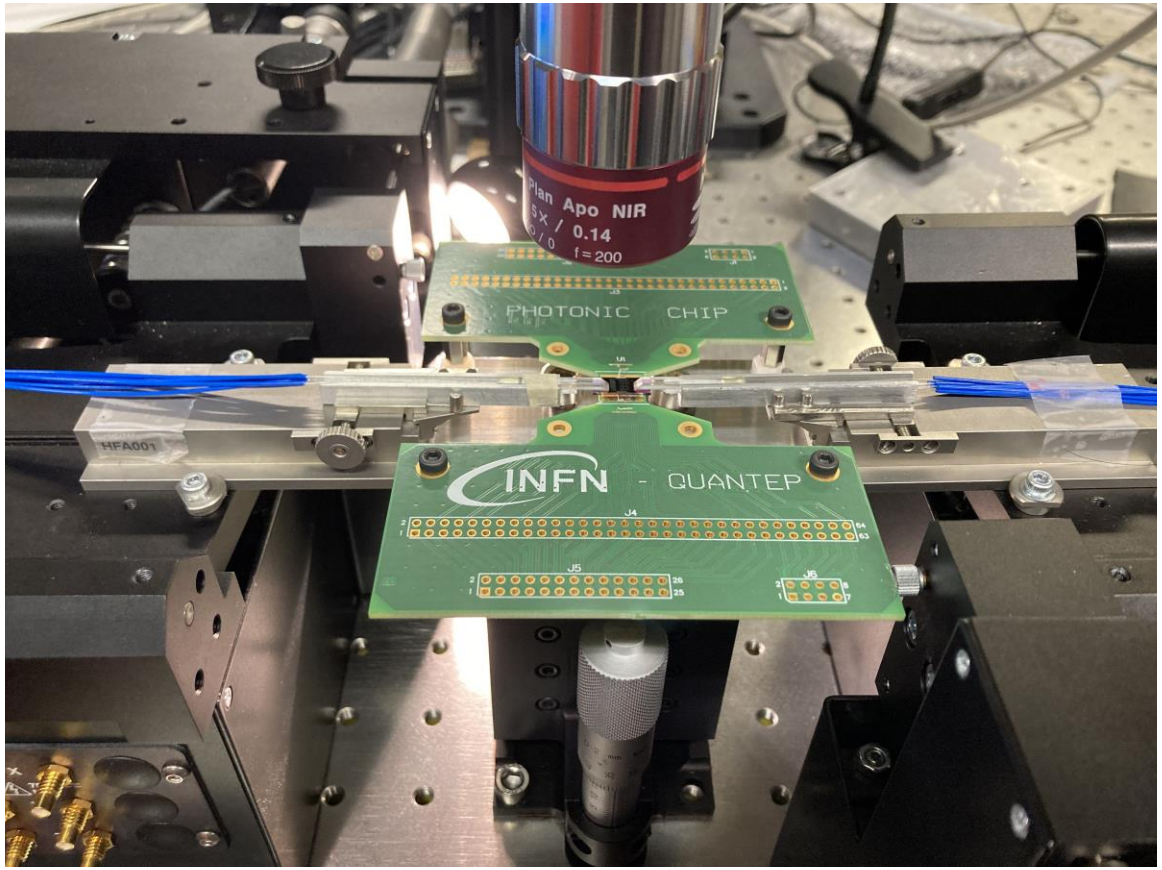
- Chip layout



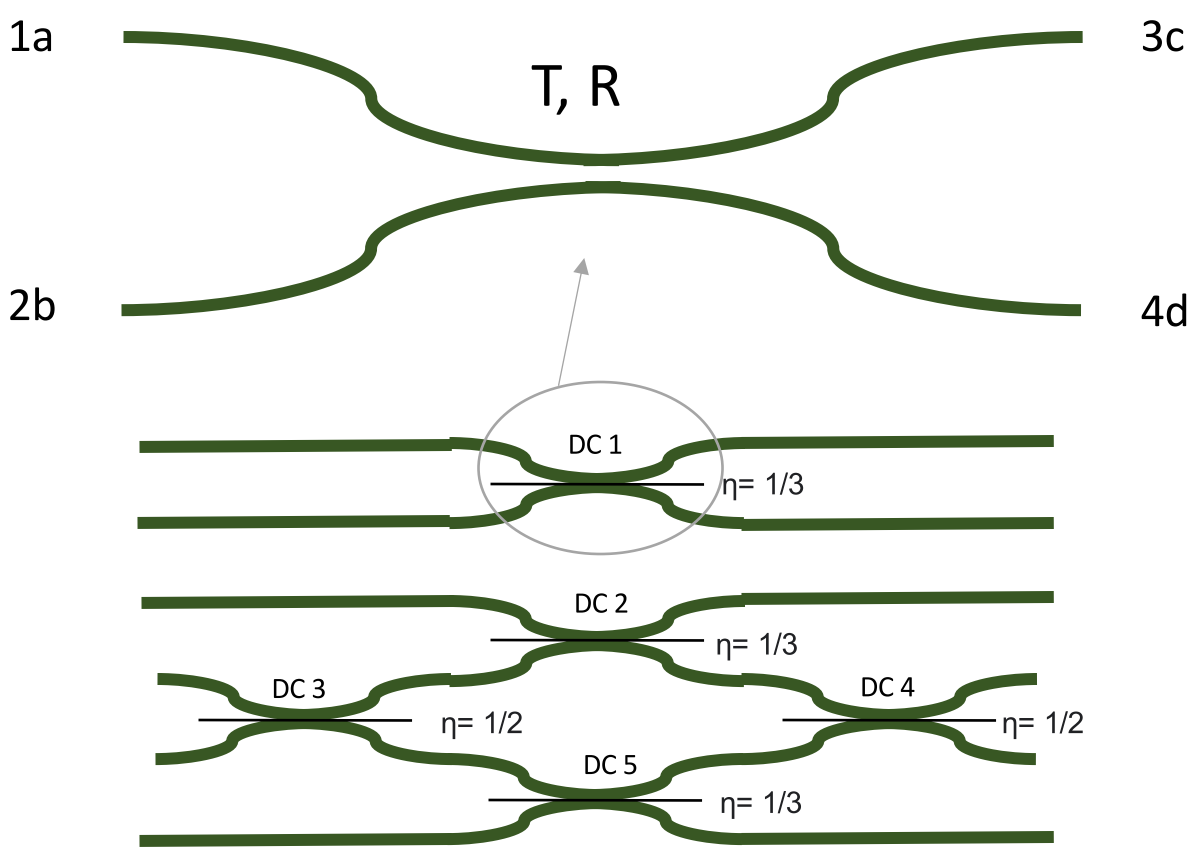


Results

- **Preliminary measurement**



Preliminary measurement



1.1) P_{ac}=PaRc
1.2) P_{ad}=PaTd

2.1) P_{bc}=PbTc
2.2) P_{bd}=PbRd

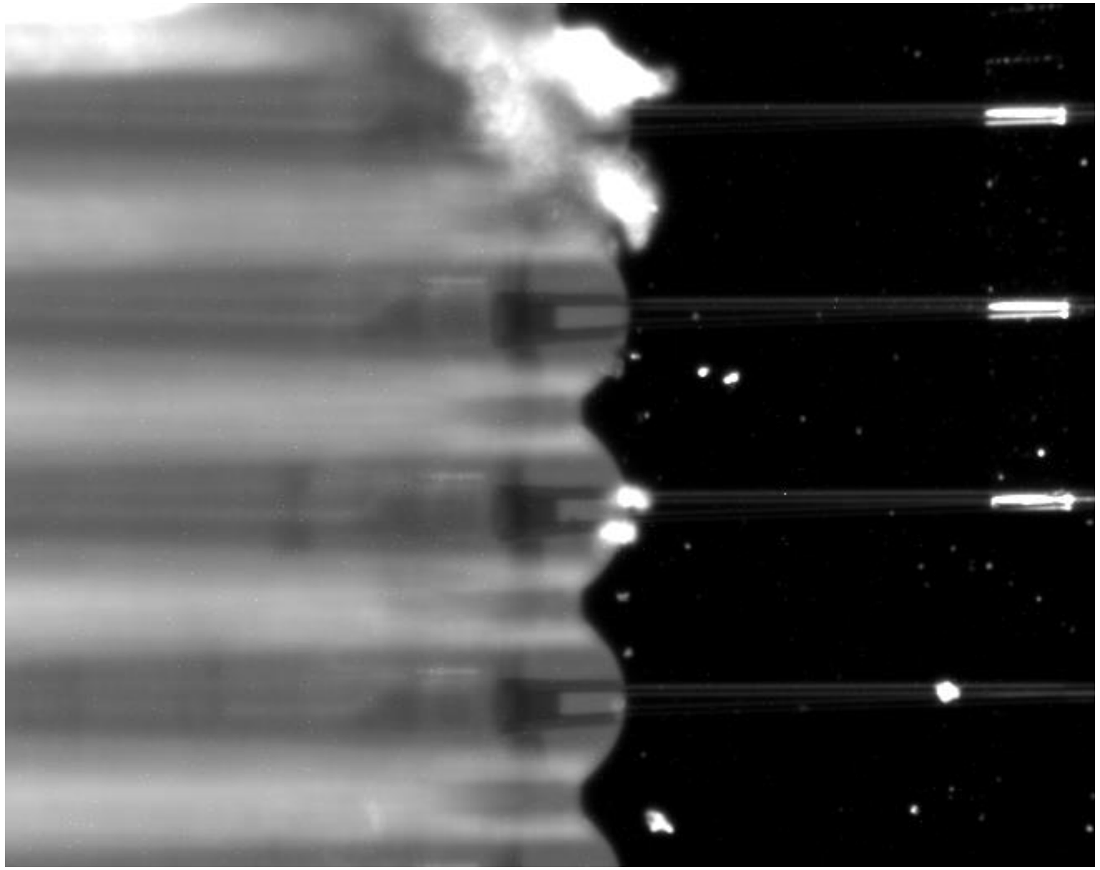
3.1) P_{ca}=PcRa
3.2) P_{cb}=PcTb

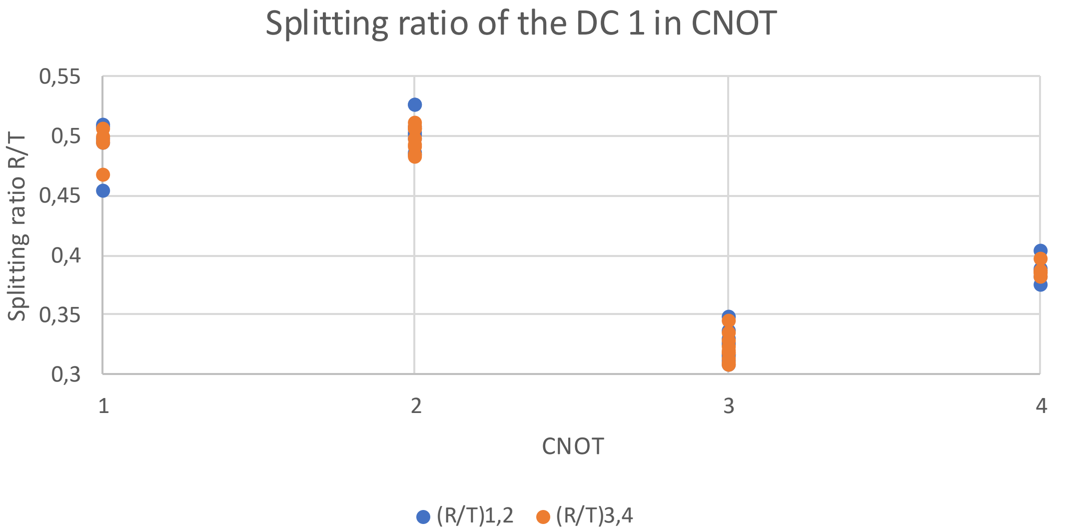
4.1) P_{da}=PdTa
4.2) P_{db}=PdRb

$$\left(\frac{R}{T}\right)_{1,2} = \sqrt{\frac{P_{11}P_{22}}{P_{12}P_{21}}}$$

$$\left(\frac{R}{T}\right)_{3,4} = \sqrt{\frac{P_{31}P_{42}}{P_{32}P_{41}}}$$

Preliminary measurement





Future work

CHARACTERIZATION AND MEASUREMENT

REPEAT THE PROCESS

Measurement with single photon

Single photon source

Single photon detector

Thank you for your attention!