Low-cost, home-made Quantum Computer

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Introduction

Among all quantum technologies currently available, quantum computers remain the most controversial. After over 100 years of quantum science in 2025, numerous applications were developed, such as quantum sensors and quantum networks. With these technologies used across medicine, military, and enterprises, quantum computers remain active mostly in the laboratories. Their applications are limited to validating fundamental laws of physics, where the number of logical qubits remains low. This feature of the so-called Noisy Intermediate Scale Quantum (NISQ) computers makes them rather of a teaching tool than real-world problem solvers. Because of that, the following research focuses on an engineering approach that allows a student the create such a tool in a low-cost manner, to discover computational quantum mechanics at home.

Deutsch-Jozsa Algorithm

One common approach to benchmarking an NISQ computer is to utilise its ability to implement the Deutsch-Jozsa algorithm, which determines whether a given function is balanced or constant in a single run, demonstrating quantum advantage over classical logic-based methods that require multiple evaluations. The following mathematical steps represent physical operations on a gate-based NISQ device to assess its foundational computational capabilities: initialising the qubits, applying Hadamard gates to create superposition, using an oracle to encode the function, applying Hadamard gates again to generate interference, and finally measuring the output to distinguish between balanced and constant functions[5].

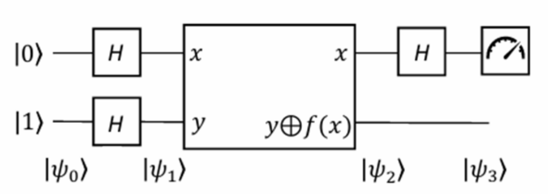


Figure 1. Gate-based implementation in Quantum Information framework.

Step 1: Initial State and First Hadamard Transformation

$$|\psi_0\rangle = |01\rangle$$
$$|\psi_1\rangle = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right) \otimes \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right) = \frac{1}{2}(|00\rangle - |01\rangle + |10\rangle - |11\rangle)$$

Step 2: Oracle Function Evaluation

For $f(x) = 0$: $|\psi_2\rangle = \frac{1}{2}(|00\rangle - |01\rangle + |10\rangle - |11\rangle)$
For $f(x) = 1$: $|\psi_2\rangle = \frac{1}{2}(|01\rangle - |00\rangle + |11\rangle - |10\rangle)$
For $f(x) = x$: $|\psi_2\rangle = \frac{1}{2}(|00\rangle - |01\rangle + |11\rangle - |10\rangle)$
For $f(x) = x \oplus 1$: $|\psi_2\rangle = \frac{1}{2}(|01\rangle - |00\rangle + |10\rangle - |11\rangle)$

Step 3: Final State Analysis

For $|\psi_2\rangle$:

$$|\psi_2\rangle = \begin{cases} \pm\left(\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right) \otimes \left(\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right) & \text{if } f(0) = f(1) \\ \pm\left(\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right) \otimes \left(\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right) & \text{if } f(0) \neq f(1) \end{cases}$$

After the final Hadamard on the first qubit, for $|\psi_3\rangle$:

$$|\psi_3\rangle = \begin{cases} \pm|0\rangle \otimes \left(\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right) & \text{if } f(0) = f(1) \text{ (constant)} \\ \pm|1\rangle \otimes \left(\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right) & \text{if } f(0) \neq f(1) \text{ (balanced)} \end{cases}$$

The measurement result of the first qubit determines the function type:

- Measure $|0\rangle \Rightarrow$ Function is constant
- Measure $|1\rangle \Rightarrow$ Function is balanced

Benchmarking 2-qubit NISQ computers

The following table compares 2-qubit, NISQ computers, quantifying their effectiveness through measured fidelity rates to assess adherence to expected balanced/constant function results, dependent on qubit infrastructure choice.

Infra.	ID⇒0	NOT⇒0	CNOT⇒1	Z-CNOT⇒1
Supercond.[1]	93%	94%	91%	84%
Silicon[7]	98%	96%	95%	93%
Ion-Trap[2]	98.1%	91.3%	97.5%	97.5%

Table 1. Fidelity scores for 2-qubit Deutsch-Jozsa implementations.

Design of Experiment

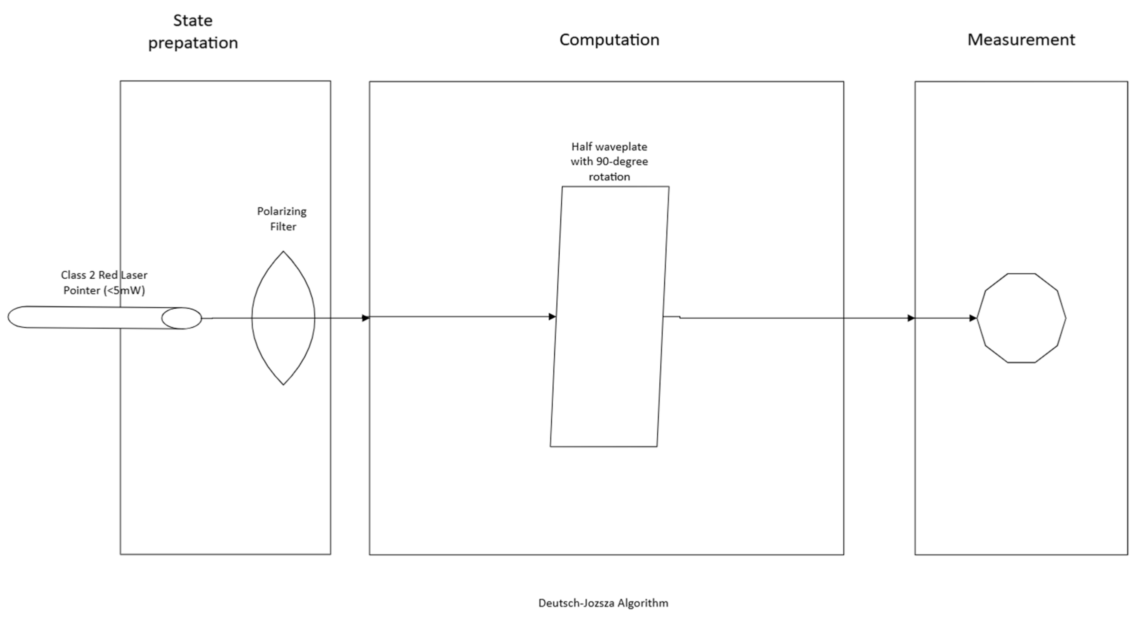


Figure 2. Project Architecture

Polarisation-encoded qubits via half-wave plates[4].

Step 1: State Preparation

1. Laser
2. Polarizer (as a Hadamaard gate)
3. Laser intensity stabilization (combination of half waveplates and polarizers)

Step 2: Computation (Oracle)

- ID gate: Beam passing through a polarisation-neutral medium.
- NOT gate: half-wave plate set at a 45° angle relative to the horizontal axis.
- CNOT gate: encode control qubit in polarisation, and target in spatial degree of freedom with a polarising beamsplitter.
- Z-CNOT gate: a half-wave plate at 45° to the control qubit, send this photon through PBS, apply another half-wave plate on the control qubit.

Step 3: Measurement

- Polariser (Analyser)
- Intensity correlation measurements using balanced photodetectors connected to oscilloscopes.
- Function determination via intensity threshold analysis:

$$\text{Outcome} = \begin{cases} \text{Total intensity} > \eta & \text{Constant} \\ \text{Modulated intensity distribution} & \text{Balanced} \end{cases}$$

where η is the intensity threshold from calibration.

Physical implementation

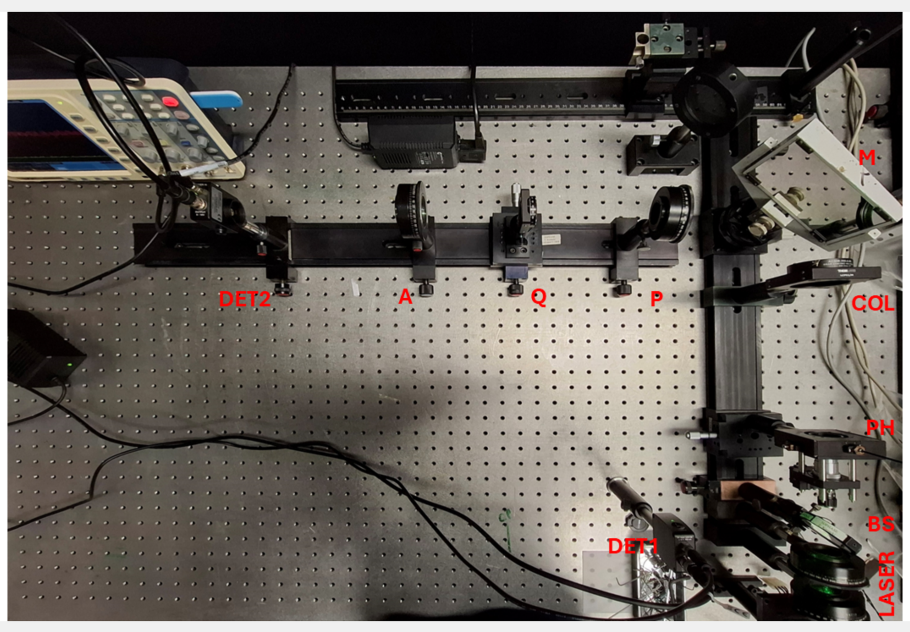
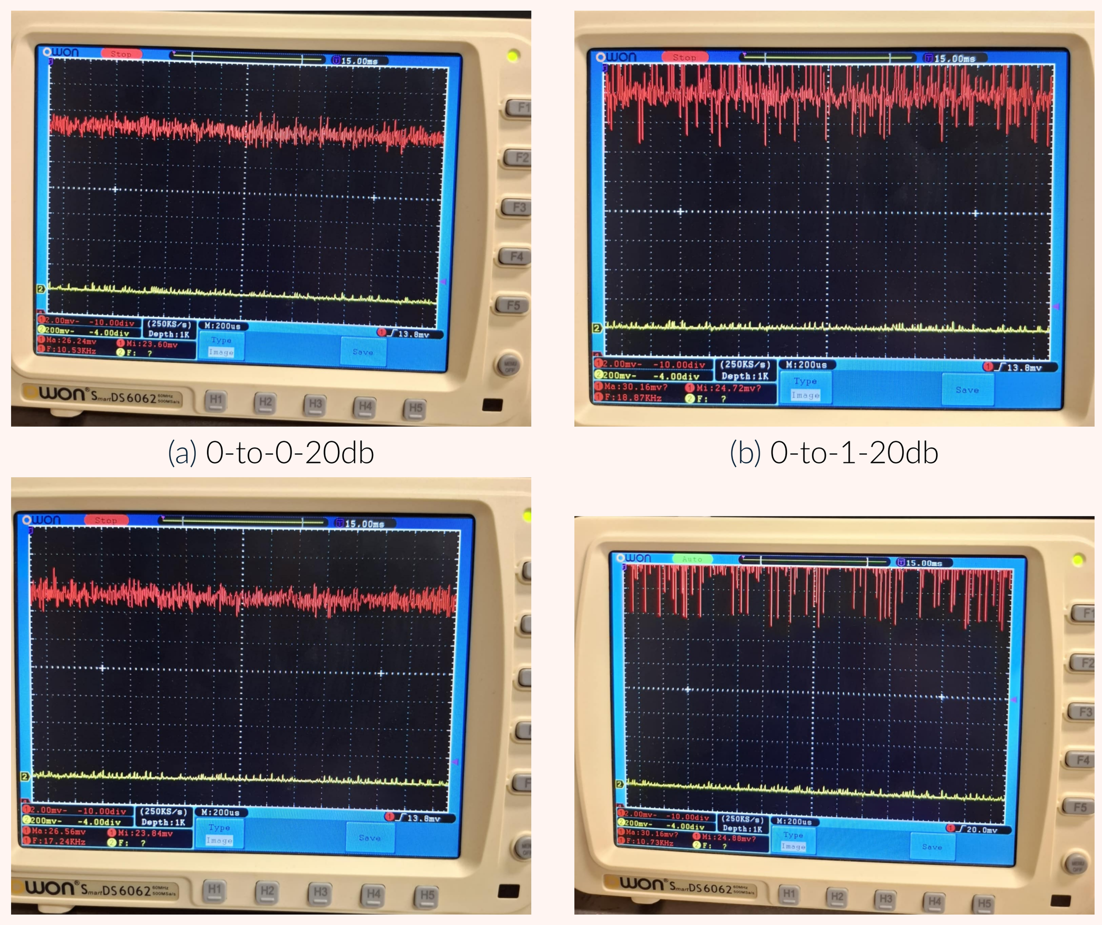


Figure 3. LASER - 523 nm laser with polariser and half-wave plate for intensity and polarisation control. BS - 50:50 beam-splitter. DET1 - irradiance detector, gain XX dB. PH - pinhole with microscope objective. COL - collimating lens f=200 mm. M - mirror. P - linear polarizer. Q - half-wave plate. A - analyzer (linear polarizer). DET2 - irradiance detector, variable gain (0 dB and 20 dB).

Technical implementation: The experimental setup employs a 523 nm diode laser with initial polarization control via a linear polarizer (P) and half-wave plate (Q), enabling precise intensity modulation and polarization rotation. A 50:50 beam splitter (BS) divides the beam, directing 50% to a reference irradiance detector (DET1, 40 dB gain) for power stabilization, while the transmitted portion passes through a spatial filtering stage comprising a microscope objective-integrated pinhole (PH, Ø50 µm) and collimating lens (COL, $f = 200$ mm) to generate a diffraction-limited plane wave. Two steering mirrors (M) guide the collimated beam through an analyzer (A) - a rotatable linear polarizer - before detection by a variable-gain irradiance sensor (DET2, 0-20 dB).

Results

The presented intensity levels after 20dB gain within oscilloscope reflect the encoding of NOT and ID, as the intensity of light show whether the output is 0 (lower intensity), or 1 (higher intensity) after 4 implemented operations.



(a) 0-to-0-20db (b) 0-to-1-20db (c) 1-to-0-20db (d) 1-to-1-20db

Figure 4. Results of implementation ID and NOT gates with optics.

Numerical implementation

The proposed experiment was modeled using the Jones matrix formalism, with QuTiP's built-in unitary transformations enabling accurate simulation of arbitrary polarization rotations. For the Deutsch-Jozsa algorithm implementation, we defined custom quantum operations corresponding to each oracle function and tracked the system's evolution using QuTiP's quantum dynamics solvers, in order to extend the functionality beyond the possibilities of the proposed architecture, such as CNOT and Z-CNOT gates. Figure 3 presents Bloch sphere reflecting polarization results:

$$|\mathrm{H}\rangle = 0.5157 - 0.0000j; |V\rangle = 0.4843 + 0.0000j$$

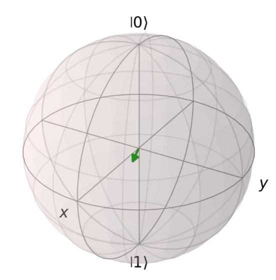


Figure 5. Bloch sphere representing 45 degrees polarization.

Summary

The project detailed specific implementation steps including state preparation through polarizers and half-waveplates, computation via various optical configurations, and measurement using intensity correlation with balanced photodetectors. Experimental results validated the theoretical framework, showing the feasibility of implementing fundamental quantum operations with accessible optical components. This research underscores the potential for democratizing access to quantum technologies by enabling students and hobbyists to build functional, albeit limited, optical computing systems outside specialized laboratories.

References

[1] L. DiCarlo, J. M. Chow, and J. M. et al. Gambetta. Demonstration of two-qubit algorithms with a superconducting quantum processor. *Nature*, 460:240–244, 2009.

[2] Stephan Gulde, Markus Riebe, and Gavin P. T. et al. Lancaster. Implementation of the deutsch-jozsa algorithm on an ion-trap quantum computer. *Nature*, 421:48–50, 2003.

[3] hubertkolcz. low-cost-home-made-qc. `https://github.com/hubertkolcz/low-cost-home-made-qc`, 2025. Accessed: 2025-04-21.

[4] Pieter et al. Kok. Linear optical quantum computing with photonic qubits. *Reviews of Modern Physics*, 79(1):135–174, January 2007.

[5] Michael A. Nielsen and Isaac L. Chuang. *Quantum Computation and Quantum Information*. Cambridge University Press, Cambridge, UK, 10th anniversary edition edition, January 2011. Contains 200 b/w illustrations, 10 tables, 598 exercises.

[6] Looking Glass Universe. What can my homemade quantum computer do?, December 2023. YouTube video, accessed 21 April 2025.

[7] Xiao Xue, Bishnu Patra, and Jeroen P. G. et al. van Dijk. Cmos-based cryogenic control of silicon quantum circuits. *Nature*, 593:205–210, 2021.

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