

Physical realization of a Qubit

Introduction to Quantum Computing

Jothishwaran C.A.

Department of Electronics and Communication Engineering
Indian Institute of Technology Roorkee

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Outline

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The Physical Bit

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One final point

What have we heard so far?

- ▶ The definition of a qubit
- ▶ State space, $\mathbb{C} \times \mathbb{C}$
- ▶ Vector space
- ▶ Superposition
- ▶ Measurement
- ▶ and many others...

What shall we do now?

- We will attempt to give a physical context to the various concepts discussed in the previous lecture.
- To do that we shall discuss a little bit of physics.
- Is a discussion of physics really necessary to learn computation?

Information, Computation and Physics

- ▶ The classical bit may exist in one of two states, these states are labelled as “0” and “1”. This is the most fundamental unit of information.
- ▶ A physical realization of the bit is required for performing computation. In a classical computer, bits are realised in the states of a register.
- ▶ By the same token, a physical realization of a qubit is required for performing quantum computation.

Light waves

- ▶ Light is described by an electromagnetic wave, consisting of electric and magnetic field components.
- ▶ The electric field of a plane polarized light is given by the following function:

$$\vec{E} = \hat{n} E_0 \sin(\omega t - kz)$$

here, the light wave is propagating (moving) along the \hat{z} direction.

- ▶ \hat{n} is a unit vector in the $x - y$ plane.

Light particles

- ▶ At around 1900, it was established that light waves consist of particles called photons.
- ▶ The electromagnetic wave can now be visualised as a stream of a very large number of photons.
- ▶ The electromagnetic wave is now associated with each photon.
- ▶ Therefore, when we refer to a property of the light waves, they also become properties of the photons.

Polarization of light waves

- ▶ The polarization of an electromagnetic wave propagating along the z -axis is in the $x - y$ plane.
- ▶ Any vector in the $x - y$ plane can be represented in terms of its x and y components.

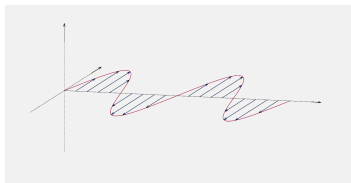


Figure 1: Horizontally Polarized Wave

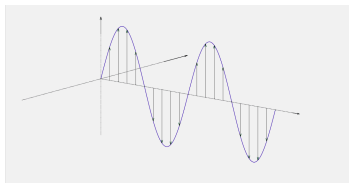


Figure 2: Vertically Polarized Wave

A little bit of Vector Algebra

- ▶ The linearly independent vectors $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ to represent vertical and horizontal polarizations respectively.
- ▶ A polarization vector inclined at an angle θ to the vertical is represented as follows:

$$\cos \theta \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \sin \theta \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix} \quad (1)$$

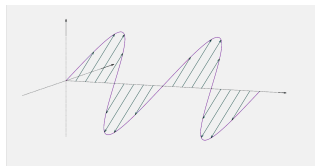


Figure 3: An obliquely polarized wave

Fun with polarizers

- ▶ Polarizers are optical filters that allow light waves of a particular polarization to pass through them.
- ▶ A vertically aligned polarizer will block all horizontally polarized light from passing through and vice versa.
- ▶ But what will happen when an obliquely polarized light wave is incident on a vertically (or horizontally) aligned polarizer?
- ▶ The following video answers the above question through demonstrations:
<https://www.youtube.com/watch?v=6N3bJ7Uxpp0>

A classical result

- ▶ When a light wave with polarization as defined in equation (1) is incident on a vertically aligned polarizer, only a fraction of this wave emerges.
- ▶ The fraction of the intensity that is transmitted is given by $|\cos \theta|^2$. In the case of a horizontally aligned polarizer, the same fraction is $|\sin \theta|^2$.
- ▶ In general, the fraction of the intensity that is transmitted is given by $|\cos \alpha|^2$ where α is the angle between the polarization vector and the direction along which the polarizer is aligned.
- ▶ It should be remembered that the polarization of the transmitted light wave is along the alignment of the polarizer.

The Quantum Perspective

- ▶ One of the earliest conclusions of quantum theory was that light waves exhibited particle like behaviour and these particles were named photons.
- ▶ Light waves discussed thus far may be visualised as a stream of a very large number of photons.
- ▶ The reduction of intensity when a light wave passes through a polarizer implies that only a fraction of the incident photons are transmitted. This fraction as mentioned before is $|\cos \alpha|^2$.
- ▶ It is once again emphasized that the polarization of the photons emerging is along the direction in which the polarizer is aligned.

The Photon as a Qubit

- ▶ Based on the ideas discussed so far, it is possible to state the following about single photons incident on a polarizer.
- ▶ It is in general not possible to state with certainty if an incident photon will be transmitted by a polarizer.
- ▶ A photon polarized along the direction of a polarizer will certainly be transmitted. A photon with a polarization that is orthogonal to a polarizer's alignment will certainly not be transmitted.
- ▶ The probability of a photon being transmitted by a polarizer is once again given by $|\cos \alpha|^2$.
- ▶ The aforementioned facts have all been verified through experiments.

Concluding Remarks

- ▶ The photon is a particle that can exist simultaneously in both (orthogonal) polarization states.
- ▶ The polarization of the photon may be represented as a linear combination of these orthogonal states.
- ▶ The outcome of an experiment to estimate the polarization of a photon can only be interpreted statistically. The experiment also leaves the state of the photon changed.
- ▶ Such photon based qubits are used extensively in Quantum Information and Communication, most notably in Quantum Key Distribution (QKD).

But what of the complex numbers?

- ▶ The photon states described so far have all been real linear combinations of the vertical and the horizontal polarization states.
- ▶ Complex linear combination of these states are used to define polarization states such as circular and elliptical polarization.

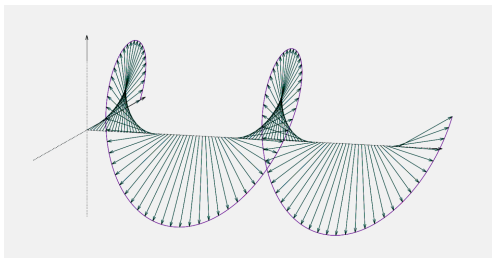


Figure 4: A circularly polarized wave