Generating and teleporting entanglement for quantum networks

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Abstract

Entanglement is a key resource of future quantum technologies. For that reason, it will be essential to distribute it in quantum networks between many and possibly very distant communication parties. To this end, it is essential to generate the photons at a wavelength that is compatible with existing fiber network infrastructure. Such networks typically feature very low loss for photons in the O and C band (1310nm and 1550nm, respectively). To more efficiently use telecom fibers for many users, the available bandwidth is split into frequency windows to enable dense wavelength division multiplexing (DWDM). In the present thesis, we will implement a Sagnac source of entanglement for photons around 1560nm that is sufficiently narrowband for the entangled photons to fit into specific DWDM frequency channels. To generate the entangled photons, we will use a 50 mm long nonlinear crystal inside a Sagnac interferometer. We will first implement and characterize this source in our laboratory and later use it for demonstrating entanglement distribution over in an existing fiber network. The wavelength of the pump laser will be stabilized to an absorption line in a Rubidium gas cell. With our help, an identical source will be set up by partners at the Jozef Stefan Institute. This will allow us to demonstrate the teleportation of entanglement (entanglement swapping) by performing a Bell-state measurement on two entangled photons from those two independent and distant sources. This technique is a prerequisite for quantum repeaters, which will be essential to distribute entanglement over arbitrary long distances in future global quantum networks. In particular, even the low losses of photons in the C band will exponentially grow with the distance. This limits the efficient distribution of entanglement to distances of a few hundred kilometers. The present work will not only feature the first realization of a source of entanglement in Slovenia but also the first realization of teleportation.
Key words: Quantum Entanglement, Quantum Key Distribution, Entanglement Swapping

1 Contents and introduction

Today I will be speaking to you about my a part of my thesis, which is generating and teleporting entanglement for quantum networks. I will begin with a bit of theory, where I will explain the basics of the Spontaneous Parametric

Downconversion (SPDC). Here I will speak a bit about Phase Matching and how we try to optimize it in the lab. I will also speak a bit about how we plan on Distributing Entanglement, so Entanglement Teleportation and Swapping. Then I will speak about the present state that we are dealing with in the lab and how far we have gone so far.

2 Motivation

Pretty much the enterity of my project is in the scope of the SiQUID project. The goal of this project is to create a Slovenian Quantum Network, train young researchers in the field of Quantum Technologies, as well as creating the sources of entanglement needed for entanglement based Quantum Key Distribution. The main goal for me in this regard would be to create a bright source of entanglement using a Sagnac interferometer. The reason we chose a Sagnac in this case is due to its long term vibrational stability, and it's a convenient way to do so as it allows for a compact design. A possible downside to this is that the alignment of this type of interferometer is a bit tedious, as you have to perfectly overlap two beams within the interferometer, and in the crystal.

3 Theory

3.1 Spontaneous Parametric Downconversion

SPDC is a process in which a pump photon of frequency ω_p gets "downconverted" to two or more photons of lower frequency, usually denoted as ω_s and ω_i. These output photons can have the same frequency, and thus this can be a degenerate process, or they can have different frequencies, or being non-degenerate. When we started this entire design process, we wanted to have a degenerate process, as we would be able to separate the two photons based on their polarization. This design utilited a type-II process, meaning that we would be able to separate the two photons on the output of the PBS.

3.2 Phase Matching

What is Phase Matching? Phase matching are the conditions at which some process will happen. In the case of SPDC the Phase Matching conditions are energy conservation ($\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$), and momentum conservation ($k_p = k_s + k_i$). The efficiency of this process is also dictated by how well we satisfy these two conditions - being slightly off from $\Delta k = 0$ could result in large losses of efficiency.

3.3 Crystals

An important step is to choose the correct material for the job. In this case, no ordinary material can be used, as the phase matching condition $k_1 + k_2 = k_3 = \frac{n\omega_3}{c} = \frac{n\omega_1}{c} + \frac{n\omega_2}{c}$ is impossible to satisfy in most cases as $n_1(\omega_1) < n_2(\omega_2) < n_3(\omega_3)$ for $\omega_1 < \omega_2 < \omega_3$.

3.4 Crystal Size

Before periodic poling you could only have a limited size of the nonlinear material along the propagation direction. This means that you would only be able to generate broad signals out of the crystals and at lower intensities, as the intensity and bandwidth of the process goes proportionally to $I \propto \text{sinc}^2\left(\frac{L\Delta k}{2}\right)$. Today we have periodic poling available to us which allows us to create oppositely oriented fields inside the crystal. This allows for higher photon generation rates, longer crystals and more narrow bandwidths.

3.5 Types of processes

There are three different types of phase matching.

- Type-0 is one in which a photon of some linear polarization, say $|H\rangle$ gets downconverted into two photons of lower energies of the same polarization - o $\rightarrow$ o + o. This process used to be physically impossible to produce as the phase matching condition $k_1 + k_2 = k_3 = \frac{n\omega_3}{c} = \frac{n\omega_1}{c} + \frac{n\omega_2}{c}$ is impossible to achieve in most cases.
- Type-I is similar to type-0, except that the produced two photons are orthogonally polarized to the input photon - o $\rightarrow$ e + e
- In type-II instead you get two orthogonal polarizations out from the crystal. e $\rightarrow$ e + o

3.6 Phase Matching Temperature

The first important step is to determine the correct Phase Matching Temperature for our crystal. For different types of poling periods these temperatures will vary, and in general, the lower the poling period the higher the Phase Matching Temperature. The opposite seems to be true for the temperature bandwidth, which would be the acceptable temperature range for the material. Similarly, one should not heat up certain crystals too much as this could destroy the Periodic Poling properties of the material. For Periodically Poled Lithium Niobate (PPLN), the safe operating regime up to around 200 °C.

3.7 Bandwidths

Next would be the bandwidth of the process. In general, you would like it to be as narrow as possible - especially for certain applications as entanglement swapping, and there are other methods to achieve this which I won't go into now. In general, type-II processes are much more narrow than type-0 ones. In the plot I have on the slide, there's about a factor of 120 in bandwidth difference. This is why Type-II was the primary choice for our group. Unfortunately, this also comes at the price of reduced intensity. The difference in intensity was around 25 times lower compared to the type-0 crystal which led to us using it in the end design.

3.8 State of the Art

3.9 Different Designs

4 Entanglement

4.1 Why do we care about entanglement?

Entanglement sources have many applications. Some notable ones are Quantum Computation, Quantum Imaging, and Quantum Sensing.

As we wish to distribute these entangled states over long distances, due to fiber losses it isn't viable to do so over distances larger than a couple hundred kilometers.

Table 1: Relevant fiber loss. *Source: Thorlabs*

λ [nm]	430	532	780	1310	1550	1900
Loss [dB/km]	50	30	12	0.32	0.18	5

Example: Loss in fiber for 1550/1560 nm 200 km of fiber $\rightarrow 10^4$ loss. Start with 1 W, end up with 0.0001 W. Due to this, it would be desirable to have a more robust way to transport photons from A to B. In our case, we generate a pair of $|V\rangle$ polarized photons in each of the branches of the Sagnac interferometer, totalling to 4 photons being created "at the same time". This leads us to the entangled state for type-0 SPDC

$$|\Psi_p\rangle = \frac{1}{\sqrt{2}}(a_H^\dagger(\omega_p) + a_V^\dagger(\omega_p))\,|0\rangle$$

$$|\Psi_{\text{Type-2}}\rangle = \frac{1}{\sqrt{2}}(\sin(\alpha)a_H^\dagger(\omega_s)a_V^\dagger(\omega_i) + \cos(\alpha)a_V^\dagger(\omega_i)a_H^\dagger(\omega_s))\,|0\rangle$$

$$|\Psi_{\text{Type-0}}\rangle = \frac{1}{\sqrt{2}}(\sin(\alpha)a_H^\dagger(\omega_s)a_H^\dagger(\omega_i) + \cos(\alpha)a_V^\dagger(\omega_i)a_V^\dagger(\omega_s))\,|0\rangle$$

as one branch of the phons will be rotated in polarization due to a wave plate being in one of the branches of the Sagnac interferometer. The reason why this is important is that if the conditions for this to happen are satisfied, you can no longer predict the result of the polarization measurement. You can no longer tell which photon is which and from where it came from. But the measurements will be perfectly anti-correlated in polarization.

4.2 Distributing Entanglement

4.2.1 Entanglement Teleportation

4.2.2 Entanglement Swapping

5 Present State

5.1 Parameters

5.2 Building a Sagnac interferometer