CHARACTERIZATION AND GENERATION OF ENTANGLED PHOTONS

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THESIS CERTIFICATE

This is certify the thesis titled '**Characterization and Generation of Entangled photons in Non linear Crystals '**submitted by Banoth Venkateswarlu,to Indian Institute of Technology, Madras for the award of the Degree of Master of Technology, is a bona fide record of research work done by him under our supervision. The contents of these thesis is full or in parts have not been submitted to any other institute or any other University for the award of any Degree or diploma .

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List of Figures

CONTENTS

Abstract

Aim of this project is to characterize and develop methodologies for generating entangled photons in nonlinear crystals. Quantum entanglement is rapid developing research area in modern physics. These thesis deals with two types of Spontaneous Parametric down Conversion(SPDC) process. We use type 1 SPDC, process to generate entangled pair of photon at 405 nm wavelength and characterized it. We also study the effect of nonlinearity introduced in the way of photon streams by using the nonlinear crystal, Beta Barium Borate (BBO). We adopt the standard performance measure of the entangled photons, which is the joint spectral intensity (JSI). We also study another important performance measure, the Hang Ou - Mandel interference which quantifies the fraction of the input light converted into the entangled photons. Such a generated photons used in Quantum computing, Quantum Key Distribution (QKD**)** and Ghost imaging

Key words :

Quantum Entanglement’s process, SPDC,Joint spectral Intensity(JSI), Quantum computing ,Quantum Key Distribution(QKD**) ,**Ghost imaging.

1.Introduction

Motivation

Quantum Entanglement is process of generating group of photons such that the state of one photon can't described without help of another photon. These two photons share information using position, spin, polarization, momentum even though these two objects spatially separated. these states can be achieved when a strong pump beam interact with nonlinear material .such photon pair created using Spontaneous parametric down conversion process **.**

Classical Description of PDC:

it is nevertheless instructional to study a classical form of a nonlinear parametric process like sum-frequency generation. Many of the relations between the classically interacting fields will also hold for the PDC case.

The electromagnetic field interaction with dielectric material induced polarization. Normally these this is linear process but when a high electric field interact with material nonlinear comes. This process alters its frequency.

Spontaneous parametric down con version (SPDC):

This is a optical process when a strong laser pump interact with non linear material

It is a three wave mixing process in which a higher energy pump photon splits into two lower energy daughter photons called as signal and idler . such that it fallows both laws of conversations of movement and energy. Those are described by the following equations .

$E_{pump}=E_{signal}+E_{idler}$.

But E=hν

Similarly for law of conservation momentum

$P_{pump}=P_{signal}+P_{idler}$.

Where p=hk where k is the wave wavector, specifying the direction of traveling of wave .

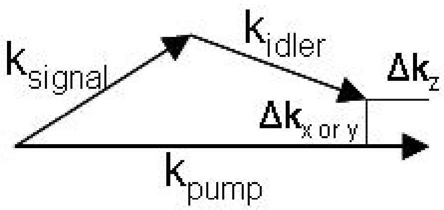

Fig 1.Law conservation of momentum visualization.

Types of SPDC .

Nonlinear crystals are major component to generate in this process. Depending on the polarization between pump and signal and idler the SPDC process is classified as following.

1.Type 1 SPDC process
2.Type 2 SPDC Process

Type 1 SPDC process:

Both signal and idler shares equal energy and they have same wavelength then such SPDC process is known as Type 1 SPDC .In this magnitude and momentum also equally shares . In these both signal and idler are ordinary polarized with respect to input pump.the following

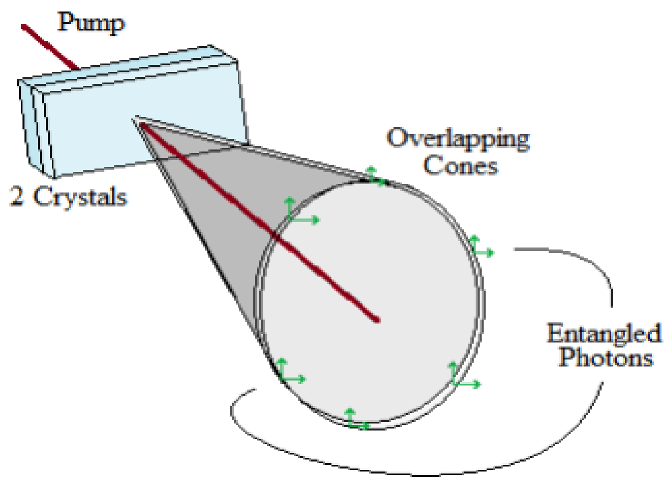

Fig 2.SPDC Type 1 process to generate entangled photons

So these generated state can be written as given below

$|\Psi\rangle = a^*|H\rangle + b^*|V\rangle$…………………(1)

Where a,b complex number such that $|a|^2+|b|^2=1$
.
a,b knows weighted probability factors to happened horizontal and vertical polarization respectively . Entangled photons are produced but required two crystals with uniaxial .the crystal axis of second crystal is rotated 90 $^{\theta}$ about the pump propagation axis from crystal 1 axis. If SPDC occurs in crystal #1 outgoing photon ordinarily polarized with respect to crystal 2 and if SPDC is occurs in crystal #2 outgoing photon ordinarily polarized with respect crystal #1.this is known as correlation. these cones are too close together to determine from which crystal the photons is originates ,so they are in

superposition of polarization states. Entangled photons can find any point on the cones opposite each other.

SPDC TYPE 2 :

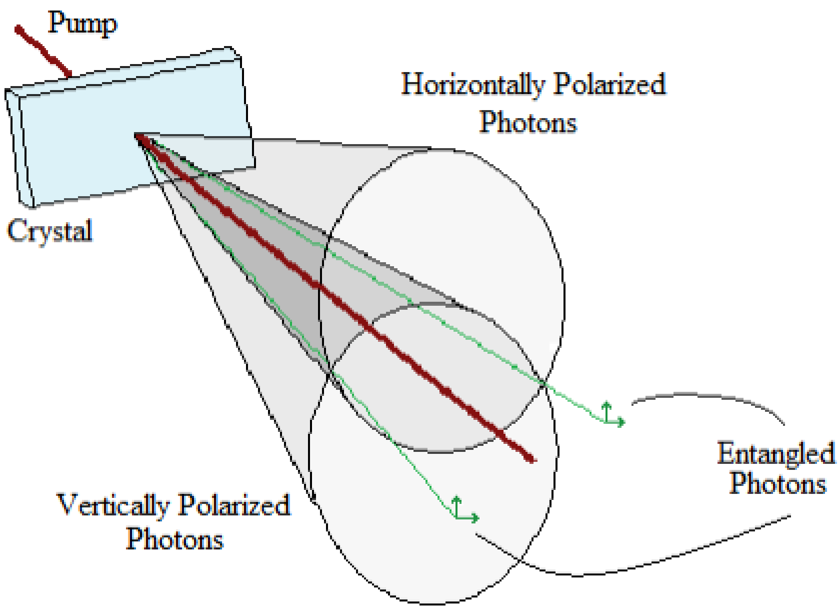

Fig 3.SPDC type 2 Process to generate photon can be found superposition of correlated states where signal and idler cones intersect .entangled photon can be found at these points. on one cone find extradinary rays on other cone ordinary rays. At intersection points it cannot to possible from which cone a photon is generated .these intersection points is combination of both horizontal and vertical polarization states. these photons called as Entangled photons .

The entangled state equation of the these system is given by

$$|\psi_2\rangle = a|H\rangle_A|V\rangle_B + b|V\rangle_A|H\rangle_{B,}|$$

Here H, V are horizontal and vertical states of the corresponding cones A,B respectively.

When a photon from one cone with horizontal polarization exist then another photon exist on another cone with vertical polarization .this is correlation .at intersection point it cannot to possible from which cone it came .at this point it is superposition of polarization states.

Modelling parameters definitions

In order to Determine the Entangled state degree, need to understand the Geometry of the non linear crystal in the Laboratory point of view

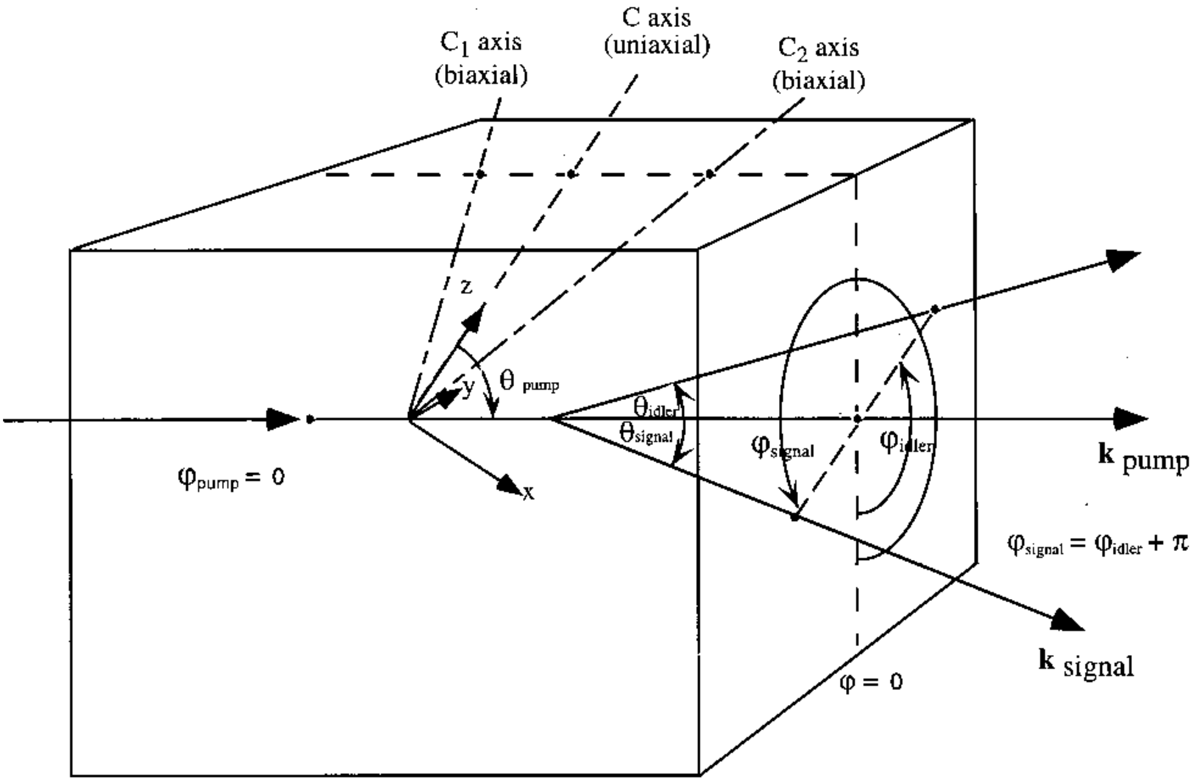

Fig 4 . a typical experimental arrangement for parametric down conversion within a crystal. In this figure, the X -Z plane (φpump=0) plane) is in the plane of the page. For uniaxial crystals, the choice φpump=0 can always be made, but for biaxial crystals, this drawing represents a special case in which the crystal axes C1 and C2 , and the pump beam all lie in the plane of the page. The signal beam is emerging low and toward the viewer, while the idler beam is propagating high and away from the viewer. The azimuthal angles W_{signal} and W_{idler} are measured from the X -Z plane. Dots indicate the points where the rays intersect the surface of the crystal. [5]

To define probability of the Entangled state degree equation follow these sequence

To incorporate the superposition of k vectors into our model, we used the result published by Hong and Mandel [7]. They derive their result by starting with an interaction Hamiltonian for the pump and daughter photons. This result is written for a superposition of plane-wave propagation modes which are then used to find the equations of motion. These are then integrated over the volume of the crystal and over the time photons spend inside it. The result is a detection probability which is dependent on the orientation and wavelengths of the pump, signal, and idler photons, the width of the pump beam, and the properties of the crystal. This result is

$$\Phi = e^{-0.5 W_O^{2(\Delta K_x{}^2 + \Delta K_y{}^2)}} \mathrm{sinc}^{2(\frac{1}{2}(\Delta K_z 2L)} \ldots\ldots\ldots$$

where

$$\Delta k_x = 2\pi\left(\frac{n_s \sin(\theta_s)\cos(\phi_s)}{\lambda_s} + \frac{n_i \sin(\theta_i)\cos(\phi_i)}{\lambda_i}\right),$$

$$\Delta k_y = 2\pi\left(\frac{n_s \sin(\theta_s)\sin(\phi_s)}{\lambda_s} + \frac{n_i \sin(\theta_i)\sin(\phi_i)}{\lambda_i}\right),$$

$$\Delta k_z = 2\pi\left(\frac{n_s \cos(\theta_s)}{\lambda_s} + \frac{n_i \cos(\theta_i)}{\lambda_i} - \frac{n_p}{\lambda_p}\right).$$

The visualization wave vectors ΔK_x, ΔK_y and Δk_z in x,yand z direction can find from the figure 1 ,where L is Length of Crystal,Ɵ is pump angle with respect pump axis and Φ is Azimuthal angle .n is refractive index it is same is in type 1 spdc and different values in type 2 spdc.P,S and I indicates pump, signal and idler .

Analytical Results :

Characterization of Entangled photons .

The major characteristics of generated entangled photons are studying are joint spectral intensity ,phase matching plots and Hang Ou Mandel interference between signal and idler .

To calculate these parameters used online software the http://spdcalc.org/

Lets define design parameters

Crystal name :BBO Crystal reference 1

Spdc process: type 1 spdc process

Theta θ =45θ

Phi ϕ =0 θ
Length of crystal L=2000 µm

Collecting signal from the crystal with following desired values

Theta **θ** = 0θ
Phi ϕ = 0 θ
Waist =100 µm
Plotting option:
Both signal vs. idler in the range of 800 nm to 820 nm range

The following are parameters of incident pump

Wave length λ =405 nm

Beam FWHM =1.0 nm

Waist size of beam =100 µm

The operating Temperature at 25 θ

Joint Spectral Intensity:

The magnitude term of gaussian beam is given by

A(Wp)=M exp(-Wp-2Wo)/(2σ^2)

Where

M is the normalized constant to make unit area of |A(Wp)|^2

Wp=Ws+Wi

Where ws is signal frequency and Wi is the idler **frequency**

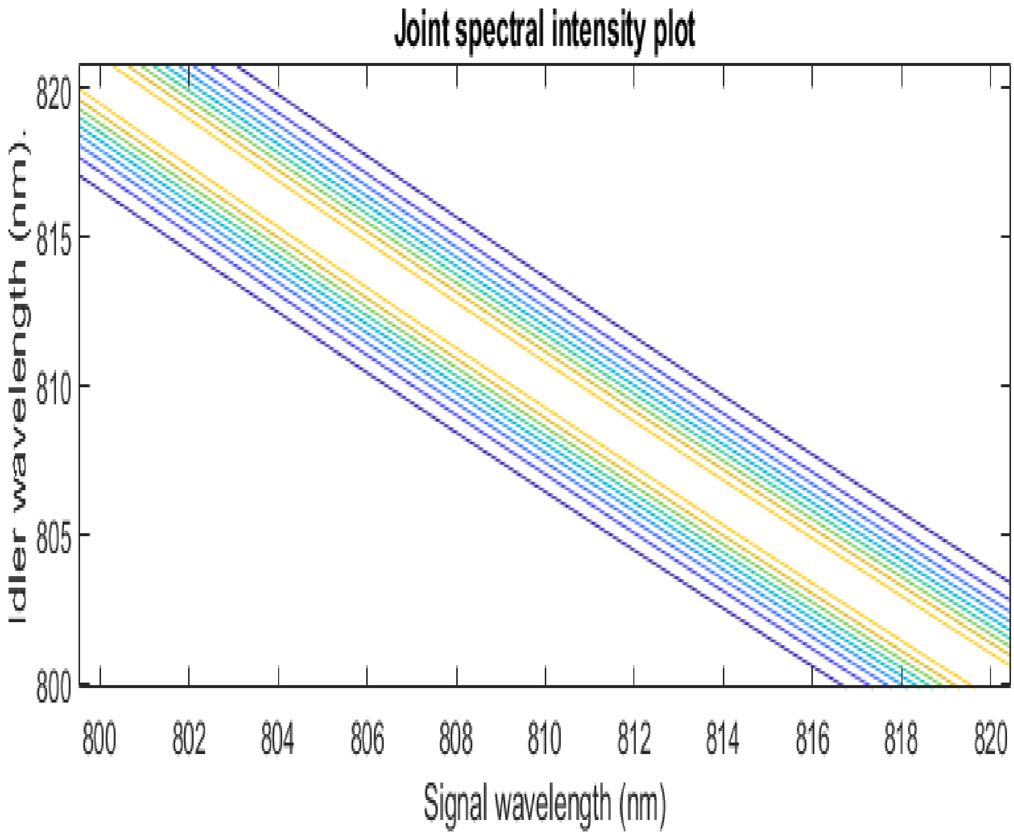

Fig 5.Joint spectral intensity (JSI) of signal and idler frequencies after approximation.

The maximum value of joint spectral intensity distribution is unity .it varies from 0 to 1 as a the wavelength combination changes from 800 nm to 820 nm of both Idler and Signal

Signal is the higher frequency component and Idler is the lower frequency component .

PHASE MATCHING PLOTS :

To match phase between signal and idler the maximum value of 1 for $|\Delta k|=0$. and falls to zero as the phase mismatch increases as $|\Delta k|$ increases.

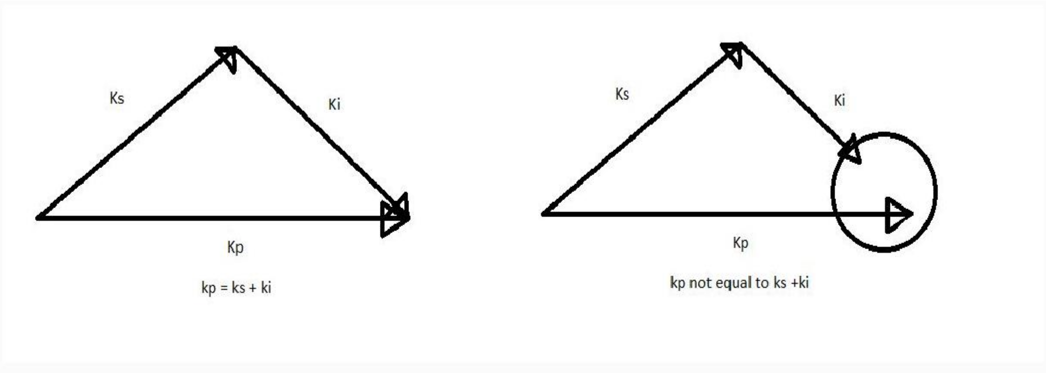

Fig 6. *Wave vectors depicting phase matching*

$$\Delta \mathbf{k} = \mathbf{k}_{\text{pump}} - \mathbf{k}_{\text{signal}} - \mathbf{k}_{\text{idler}} \,,$$

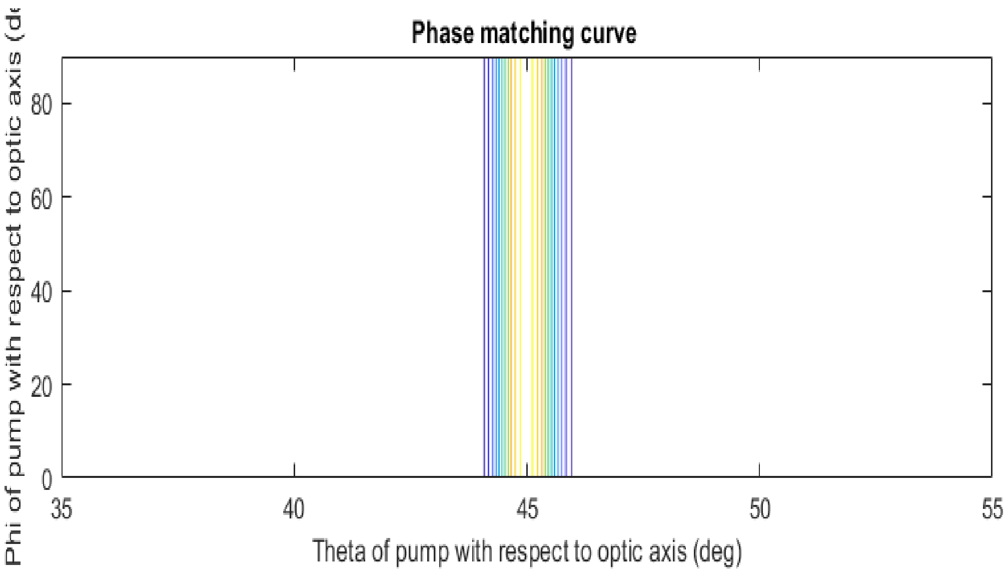

Fig 7 :Theta pump with respect to optical axis. Pump is launched at 45 $^{\theta}$ so the Gaussian beam distributed around at this angle.

The following is phase matching plot in terms of emission angle

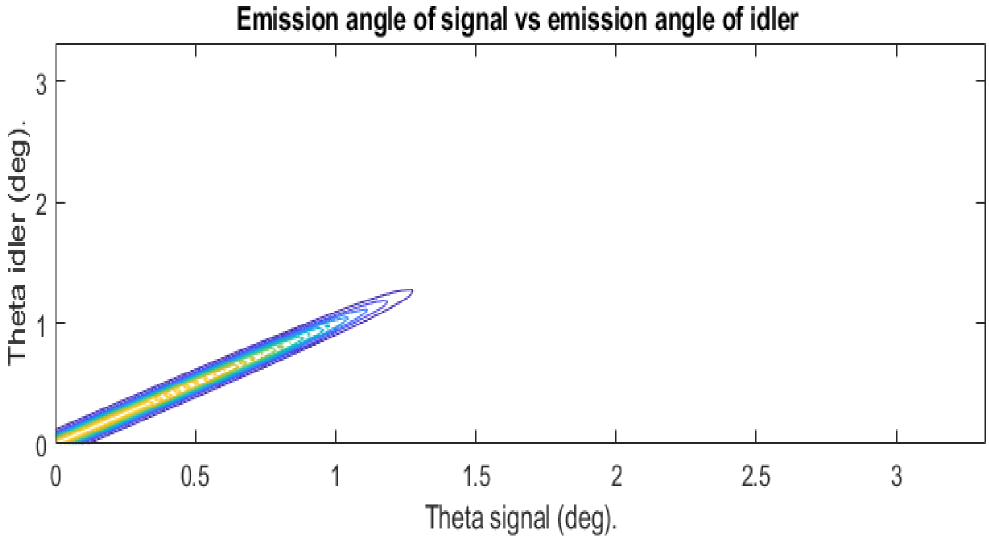

Fig 8. Graph of theta signal versus theta idler (ϕ=0 $^{\theta}$) for a BBO crystal (2000-µm)

Crystal length and 1.0-nm pump width) with λ(pump) =405 nm , ϕ(pump)=0$^{\theta}$,theta pump = 45 $^{\theta}$,λ (signal)=810 nm, the plot is collinear because of ϕ=0$^{\theta}$

Hang –Ou –Mandel Interference between signal and idler :

This phenomenon occurs in Quantum optics when two photon enters into a beam splitter **.** When the photons are identical, they will extinguish each other. If they become more distinguishable, the probability of detection will increase. The coincidence rate of the detectors will drop to zero when the identical input photons overlap perfectly in time. This is called the *Hong–Ou–Mandel dip*, or HOM dip. The coincidence count reaches a minimum, indicated by the dotted line. The minimum drops to zero when the two photons are perfectly identical in all properties. When the two photons are perfectly distinguishable, the dip completely disappears. Common shapes of the HOM dip are Gaussian and Lorentzian

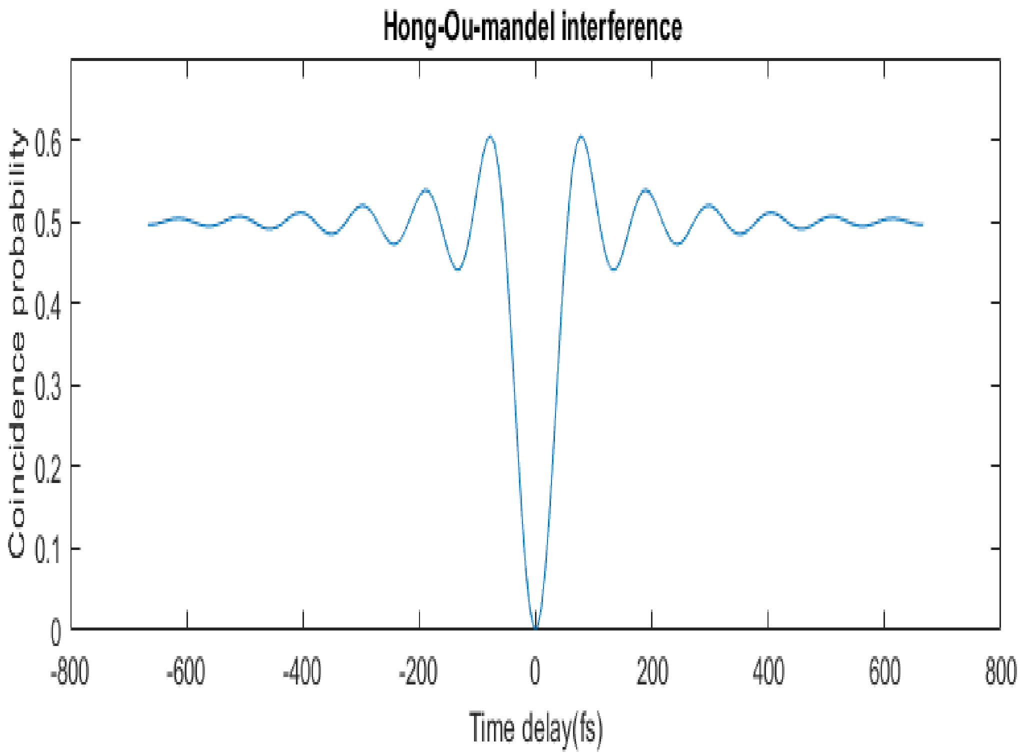

Fig 9. Hang –Ou –Mandel Interference between signal and idler

Ghost imaging Technique

Ghost imaging (GI) use correlated light to produce image of an object by combining outputs of two beams from a single pixel bucket detector-which views the object but not provide spatial resolution and multi-pixel reference detector (e.g. CCD array) does not view the object .

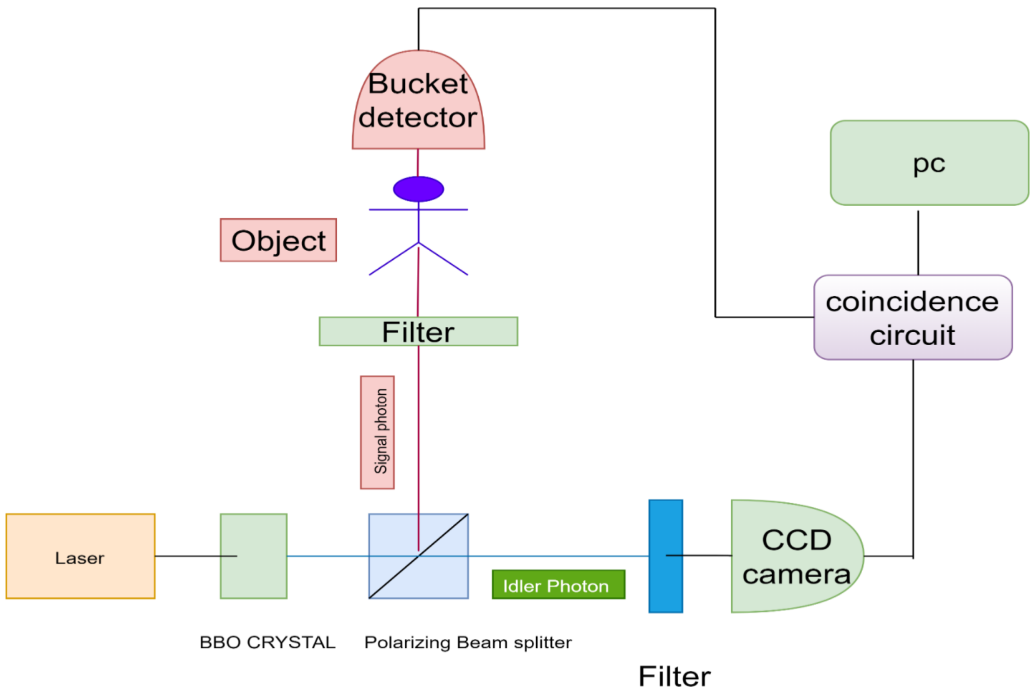

Fig 10. Quantum Ghost imaging

COMPONENTS FOR EXPERIMENTS

1 Laser source: GaN Laser operating at 405 nm pump in infrared region

2**.crystal** :BBO(Beta barium crystal) as non linear materials operating at 25^{0} .the major parameters of crystal are structure ,length

3. Polarizing beam splitter is used to split the light as idler and signal .one arm light incident on CCD camera and other on BUCKET detector

4. Band pass filter: Band pass filters act like a modulator to control the waves produced and are transmitted. It has a bandwidth of 10 nm.

5.Detectors :CCD camera used detector in one arm and APD bare dectector used in other arm .

other common components for the experiments point of view are laser mounts ,optical bread board ,electronics FPGA kit.

Conclusion and future Work

As of now in this work characterized Entangled photons state using basic Nonlinear SPDC process in terms of joint spectral intensity, phase matching plots and Hang -Ou -mandel Interference using online software.by mathematical modelling the probability of Entanglement-BER can be measured for pump photon to generated photon. In these application such as Quantum key distribution, Quantum computing, Ghost imaging These work further can extend by implementing with hardware electronics in the lab.

This research can further be continued from this point to model the electronics to generate the same photon pairs and create a Alice, Eve and Bob QKD channel to find the values of BER and Q-SNR practically.

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