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Source of Photon Pairs Using Spontaneous Parametric Down-Conversion Process

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ABSTRACT: The importance of photon pair generation can never be overemphasized. It has formed the basis of most fundamental quantum optical experiments like Bell-experiments, quantum teleportation and entanglement swapping. However for considerable number of years Quantum Mechanics in general has remained largely theoretical and within the four corners of laboratories. Quantum Key Distribution is one of the first quantum applications to break this barrier. It provides us with unconditionally secured communication by providing us with efficient alternative to classical cryptography. This study forms part of the effort in realizing efficient way of generating photon pairs through the Spontaneous Parametric Down-Conversion process using a nonlinear crystal cut for type-I phase matching. After generating the photon pairs, the paper examined how they can be detected efficiently. We measured the rate of single photon generation (up to 200 kHz) as well as the rate at which they are detected in coincidence (150 coincidences per second). We further investigated a quantum interference effect (the Hong-Ou-Mandel effect) which classical wave theory has failed to describe. This effect has numerous applications in scalable quantum networks and in linear quantum computing. Finally, a remarkable conversion efficiency of 2.2×10^{-9} was obtained. The results in this paper compares favorably with previously reported schemes.

KEYWORDS: photon pair, spontaneous, down-conversion, quantum interference, phase matching, nonlinear, crystal.

1 INTRODUCTION

Since the realization of Quantum Key Distribution (QKD) there has been a surge of interest in the field of Quantum Mechanics. Many organizations and national government agencies have spent and continue to spend so much money in that field. Some of these future technologies are quantum lithography [1], [2] quantum metrology [3], [4] and the most intriguing amongst them all, is the implementation of a Quantum Computer [5]. The need to fabricate devices with smaller and smaller features has been one of the key challenges faced by semiconductor industry. Classical optical lithography is fast approaching its limit imposed on it by the Rayleigh criterion. However quantum lithography could use entangled photon-number states to overcome this limit and therefore could make it possible to fabricate devices smaller than is achievable with classical lithography. Similarly quantum metrology can also provide us with an increase in measurement precision than is possible using its classical counterpart. A quantum computer on the other hand will guarantee an amazingly faster computation and processing power [6], [7]. All these and many more novel technologies have, at their very foundation, one thing in common – single photons.

Single photon generation and detection is therefore imperative if all these technologies are to be realized. It is also necessary that these sources must be highly efficient, indistinguishable (in some cases), and have low loss. Several researches have been carried out in order to make available ways of generating these photons efficiently and in large numbers [8], [9], [10], [11], [12], [13].

We present, in this paper, how to build a source of photon pairs using the process of Spontaneous Parametric Down-Conversion (SPDC) which are very useful as seen in [1], [2], [3], [4], [5], etc. We also present how to detect these photons efficiently. We further measure the rate at which these photons are detected in coincidence. Finally, we investigate a quantum interference effect popularly known is the Hong – Ou – Mandel effect which has found many application in Scalable Quantum Networks (SQN) and Linear Quantum Computing (LQC).

2 Principle

2.1 Photon Generation

There are many ways of generating photon pairs depending on the experiment or the application they will be used for. We have chosen to use the process of SPDC because it has the capability of generating larger number of photons and with appropriate technique it is possible to achieve high conversion efficiency.

2.2 Spontaneous Parametric Down-Conversion (SPDC)

SPDC is a quantum optical process where a nonlinear $\chi^{(2)}$ crystal is used to down convert a pump photon of higher energy into a pair of photons (signal and idler) of lower energies. Fig. 1 depicts the process using bulk crystal configuration.

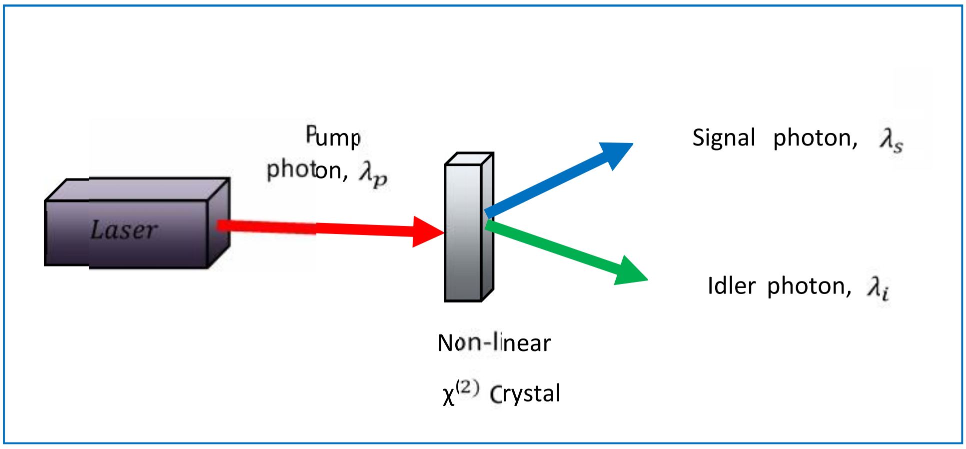

Fig. 1. Spontaneous Parametric Down-Conversion Process

A laser source (which could be continuous or pulsed) is used to pump the nonlinear crystal as in [8], [10], [13]. The pump photon is then split into a pair of photons with total energy and momentum equal to that of the pump photon. If the signal and idler photons both have the same energies, then we have what is called the degenerate case:

$$\varphi_{signal} = \varphi_{idler} = \frac{1}{2}\varphi_{pump} \tag{1}$$

φ_{signal}, φ_{idler} and φ_{pump} are the energies of the signal, idler and pump photons respectively. The photon pairs generated through the SPDC in this paper were of this type. For all other combinations of signal and idler photons we have the non-degenerate case. Whether degenerate or otherwise, both energy and momentum must be conserved.

$$\varphi_{pump} = \varphi_{signal} + \varphi_{idler} \tag{2}$$

$$\vec{k}_p = \vec{k}_s + \vec{k}_i \tag{3}$$

$\vec{k}_p$, $\vec{k}_s$ and $\vec{k}_i$ are the k-vectors of the pump, signal and idler photons respectively.

The following equation together with equation (3) represents the general phase matching condition:

$$\omega_p = \omega_s \pm \omega_i \tag{4}$$

The nonlinear crystal in an SPDC process may be cut for either type-I or type-II birefringent phase matching. In type-I phase matching, the down-converted photons emitted will have the same polarization. For instance the pump photon may be polarized in the extraordinary axis while the *signal* and *idler* photons are both polarized in the ordinary axis. In this case the photon pairs will not be directly entangled and therefore further optics has to be employed to make them entangle if the need arise. One of such methods is to use two-crystal geometry as was published in [13]. In that paper, a beam from Ar^+ laser (polarized at 45^0) was used to pump two BBO crystals each cut for type-I phase matching and arranged such that their optic axis are mutually perpendicular. Fig. 2 shows how the technique was achieved.

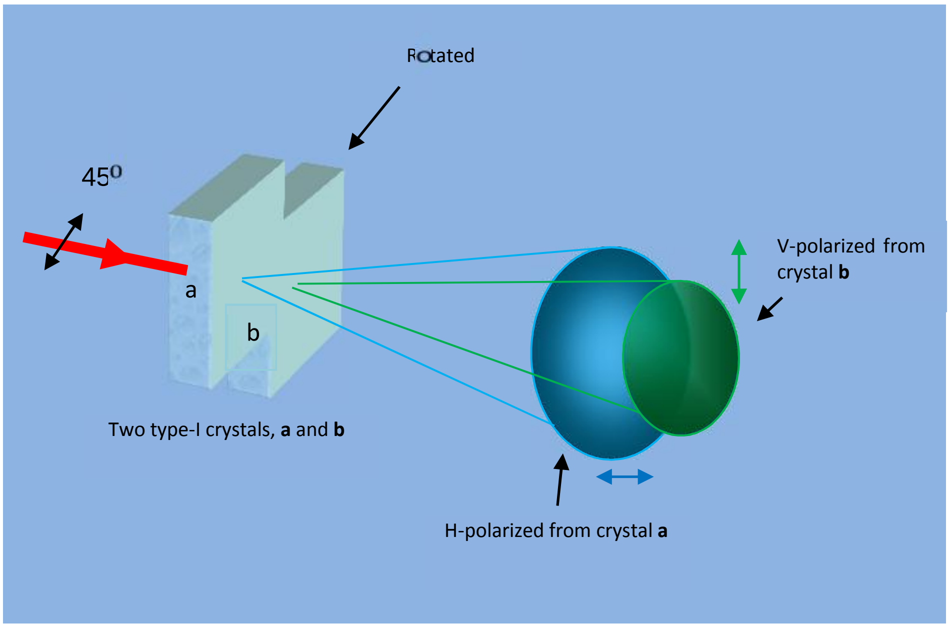

Fig. 2. Polarization-entangled photons from two crystal configuration

The first crystal (a) generates the horizontally-polarized photons while the second rotated crystal (b) produces the vertically-polarized photons. However if the crystal is cut for type-II phase matching as in Fig. 3, then polarization-entangled photons can be directly realized. This makes the type-II SPDC [14], [15] very popular when it comes to experiments requiring the production of polarization-entangled photons. The disadvantage, as seen in [8], is however in the low number of photons usually generated. Fig. 3 shows how type-II SPDC is generally implemented.

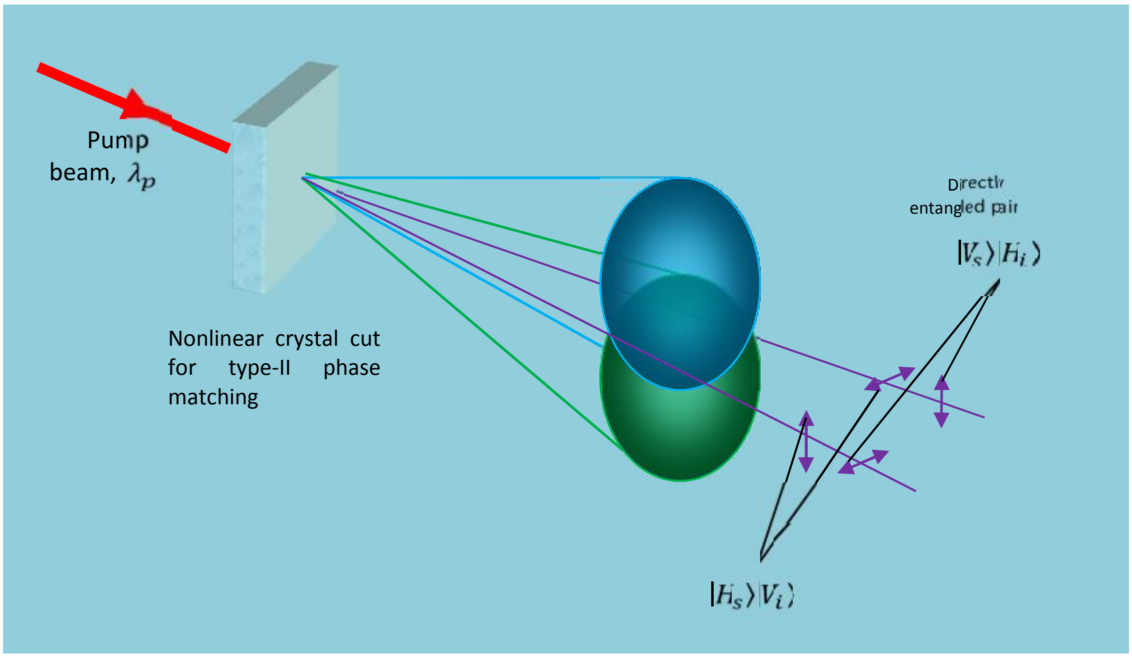

Fig. 3. Type-II SPDC

The crystal in Fig. 3 is pumped by an *e*-polarized pump beam which then creates pairs of photons, one *e*-polarized and the other *o*-polarized. These pairs are collected from the intersection of the two spatially tilted cones as illustrated in Fig. 3. In theory it is possible to collect the down converted photons exactly at the degeneracy wavelength $2\lambda_p$. However, in real experiments a set of the down converted photons are normally collected through an interference filter centred at the degeneracy wavelength. The emission pattern may be represented as in Fig. 4.

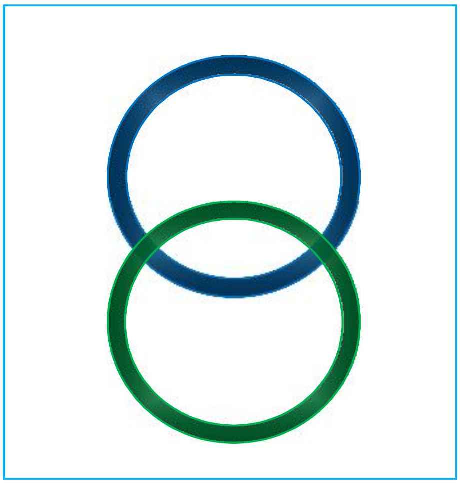

Fig. 4. Set of Collected photons through a band pass filter centred at $2\lambda_p$

2.3 Quantum Interference Effects And Visibility Of A Source

Generally the operation of quantum optical networks at one point may require photons to pass through the two inputs of a beam splitter (BS). This necessarily results in quantum interference of the photons at the BS. Fig. 5 shows a typical BS.

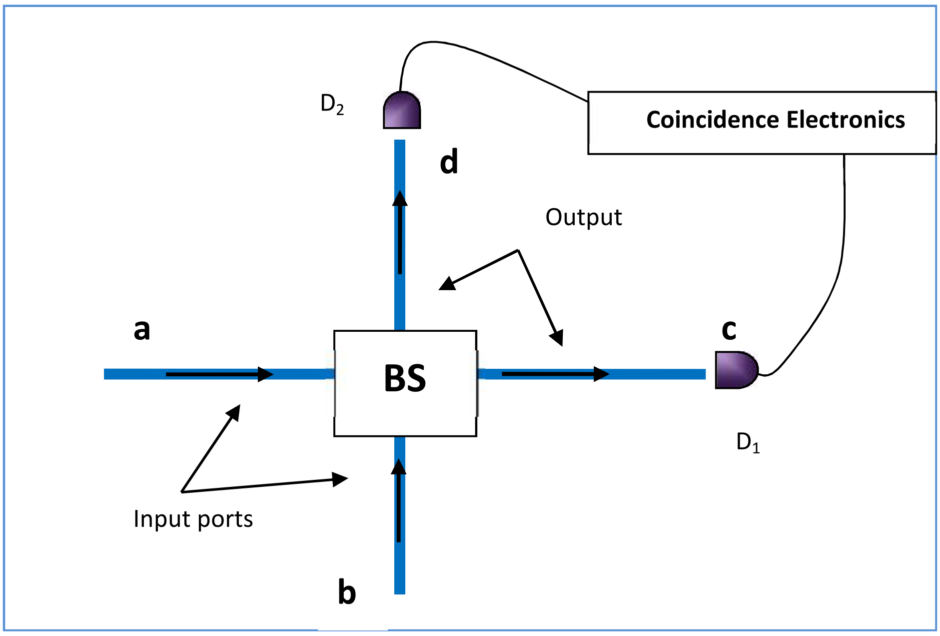

Fig. 5. Schematic diagram of a Beam Splitter

Two indistinguishable photons arriving from the two input ports simultaneously at the BS, lead to both emerging through one of the output port with a certain probability. The photons interfere at the BS and may lead total cancellation of the coincidence rate. In our experiment for instance (See Fig. 7) the signal and idler photons generated were coupled into Polarization Maintaining Fibers (PMF) which was subsequently directed to the input ports of a 50/50 fiber-optic BS. The BS mixes the two beams and thus removes the spatial distinquishability. A motorized translation stage was used to vary the length of the optical path (and thus introduce a relative delay) from the crystal to the BS. The output ports are connected to the two APDs D_1 and D_2 for detection. The outputs of D_1 and D_2 provided the start and the stop signals which were used by the Time to Amplitude Converter (TAC) to record the coincidence histogram. Using a time-window of approximately $1ns$ a Channel Analyser counts the rate of the coincidences.

The expected number of coincidences N_c is mathematically related to the correlation time $g(\tau)$ and the relative optical time delay $\delta\tau$ between the two channels from the crystal to the BS by

$$N_c = K\left[R^2 + T^2 - 2RT\frac{\int_{-\infty}^{\infty} g(\tau)g(\tau-2\delta\tau)d\tau}{\int_{-\infty}^{\infty} g^2(\tau)d\tau}\right] \quad (5)$$

R and T are the reflectivity and the transimittivity of the BS and K is a constant. It can be easily seen from equation 5 that when there is no relative delay between the arrival of the photon pairs (i.e. $\delta\tau = 0$), then N_c will simplify to $N_c = K(R-T)^2$. A 50/50 BS has $R = T = \frac{1}{2}$ and therefore N_c will be equal to zero (the reason why it is sometimes called null coincidence counting rate). Theoretically we should expect no coincidence count at all for a perfect 50/50 BS and perfectly indistinguishable photon pairs; but in practice we see a sharp dip close to $\delta\tau = 0$. The width of the dip depends on the coherence time of the down-converted photons. Fig. 8 shows a graph of the number of coincidence per second plotted against the relative delay in one of the channel. The delay in the other channel was kept constant. The visibility of the source could be determined by the formula

$$V = \frac{N_{cmax} - N_{cmin}}{N_{cmax}} \quad (6)$$

N_{cmax} and N_{cmin} are the maximum and minimum number of coincidences per second respectively. In theory

$$V = \frac{N_{cmax} - N_{cmin}}{N_{cmax}} = \frac{N_{cmax} - 0}{N_{cmax}} = 100\%$$

Another way of obtaining the visibility as seen in [9], [16] is to use the measured coincidence detection probability P which could be approximated as

$$P \cong C\left[1 - Ve^{-\frac{c^2\delta\tau^2}{2}} cos\{(\omega_s - \omega_i)\delta\tau\}\right] \quad (7)$$

V is the visibility of the source, ω_s and ω_i are the frequencies of the signal and idler photons respectively and C is a constant. The frequency response of the band pass filters is assumed here to be Gaussian with rms width of σ. Fitting the measured coincidence count with the above equation, it is possible to find the visibility.

2.4 Other Photon Pair Sources

Several sources [17], [18], [19], [20], [21], [22] have been reported. In [17], [18] four-wave mixing in (single mode micro-structured) fibers was reported where the fiber is pumped with pulsed laser to generate the photon pairs. This approach seemed to have some advantages over the conventional three-wave mixing. In [19], a single semiconductor quantum dots was used. InP and CdSe quantum dots were used in [20], [21]. There are still other sources like those involving diamond NV-defect centers [22], [23], molecules [24] and even atomic systems [25], [26].

Periodically Poled Lithium Niobate (PPLN) has also been used as a substrate in [11]. The PPLN substrate is the type where by the ferroelectric polarization of the material involved is inverted periodically.

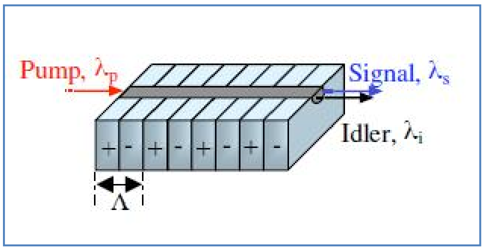

Fig. 6. The PPLN Waveguide [27]

Fig. 6 shows the PPLN Waveguide where λ_p, λ_s and λ_i are respectively the pump, signal and idler wavelengths. Λ also denotes the poling period while the '+' and '-' represent the alternating signs for the second order nonlinear coefficient (i.e. the $\chi^{(2)}$ coefficient).

2.5 Photon Detection

The detection stage is very important since inefficient detection would ultimately leads to poor source of photons in general. There is therefore the need for highly efficient detectors.

When the signal and idler photons exit through the output port of their respective APDs (see Fig. 5) they are directed to a counting machine which counts the rate at which the photons are detected. For the coincidence counting, the machine works as follows:

If one of the pairs (say the signal photon) is detected by the first detector D_1 then the second pair (the idler) is also expected to be detected at the same time by the second detector D_2. Suppose the pairs arrived simultaneously, as expected theoretically, with accuracy better than their coherence time, then they are countered as detected in coincidence. In practice however the arrival of the first pair is used to signal the start of a time window ($1ns$ *in our case*) within which the other pair is expected to arrive. If it does arrive then they are counted as coincidence; otherwise they are not in coincidence.

3 EXPERIMENTAL SETUP

Fig. 7 depicts how the experiment was setup in the laboratory.

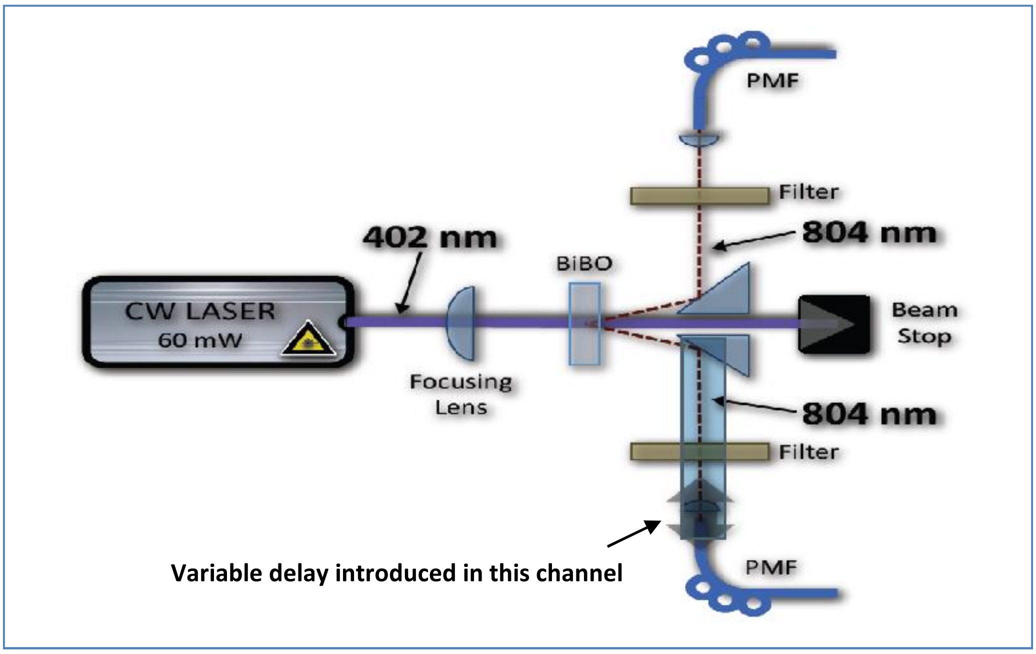

Fig. 7. Schematic diagram of the experimental set up for generating photon pairs using SPDC

A continuous wave (CW) laser emitting at a wavelength of 402nm and operating power of 60mW was used through the focusing lens to pump a BiBO (BiB_3O_6) nonlinear crystal. The crystal is cut to have non-collinear degenerate type-I phase matching when the pump beam is nearly orthogonal to the crystal surface. The down-converted photons (signal and idler) produced through the process of SPDC were directed by the prisms through the band pass filters. The filters, centered at 804 nm wavelengths with bandwidth of 2nm, were used to cut off the background fluorescence. A fiber-optic collimator mounted on a motorized XY translation stage was used to scan the resulting spatial distribution of the down-converted light. The photons were then sent via the Polarization Maintaining Fiber (PMF) to be detected by APDs of 70% efficiency. The detectors are in turn connected to a photon counter which counts the number of photons generated per second as well as the coincidence rate.

4 EXPERIMENTAL RESULTS AND ANALYSIS

4.1 RESULTS

We have recorded **150** coincidences per second with singles reaching up to a remarkable **200,000** counts per second.

4.2 EFFICIENCY OF OUR SOURCE

The conversion efficiency (in terms of photon pairs generated per pump photon) of the source is normally related to the rates of the singles S_1 *and* S_2 and the coincidence rate R_c by the equation reported in [28].

$$\eta = \frac{S_1 S_2}{R_C} \frac{hc}{P_p \lambda_p} \tag{8}$$

P_p *and* λ_p are the pump power and wavelength respectively; h *and* c are the usual Plank's constant and the speed of light in vacuum. Using this formula we obtained a remarkably high efficiency of 2.2×10^{-9} in our experiment. This result is significantly better than what was reported in [8], [10], and [13]. The table below shows the comparison between the efficiency of our source (shown in the table in red) and other published works.

Table 1. Comparison of our source with other published papers

	Type-I BiBO Bulk [our work]	Type-I LBO Bulk [10]	Cascade BBO Bulk [13]	Type-II BBO Bulk [8]
Pump power, P_p (mW)	60	615	150	400
λ – λ ( )	402 - 804	775 - 1550	351 - 702	775 - 1550
APD detection efficiency (%)	Silicon (70%)	InGaAs/InP (10%)	Silicon (65%)	InGaAs/InP (10%)
Single count rates,	200,000	2,800	40,000	20,000
Net coincidence rate, (c/s)	150	29	2000	75
Conversion efficiency, η	2.2 × 10	1.1 × 10	3.0 × 10	3.4 × 10

4.3 Visibility

A novel mechanism was devised to facilitate reaching as high visibility as possible. To do this the positions of the fiber-optic collimators must be chosen such that as many indistinguishable phot [illegible] collected [illegible] s po[illegible] positio[illegible]ssible. Several couplin[illegible] fins of the chosen by the aid of the two translation stages a[illegible] bers wer [illegible] the vis[illegible]ion of the HOM Dip a[illegible]s ability wa After checking me the polarization and spectrum o[illegible] nalyzed. [illegible] they a[illegible]hotons and making su[illegible]he right, osition (i.e. the -convert on the two stages) of the (1 2 [illegible] initial p[illegible] (18.50[illegible]annel) was recorded a[illegible] 30μm, 30. highest visibi[illegible]nel, righ 93.36 ± 1.2% was recor[illegible] μm).The [illegible] positio[illegible]kwise from the initi[illegible]of n (0.0) channel and 10μm anticlockwise from that of the right cha the left [illegible] nel. Fig 8 shows the result of that particular position.

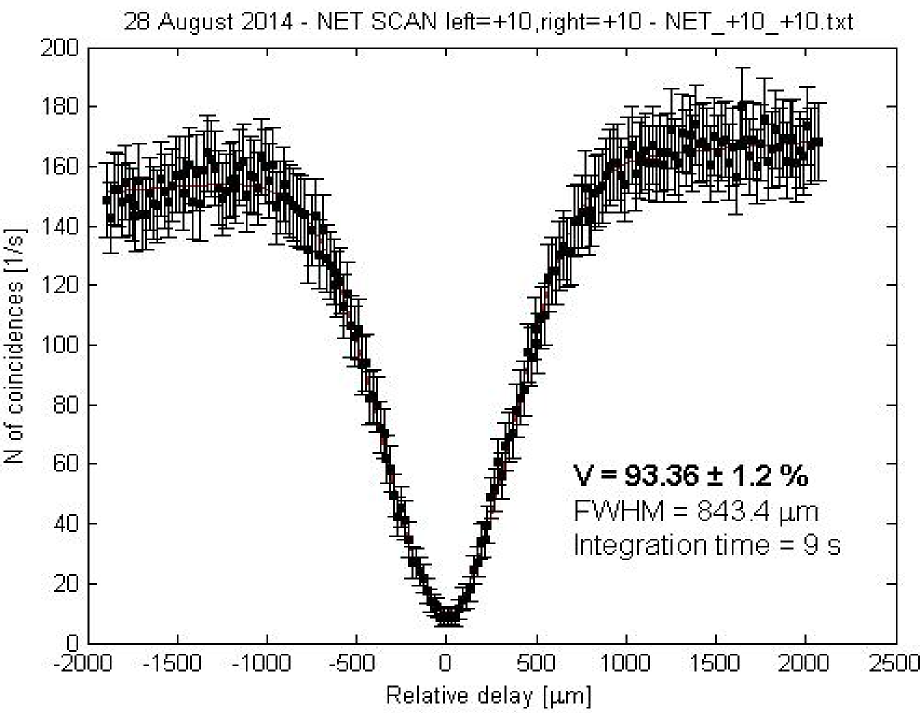

Fig. 8. Two photon quantum interference pattern (HOM Effect)

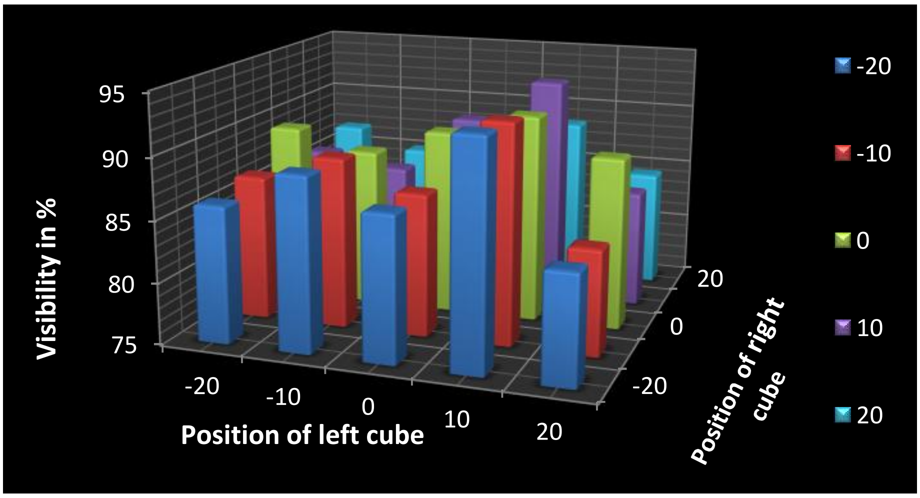

Fig. 9. 2D Position scan of Visibilities

Fig. 9 shows various positions of the cubes relative to an initial position $(0,0)$ with the observed visibilities as the height. This confirms the results in Fig. 8. It can be seen that the highest visibility was achieved at position $(10,10)$.

5 Conclusion

We have presented a source of photon pairs using SPDC process. The source compares favorably with previously reported schemes.

Future work could be for instance to further enhance the visibility of the source by replacing the bulk crystal configuration with Periodically Poled Lithium Niobate (PPLN) waveguide and also using more efficient detectors (super conductors could be strong candidates). Also, the source could be made in the 1550nm telecommunication band so that is compatible with the existing fiber-optic networks.

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