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# Hong-Ou-Mandel Dip Measurements of Two Independent Weak Coherent Pulses for Free Space Quantum Key Distribution Systems

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**Abstract:** Preparation of identical independent photons is the core of many quantum applications such as entanglement swapping and entangling process. In this work, Hong-Ou-Mandel experiment was performed to evaluate the degree of indistinguishability between independent photons generated from two independent weak coherent sources working at 640 nm. The visibility was 46%, close to the theoretical limit of 50%. The implemented setup can be adopted in quantum key distribution experiments carried out with free space as the channel link, as all the devices and components used are operative in the visible range of the electromagnetic spectrum.

**Keywords:** Two-photon interference, indistinguishable photons, MDI-QKD protocol

## 1. Introduction

The request of implementing quantum key distribution (QKD) protocols with commercially available devices is increasing. The goal is to achieve reliable QKD systems with practical devices and components. This will combine the perfect secrecy offered by QKD protocols and the reliability of the available devices [1].

In 2012 a protocol named measurement-device-independent QKD (MDI-QKD) was presented [2], it removes all loopholes that may cause a security problem in detectors. The key idea of MDI-QKD is that both users (Alice and Bob) act as senders. They transmit signals to a third party (Charlie) which might be untrusted and is supposed to perform a Bell state measurement (BSM) on the incoming signals. Alice and Bob can use imperfect single-photon sources such as attenuated lasers and conclude the contributions from signals containing single-photon. Charlie performs BSM setup using linear optical components, which consists of a 50/50 beam splitter (BS), two polarizing beam splitters (PBSs), and four single-photon detectors (SPDs) [2].

Measuring independent photons with BSM setup will project theses photons into one of the four bell states if theses photons were distinguishable, i.e. they differ in one or more of their characteristics. If the independent incoming photons were indistinguishable in all of their degrees of freedom and met at the beam splitter at the same instant of time then an interference between them will occur causing what is called a Hong-Ou-Mandel (HOM) effect. In this effect, the coincidence measurement between the outputs of the BS will be minimum, known as HOM dip. If single-photon sources were used as independent sources, then coincidences is suppressed completely. For the case of using weak coherent pulses (WCP) as independent sources, the coincidence between them is limited to 50% of their non-interfered case [3].

The basic principle to explain interference is the superposition principle. In classical physics, light is composed from electromagnetic waves, the interference effect is explained by making superposition of these waves. In quantum physics, light quanta is adopted instead of electromagnetic waves, the interference is described by superposition of probability amplitudes. Despite the different approaches, both descriptions typically give the same behavior of single-photon interference [4].

In order to study the interference in quantum physics, two-photon interference is used along with single-photon interference. As the two-photon interference is a second-order interference effect, and it is the simplest higher-order interference of light. Two-photon interference is referred to quantum interference as a result of the quantum nature of the photon [5, 6].

Generating and engineering quantum states are important demands for many quantum applications, in addition with investigating HOM effect for these quantum states, different processes could be realized such as entanglement swapping and entangling independent photons generated by independent sources [7, 8]. In such experiments, precise timing synchronization between the photons from independent sources is required in order to provide accurate temporal matching. [9]

Spontaneous parametric down conversion (SPDC) process was used to generate photon-pairs that was first used to observe two-photon interference between single photons when fed to a beam splitter in its input ports resulting in a decrease in the coincidence counts at the outputs yielding a HOM dip. The same experiment is conducted with independent SPDC-based sources as independent sources, producing entanglement swapping process. WCP's can be used to observe two-photon interference in a setup where coincidence measurements are used to post-select two-photon states from mixed states which is known as entangling process [5, 10-14].

In this paper, a HOM experiment is performed in order to check the indistinguishability of the photons generated from two independent laser sources. These laser sources produce WCP that will be fed to HOM setup. Different optical components will be used in the experiment such as optical filters, attenuators, beam splitter, polarization controllers, fiber coupler and single-photon detectors.

## 2. Hong-Ou-Mandel Setup

In 1987, Hong, Ou, and Mandel (HOM) had demonstrated an experiment to investigate the two-photon interference effect [15]. This effect occurs if two identical single photons interfere at 50:50 beam splitter. If they overlap perfectly in time, the two photons will always leave the beam splitter from the same port. High degree of interference is directly associated to how much the two photons are identical in their polarization, intensity and wavelength, and how perfectly they will interfere spatially and temporally at the beam splitter. However, when the photons are completely generated from independent sources, this is never easy to achieve. Observing high visibility with fully independently generated photons might be considered as an indicator of approving photon indistinguishability and time overlap [15-18].

If two photons are incident on 50/50 beam splitter at its two input modes as shown in Figure 1.

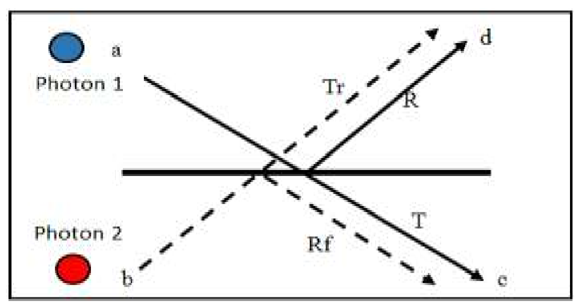


**Figure (1)**: Schematic diagram of ideal beam splitter

They will exit the beam splitter according to the following transformation formula [15,18].

$$|1,1\rangle_{ab} = \hat{a}^\dagger \hat{b}^\dagger |0,0\rangle_{ab} \rightarrow (Tr\hat{c}^\dagger + Rf\hat{d}^\dagger)(Rf\hat{c}^\dagger + Tr\hat{d}^\dagger)|0,0\rangle_{cd} = (Tr^2 + Rf^2)|1,1\rangle_{cd} + \sqrt{2}TrRf\,(|2,0\rangle_{cd} + |0,2\rangle_{cd}) \quad \ldots\ldots\ldots\ldots (1)$$

Where a and b denotes the input modes of the beam splitter, c and d are the output modes, *Tr* is the transmittance of the beam splitter and *Rf* is its reflectance.

According to equation 1 there are four possibilities, first: both photons are transmitted, second: both photons are reflected, third: photon (1) is transmitted and photon (2) is reflected, fourth: photon (1) is reflected and photon (2) is transmitted [9].

In general, HOM setup is constructed as shown in Figure 2.

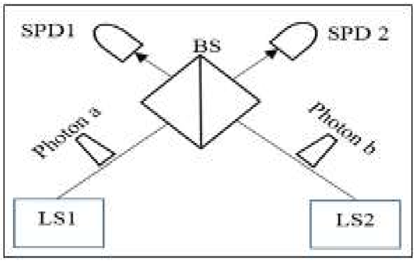


**Figure (2)**: Basic HOM setup. LS: laser source, BS: 50/50 beam splitter, SPD: single-photon detector [9]

If the photons (a and b) were distinguishable, i.e. differ in one or more of their properties such as polarization, frequency or intensity, then all the above mentioned possibilities will be equally likely to occur.

If the photons were indistinguishable, i.e. identical in all of their properties, then the cases when the photons are both transmitted or both reflected, are cancelled out. Only two outcomes will occur by which the two photons will always take the same output path and they will be both directed to the same SPD. Achieving two-photon interference with indistinguishable photons require a temporal and spatial overlap between the two photons at the beam splitter [9].

Visibility is defined generally as

$$V = 1 - \frac{P_1}{P_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $P_1$ represents the coincidence count rate for perfect overlap between photons and $P_2$ represents the coincidence count rate when the photons are sufficiently off with respect to each other. Theoretically when using indistinguishable single photons in a HOM experiment then $V$=1 as $P_1$=0 for perfect interference case.[18]

If two WCPs are used, the relation between the visibility and mean photon number per pulse in addition with the polarization mismatch between the pulses is defined as [18, 19]

$$V = \frac{2M * cos^2\phi}{(M+1)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where $M = \mu_1/\mu_2$, $\mu_1$ *and* $\mu_2$ are the mean photon number of WCP1 and WCP2 respectively. $\phi$ is the angle of polarization difference between WCP1 and WCP2. In order to conclude maximum visibility, $\mu_1$ *and* $\mu_2$ must be equal and $\phi$ must be zero. The maximum achievable visibility when using WCPs is $V$=0.5. To achieve this, the two interfering coherent states should be identical (i.e., polarization, intensity, frequency in addition with spatial and temporal overlap). For such identical states, laser pulses should be prepared properly.

Checking for a stable HOM interference with high visibility (near 0.5) is a mark for reaching high degree of indistinguishability between independent photons [14] . Figure 3 shows the coincidence counts resulted from the original experiment carried out by Hong, Ou and Mandel in 1987 , in this experiment the position of the beam splitter was shifted in order to achieve perfect spatial overlap between the photons. From the figure, the obtained visibility $V$=1 as the photons used in the experiment were originated from SPDC process [15]

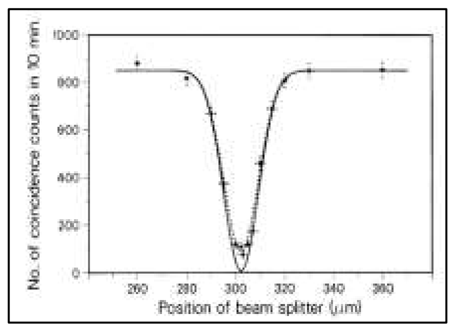


**Figure (3)**: The measured number of coincidences as a function of beam-splitter displacement [15]

## 3. Detector's Timing resolution

Joint measurements of independent photons are the base for different quantum processes like entanglement swapping, teleportation, etc. To guarantee the required indistinguishability, the two photons, which are originated from different sources, have to meet together at a certain and fixed temporal delay. In order to practically achieve simultaneity, it is useful to use sources working in pulsed excitation mode, by which, the synchronization of the emission times can be controlled and the path lengths are equalized, such that the photons will arrive at the beam splitter at the same time [9, 17, 20]. A different approach might be considered, without performing any timing control for simultaneous emission of independent photons. Time-resolved detection of the photons might be adopted. In this approach, photons are detected at random times due to their random emission times. Among all these randomly arriving photons, only those detected at the same time, are considered for post-selection. This will help to distinguish between photons depending on their arriving times. In such process, the timing resolution of the detectors becomes crucial [21-23] .

For better understanding, consider a detector with timing resolution ($T_d$), a photon with coherence time ($\tau_c$). Two cases might be discussed as shown in Figure 4.

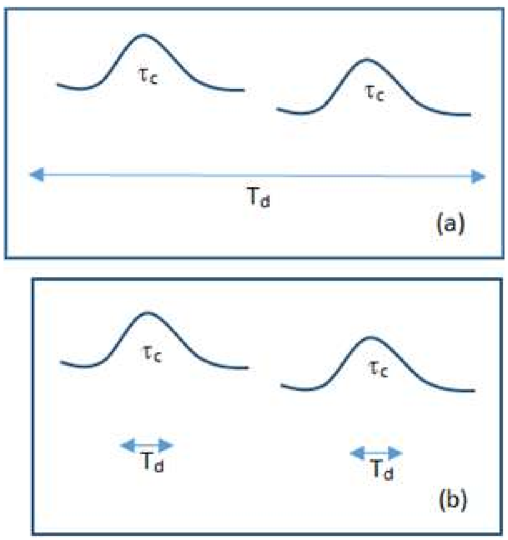


**Figure (4):** Two photons arrive with a delay of more than their coherence time τ. (a) A detector with a temporal resolution of $T_d > \tau_c$ cannot distinguish them. (b) A detector with a temporal resolution of $T_d < \tau_c$ can distinguish them. [21]

If two photons arrive with a delay **t** between them such that $\tau_c < t < T_d$ , as shown in figure 4(a), they will be detected at the same time as the detector cannot distinguish between them although they are distinguishable in principle.

But if $\tau_c > T_d$ as shown in Figure 4 (b), the two photons will be detected at different times as the detector will distinguish between them. Based on such possibility, joint measurement experiments depend on the relation between the coherence time of the photons and the timing resolution of the detectors used [21-23].

## 4. Experiment and Results

In order to measure the frequency difference between laser sources used. A simple setup is implemented which consists from laser sources, beam splitter and a photodiode, as shown in Figure 5(a). The detected signal represents the beating signal between the two interfered signals which is the frequency difference of the two sources. The fast Fourier transform (FFT) signal is displayed on an oscilloscope as shown in Figure 5(b). The beating frequency is found to be within the limit of 20 MHz. This frequency difference is much smaller than the bandwidth of the optical pulses used in the experiment, as the pulse width is 5 ns and the corresponding bandwidth is 200 MHz. [2,18].

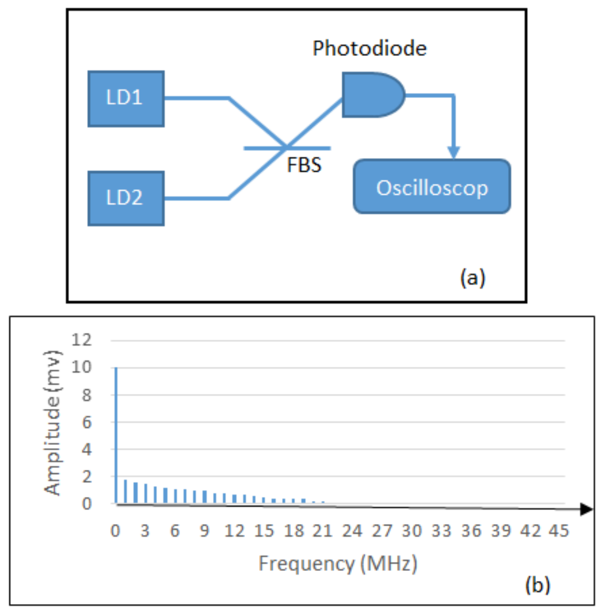


**Figure (5):** Beating Signal Measurement. (a): experimental setup, (b): FFT of the beating signal

In order to experimentally check the in distinguishability between the optical pulses of our laser sources, the following setup was built as shown in Figure 6.

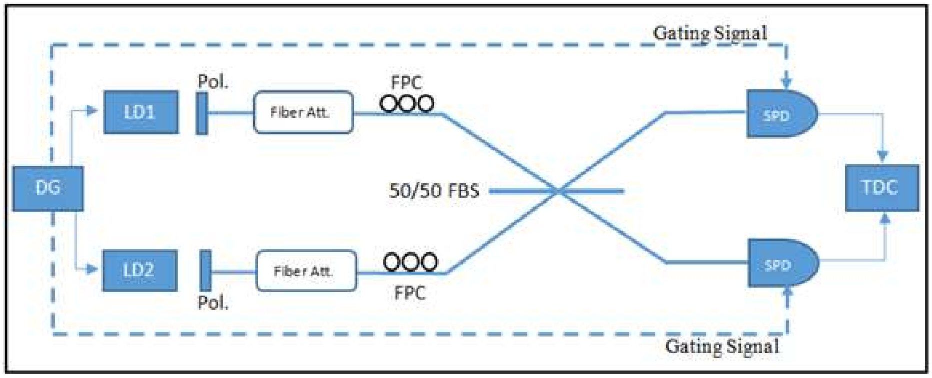


**Figure (6):** Experimental setup. DG: delay generator, LD: laser diode, Pol.: polarizer, Att.: attenuator, FPC: fiber polarization controller, FBS: fiber beam splitter, SPD: single-photon detector, TDC: time-to-digital convertor.

For the experiment, two laser diodes (NPL64B from Thorlabs) were used, the wavelength is 640 nm, the output pulse width of the lasers can be adjusted from 5 ns to 39 ns. Different fiber-based components were used such as fiber polarization controller (FPC), fiber coupler and variable optical attenuator. These components (from Thorlabs) were selected such that their operation is in the (600-800) nm range.

The detectors are single-photon detectors (PDM series from Micro Photon Devices) with detection efficiency of 40% at 640 nm. The timing resolution is about 250 ps, and they can be operated in two modes free-running and gated mode. Time-to-Digital converter (TDC) device was used (id800 from id-quantique), it contains 8 channels as inputs, with 81 ps bin width.

The procedure of the experiment is as follows: both LDs are run and controlled using the delay generator, their output pulses must have the same polarization states and the same mean photon number. These identical pulses are to interfere with each other at the fiber beam splitter (FBS) which is used to guarantee the spatial overlap between the pulses. The outputs of the FBS are connected to the detectors. A coincidence counts between the outputs of the detectors are to be monitored and registered by TDC. The pulse widths of the laser diodes are set to their minimum value (5ns) and the repetition rate is set at 10 MHz . A delay in the starting time of one of the lasers with respect to the other is carried out by the delay generator. The polarization of the lasers is set to horizontal polarization using optical polarizers. Precise alignment of each FPC is produced by rotating its paddles until observing maximum count rates at the detectors output. The mean photon number,$\mu$, of the LDs is set to 0.3 photon/pulse during the experiment, this was done by adjusting both VOAs. The single-photon detectors were operated in gated mode. The width of the gating signal was set to 70 ns. The output of both SPDs are connected to TDC to monitor and record the coincidence counts between the lasers for different time delay points in order to observe the HOM effect. The delay between the independent LD pulses is changed in steps of 100 ps so that the pulses are first separated and then they gradually overlapped with each other till they overlap completely, the process continues till they are separated again, meanwhile the coincidence counts between the detectors are registered at each step. The width coincidence window was 20 ns.

The complete coincidence counts versus time delay are plotted in Figure 7.

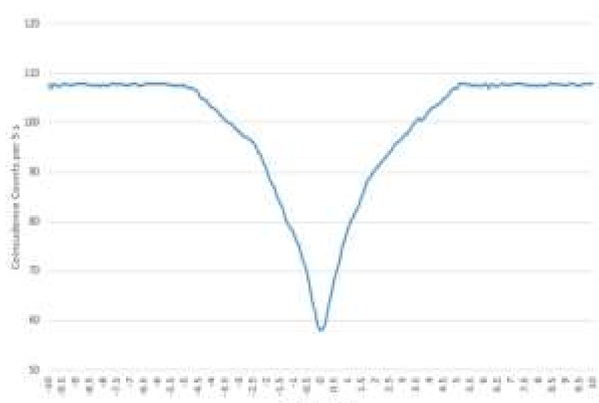

**Figure (7):** Coincidence counts versus delay time

From Figure 7, the visibility is calculated (equation 2) to be $V$=46%, close to the theoretical limit of 50%. Different factors might cause the difference in the experimental and the theoretical values such as polarization mismatch, intensity mismatch or spectrum difference.

## 5. Conclusions

From this work, a Hong-Ou-Mandel experiment was implemented using the experimental setup shown in Figure 6. The results showed that this setup can be used to perform joint measurement to check the indistinguishability between independent photons from two independent weak coherent sources. Which means that these sources are suitable to be used with quantum communication protocols such as MDI-QKD protocol. Based on the laser sources and optical components used in the experiment, since they are all operate in the visible range, free space channel link can be adopted in the implementation of the experiment and taking the advantage of using available laser sources in the visible range. Another advantage is the usage of high detection efficiency offered by the available single-photon detectors, which will help to improve the efficiency of the experiment.

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## قياسات قعر هونك-او-ماندل لنبضتين متشاكهتين ضعيفتين مستقلتين لأنظمة توزيع المفتاح الكمي في الفضاء الحر

**احمد اسماعيل خليل، شيلان خسرو توفيق**

**معهد الليزر للدراسات العليا, جامعة بغداد، بغداد - العراق**

**الخلاصة:** عملية تحضير فوتونات متماثلة هي محور للتطبيقات الكمية كتبادل الفوتونات المتشابكة و عملية التشابك.تم تقديم تجربة (هونك-او-ماندل) لحساب درجة عدم التمايز بين فوتونات تتكون من مصدرين منفصلين بطاقة ضعيفة و متشاكهين تعمل بطول موجي 640 نانومتر. مقدار الرؤية كان بقيمة (46% ) و قريبة من الحد النظري بقيمة (50%). بالأمكان استخدام هذه التجربة في تجارب توزيع المفتاح الكمي و التي تنفذ في الفضاء و اعتباره كقناة اتصال ، باعتبار ان كل الأجهزة و المواد و التي تم استخدامها في منطقة الطيف المرئي من المجال الكهرومغناطيسي.