HONG-OU-MANDEL DIP MEASUREMENT OF TWO INDEPENDENT WEAK COHERENT PULSES

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ABSTRACT

Due to the simplicity of Hong-Ou-Mandel (HOM) interferometer setup, it becomes very important in various quantum-based applications, especially when the photon indistinguishability is required such as measurement device independent quantum key distribution (MDI-QKD). In the present work, the HOM experiment setup is designed to study the quantum interference between two indistinguishable photons (frequency, time of arrival and polarization should be same for both photons) coming from two independent laser sources (attenuated laser). The aim is to achieve high visibility as it indicates the photon indistinguishability from two independent sources. Theoretically, the visibility is 50% for indistinguishable photons from attenuated laser sources but in the experiment, due to various devices imperfections and other factors it is less than 50%. The HOM visibility achieved from our setup is 40% tested for a distance of 20 km over standard single mode fiber (SMF). The main point to be noticed in this work is that, this experiment is performed using single photon avalanche diode.

Keywords - Two-photon interference, indistinguishability, visibility, temporal overlap, polarization overlap, coincidence counts.

1. INTRODUCTION

Over the last three decades, efforts are being made to understand the basic principles of quantum mechanics such as superposition theoretically and experimentally, to explore the possibility of the development of quantum technologies such as quantum communication [1], quantum computing [2], quantum metrology [3] and many more. Several experiments were performed to show the superposition principle in quantum mechanics. The two-photon interference is basic to understand the superposition [4], [5]. The two-photon interference (also known as Hong-Ou-Mandel (HOM) effect) experiment [6] reveals indistinguishable photons which are a basic building block in various quantum-based experiments. Also, HOM effect is not restricted to photonic systems but also this effect can be observed in fermionic systems, phonons etc. As HOM effect has no classical counterpart, so it outperforms classical computation [7]. The HOM effect can be explained as, when two indistinguishable photons arrive and interfere on a 50:50 beam splitter (BS), they will always exit the BS together in one of the output ports. The probability of coming the photons from different ports is zero. As depicted in Fig. 1, if the input (output) ports of BS are a, b (c, d) then the arrival of two indistinguishable photons at the BS leads to four different possibilities such as (i) both photons exit from port c (ii) both photons exit from port d (iii) one (other) photon exit from port c (d) and (iv) one (other) photon exit from port d (c). In case of indistinguishable photons, only (i) and (ii) happens. Mathematically, it can be described as

$$|1,1\rangle_{a,b} \xrightarrow{BS} \frac{1}{\sqrt{2}}\left(|2,0\rangle_{c,d} - |0,2\rangle_{c,d}\right) \tag{1}$$

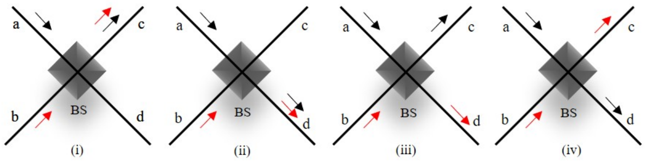

Figure 1 – The four possible combinations when two indistinguishable photons arrive at 50:50 BS.

In 1987, HOM effect was experimentally verified by Chung Ki Hong, Zhe Yu Ou and Leonard Mandel [6]. HOM effect finds applications in various domains of quantum technology such as quantum teleportation [8], clock synchronization [9], quantum state engineering, quantum key distribution (QKD), etc. As HOM can be used for Bell state measurement (BSM), it plays a significant role in MDI QKD [10], a quantum communication protocol which removes all detector side channel attacks. So, HOM plays a vital role in BSM related experiments. In this work, we have performed HOM experiment of weak coherent light. In our experimental setup we have used photons from two independent laser sources (attenuated) and tried to achieve their indistinguishability maintaining their polarization, frequency and time of arrival at the BS identical. Photons from attenuated laser sources are fed to HOM setup to achieve better visibility and lower coincidence events. Literature enlightens that for indistinguishable weak coherent light, the HOM visibility is 0.5 (or 50%) theoretically. In the experiment, due to imperfection of devices and other factors, it goes below 0.5 (or < 50%). The rest of the paper is organized as follows. In Section 2, HOM experimental setup is explained in detail. In Section 3, we have described our results and observations. Finally, we conclude in Section 4, including some future scopes.

2. THE HONG-OU-MANDEL EXPERIMENT

Here, the aim is to perform HOM experiment between the photons generated from two parties named as Alice and Bob. Alice and Bob use attenuated independent laser sources for this purpose. This is done using an intensity modulator (IM) and variable optical attenuator (VOA). They send their photons to a third party, Charlie for Bell state measurement, as shown in Fig. 2. To obtain indistinguishability, we have maintained three feedback mechanisms between Alice, Bob and Charlie namely frequency overlap, polarization overlap and temporal overlap which is explained in detail.

2.1 Frequency overlap

In our experimental setup, Alice and Bob use 10% of their laser light to achieve frequency overlap, the rest 90% they use for the HOM experiment implementation. The incoming unmodulated continuous laser light (10%) from Alice and Bob is fed to 2 x 1 optical coupler at Charlie node. The output of the coupler is then fed to optical to electrical (O2E) converter which is processed by the Charlie's field programmable gate array (FPGA). Whenever the frequency difference f is greater than the threshold frequency of 10 MHz, it is communicated to Alice via the feedback channel and its laser wavelength is tuned as shown in Fig. 3. In this way, frequency overlap is achieved which is a very important step to make photons indistinguishable.

Table 1 – Various parameters used in the experiment

S. No.	Parameter	Alice Value	Bob Value
1	Transmitted Power	-78.8dBm	-78.3dBm
2	Central Wavelength	1550.12 nm	1550.12 nm
3	Pulse Repitition Rate	32 ns	32 ns
4	Fibre Length	20 km	20 km
5	Fibre Loss	5 dB	5 dB
6	PC Insertion Loss	0.8 dB	0.8 dB
7	PBS Insertion Loss	0.8 dB	0.8 dB
8	Power at the input of 2 x 2 PMBS	-85.4 dBm	-84.9 dBm
9	Mean Photon number at the input of 2 x 2 PMBS	0.72	0.8

2.2 Polarization overlap

To make both photons indistinguishable at Charlie's node, one of the conditions is that their polarization should be same. In order to achieve the same, we make use of two polarizing beam splitters (PBSs) which are inserted on the quantum channels coming from Alice and Bob. Further, a polarization controller (PC) is used to control the required polarization state. One arm of the both PBSs (Alice's as well as Bob's) is connected to a single photon avalanche diode (SPAD3 and SPAD4). The minimum clicks on both the SPADs indicate that the photons on the other arm of PBS are nearly identical in polarization degree of freedom. This arm is in turn connected to a 2 x 2 polarization maintaining beam splitter (PMBS) which is then connected to two SPADs (SPAD1 and SPAD2) of which one is free running SPAD and the other is a gated SPAD as shown in Fig. 4.

2.3 Temporal overlap

The next challenge to make photons indistinguishable is their temporal overlap. The photons from both the sources must meet at the same time at Charlie's node. Charlie measures the time of arrival of photons from Alice and Bob at a fixed point. It is done in two steps:

- Delay calculation of photon from Alice and Bob to PMBS.
- Offset in SPADs after PMBS.

The delay in the arrival of the photon is calculated by Charlie's FPGA, and the corresponding shift is communicated to any one of the two parties. In our work, the delay is adjusted at Bob node. The time shift is provided through FPGA in the resolution of 125 ps. The concept of photon indistinguishability is quantified in terms of visibility. The visibility measures the probability that both photons will emerge together through a single output port of the BS. Mathematically, the visibility is defined as

$$V = \frac{C_{max} - C_{min}}{C_{max}} \tag{2}$$

where Cmax and Cmin are the maximum and minimum coincidence counts at the output of the BS respectively.

3. RESULTS AND DISCUSSION

When the temporal, spectral and polarization overlap of the photons on the Charlie's BS is perfect, the two photons will exit the BS together in the same output port. There is zero probability that both of the photons will exit separately. In our experiment, we have used two lasers of 1550.12 nm wavelength, having a pulse width of 880 ps with a repetition rate of 32 ns (shown in Fig. 5 and Fig. 6 respectively). The power of the pulse generated by laser sources present in Alice and Bob is 78.8 dBm and 78.3 dBm respectively, the other parameters are given in the Table I. Fig. 7 shows the clicks on the two SPADs (SPAD1 and SPAD2) out of which one (SPAD1, blue colored line) is in the free running configuration which has high click count and the other one (SPAD2, red colored line) is in gated mode which has low click count. Free running detector triggers (gates) the second detector. Fig. 8 shows the coincidence counts with respect to time difference between two pulses, as the time between the two pulses reduces, coincidence count reduces. The

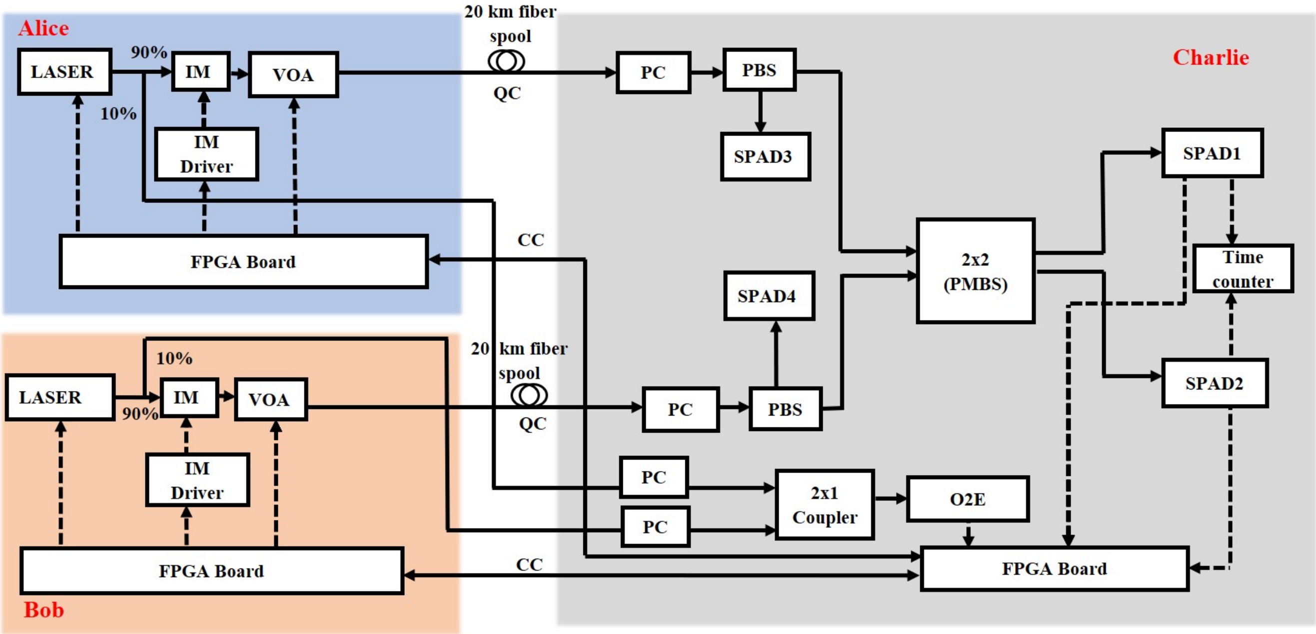

Figure 2 – Schematic of HOM experiment. Here, PC: polarization controller, PBS: polarizaing beam splitter, PMBS: polarization maintaining beam splitter, SPAD: single photon avalanche photodiode, VOA: variable optical attenuator, IM: intensity modulator, QC: quantum channel, CC: classical channel. Solid lines represent optical connections and dashed lines are for electrical connections.

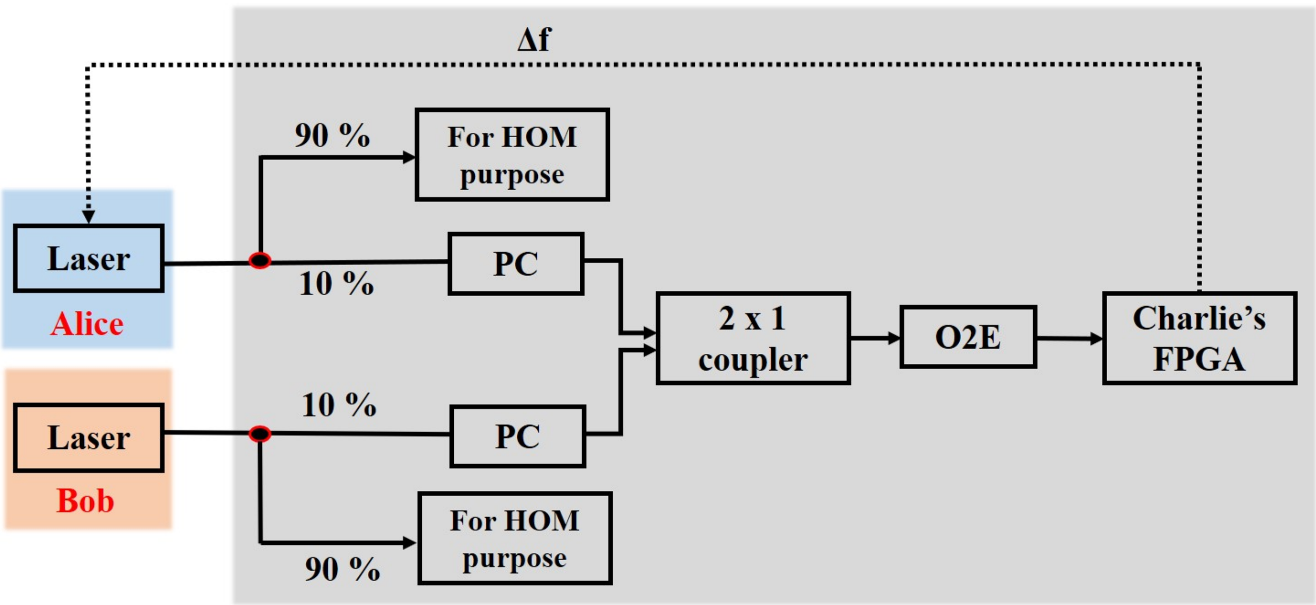

Figure 3 – Block representation to achieve frequency overlap between photons from independent sources.

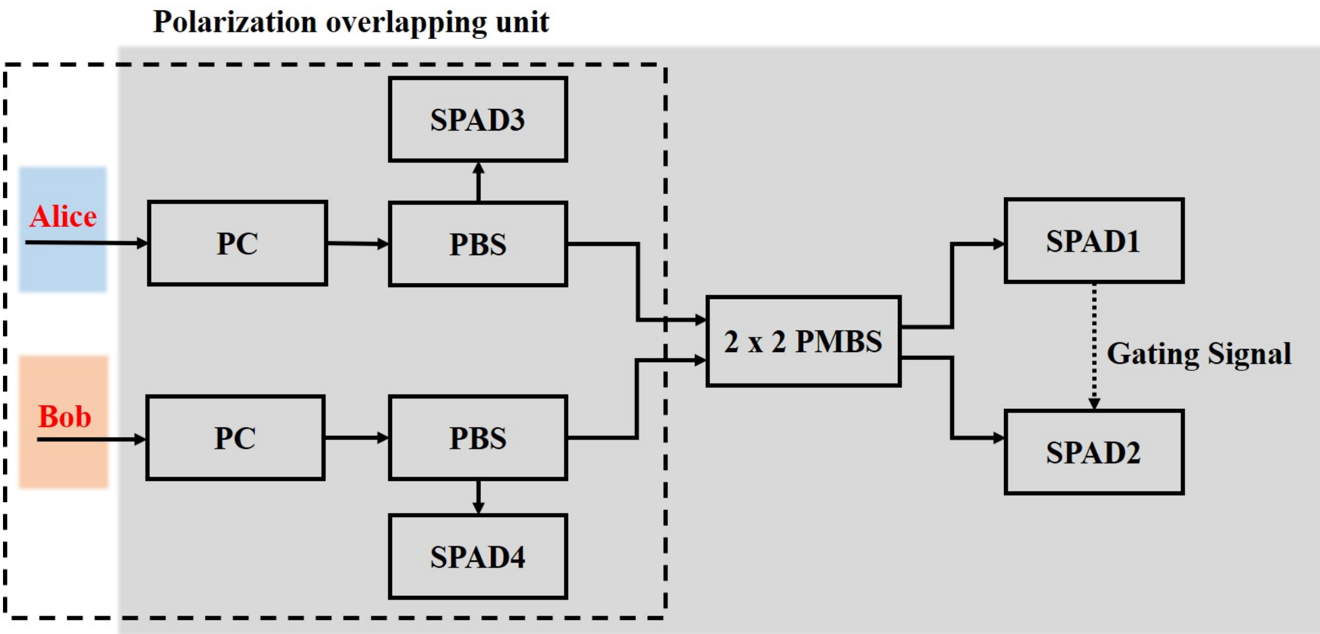

Figure 4 – The dashed block in the figure represents the setup to achieve polarization overlap between two independent photons.

measured coincidence counts exhibit an interference effect with visibility of 40% tested for a distance of 20 km over standard SMF.

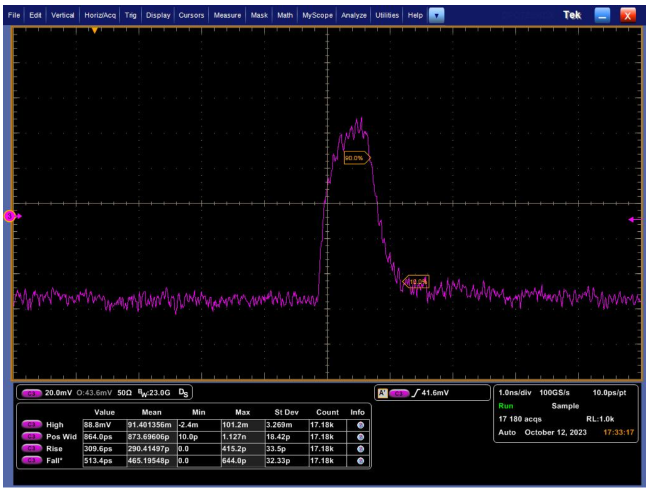

Figure 5 – Alice laser pulse.

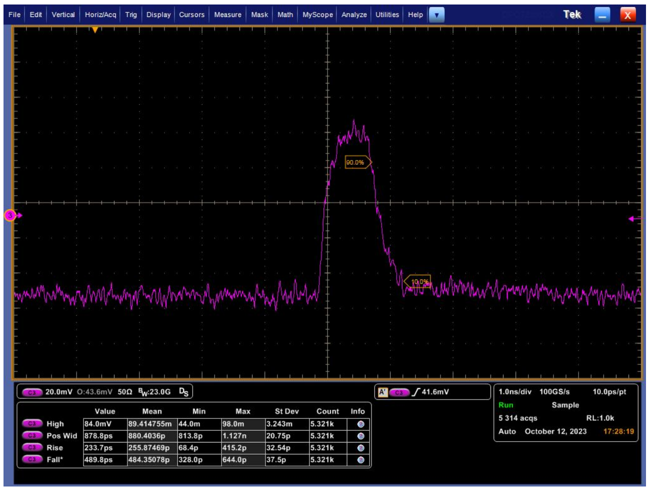

Figure 6 – Bob laser pulse.

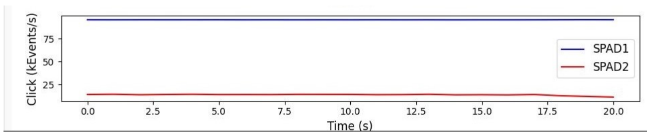

Figure 7 – SPAD1 and SPAD2 counts.

4. CONCLUSION AND FUTURE SCOPE

In this work, we have demonstrated the HOM experiment using two attenuated laser sources and analyzed the resulting coincidence counts. The achieved visibility indicates potential use in QKD protocols, such as MDI-QKD, for secure key generation. Superconducting nanowire single photon detectors (SNSPDs) offer significantly lower dark count rates and near-zero afterpulse probabilities compared to the SPADs used in the present experiment. Future efforts can focus on improving the visibility to approach the theoretical limit of 50%, utilizing SNSPDs over longer distances to enhance practical applicability.

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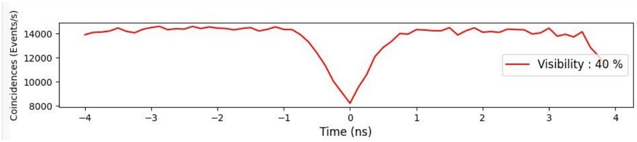

Figure 8 – Coincidence counts versus time representing the Hong-Ou-Mandel dip.

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