Enhancement of the correlation of the photons of thermal light

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Abstract
The scheme of the arrangement of five 50/50 non-polarizing beam splitters is considered. It may provide for the enhancement of the correlation of the photons of thermal light up to 75%. The correlation of the photons after the arrangement can be measured using ghost imaging, Bell test, Hong-Ou-Mandel interference.

1 | INTRODUCTION
Thermal light is considered classical. The correlated photons of thermal light can be prepared at a 50/50 non-polarizing beam splitter, with the two-photon correlation 50%. For comparison, the correlation of the entangled photons is 100%. The correlation of the photons of thermal light after the beam splitter can be measured using several types of experiments such as ghost imaging [1, 2], Hong-Ou-Mandel (HOM) interference [3], Bell test [4]. There are two interpretations of ghost imaging with thermal light, nonlocal two-photon interference (quantum) [5] and local intensity fluctuation correlation (classical) [6]. According to the quantum interpretation, the reason for the correlation is the indistinguishability of the two-photon amplitudes. The mechanism behind the correlation of the photons of thermal light after the 50/50 non-polarizing beam splitter was considered in [7].

We shall follow the quantum interpretation of the correlation of the photons of thermal light. In this case, the correlation is due to indistinguishability of the two-photon amplitudes. The quantum interpretation implies the possibility of summation of the correlations. We shall consider an arrangement of five 50/50 non-polarizing beam splitters designed for summation of the correlations.

2 | SCHEME OF THE ARRANGEMENT OF FIVE 50/50 NON-POLARIZING BEAM SPLITTERS
Consider the arrangement of five 50/50 non-polarizing beam splitters depicted in Figure 1. Let the beam of thermal light enter the first 50/50 non-polarizing beam splitter and be split into two beams traveling the arms \(a\) and \(b\). The beam on the arm \(a\) enters the second 50/50 non-polarizing beam splitter and is split into two beams traveling the arms \(c\) and \(d\). The beam on the arm \(b\) enters the third 50/50 non-polarizing beam splitter and is split into two beams travelling the arms \(e\) and \(f\).

The beams on the arms \(c\) and \(e\) couple at the fourth 50/50 non-polarizing beam splitter. The beams on the arms \(d\) and \(f\) couple at the fifth 50/50 non-polarizing beam splitter. The loop between the first and fourth beam splitters connected by the arms \(ac\) and \(be\) is a Mach–Zehnder interferometer. It can be tuned such that all the photons leave the fourth beam splitter through the same port toward the arm \(g\). The loop between the first and fifth beam splitters connected by the arms \(ad\) and \(bf\) is a Mach–Zehnder interferometer. It can be tuned such that all the photons leave the fifth beam splitter through the same port toward the arm \(h\).

Assume that the 50/50 non-polarizing beam splitter prepares two indistinguishable two-photon amplitudes. Indistinguishability of the two-photon amplitudes is the reason of 50% correlation of the photons of thermal light. After the first beam splitter, the photons in the state \(|\psi_{ad}\rangle\) are 50% correlated. Thereafter, the photons in the state \(|\psi_{bf}\rangle\) are 50% correlated, and the photons in the state \(|\psi_{de}\rangle\) are 50% correlated. After the second beam splitter, the photons in the state \(|\psi_{cd}\rangle\) are 50% correlated. After the third beam splitter, the photons in the state \(|\psi_{ef}\rangle\) are 50% correlated. The correlation of the photons on the arms \(g\) and \(h\) is defined by the sum of the correlations:

\[
\langle \psi_{gh} | \psi_{gh} \rangle = \frac{1}{2} \left( \frac{1}{2} \langle \psi_{cf} | \psi_{cf} \rangle + \frac{1}{2} \langle \psi_{de} | \psi_{de} \rangle \right) + \frac{1}{4} \left( \langle \psi_{cd} | \psi_{cd} \rangle + \frac{1}{4} \langle \psi_{ef} | \psi_{ef} \rangle \right). \tag{1}
\]
This gives the value of 0.75. Thus, the arrangement allows to have the correlation of the photons of thermal light 75%.

The correlation of the photons after the arrangement can be measured in several experiments. Consider the scheme of ghost imaging depicted in Figure 2. The photons from the arm $g$ go through the object and then are absorbed by the bucket detector. The photons from the arm $b$ go freely and then are absorbed by the scanning detector. The image-forming correlation can be observed in the joint detection of the outputs of the detectors. In ghost imaging, the photons of thermal light after the arrangement can provide for the formation of the image, with the maximum visibility 75%.

The scheme of the Bell test is shown in Figure 3. The photons from the arms $g$ and $b$ enter the input ports of the polarizing beam splitter. After the beam splitter, the polarization states of the photons traveling the arms $i$ and $j$ are 75% correlated, in the horizontal projection $|H_i\rangle$ $|H_j\rangle$, and in the vertical projection $|V_i\rangle$ $|V_j\rangle$. The photons on the arms $i$ and $j$ are projected onto the polarization states in the $H/V$ basis to perform the Bell test, with the expected effect 75%.

The scheme of the HOM interference is shown in Figure 4. The scheme is similar to that depicted in Figure 3. After the polarizing beam splitter, the photons are directed to the input ports of the 50/50 non-polarizing beam splitter. After the beam splitter, the photons go through the polarization analyzers which select the photons of the same polarization, horizontal or vertical. Then, the photons are absorbed by two detectors. The coincidence rate of the detectors is measured to determine a dip due to the HOM interference versus zero relative delay between the correlating photons. The correlation of the photons 75% yields the HOM dip 0.25.

The arrangement under consideration allows to enhance the correlation of the photons of thermal light up to 75%. This is between the classical correlation of 50% and the quantum correlation of 100%. One can achieve the quantum correlation with the use of entangled photons. It is reasonable to think that the photons of thermal light prepared in the arrangement can mimic the entangled photons, with the probability 75%.

The arrangement can be divided in two zones. The first zone includes the first beam splitter, and the second zone includes the block of four other beam splitters. One can extend the arrangement by adding the blocks of four beam splitters in series. In this way, one can enhance the correlation of the photons. With the use of $n$ blocks, one can obtain the correlation, $1 - 1/2^{(n+1)}$. When increasing $n$, the correlation tends to 100%. On the other hand, the losses will increase with $n$, reducing the correlation.

Entangled photons are used to perform a number of tasks in quantum communication due to their correlation 100%, including quantum dense coding [8], quantum teleportation [9], entanglement swapping [10] and quantum communication complexity protocols [11]. Also, entangled photons are used in quantum cryptography [12-14], quantum computing [15], quantum imaging [16] and quantum sensing [17]. Enhancement of the correlation of the photons of thermal light after
the arrangement up to 75% and higher will allow using them instead of entangled photons in the aforementioned tasks.

3 | CONCLUSION

Following the quantum interpretation of the correlation of the photons of thermal light, we have considered an arrangement designed for summation of the correlations. The arrangement includes five 50/50 non-polarizing beam splitters. After the arrangement, the correlation of the photons of thermal light is expected to be 75%, more than the classical correlation 50%. One can extend the arrangement to get further enhancement of the correlation. Several schemes of experiments have been considered, designed to measure the correlation of the photons of thermal light prepared in the arrangement, including ghost imaging, Bell test and HOM interference. The arrangement can be used in quantum communication, quantum cryptography, quantum computing, quantum imaging and quantum sensing.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest to report regarding the present study.

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