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13. ABSTRACT (Maximum 200 words)

We report our studies of the generation and characterization of EPR and entangled bi-photon state using optical parametric downconversion (PDC) with ultrashort-duration pump pulses. We have advanced a method of generating photon pairs that are highly entangled in their continuous space-time degree of freedom and have developed theoretical tools for quantifying the the degree of entanglement for this and other continuum-variable systems. In addition, we have shown for the first time the violation of a Bell-type inequality for the EPR state generated in parametric downconversion.

We have also shown theoretically that it is possible to design sources such that the photon entanglement causes complete nonlocal cancellation of dispersion of arbitrary order, and have demonstrated the increase in visibility using properly mode matched photons. In addition we have analysed the effects of non-measured degrees of freedom of photons generated by PDC on the basic elements of linear optical quantum logic gates, such as a prototypical Bell-state analyzer.

Our results have implications for novel methods of quantum communications using both entangled and unentangled modes and photons.

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(1) List of Manuscripts

1. A. Kuzmich, D. Branning, L. Mandel and I. A. Walmsley, “ Multiphoton interference effects at a beam splitter”, J. Mod. Opt, 45, 2233 (1998)

2. D. Branning, W. P. Grice, R. Erdmann and I. A. Walmsley, “Engineering indistinguishability and entanglement of two photons”, Phys. Rev. Lett., 83, 955 (1999)

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4. C. K. Law, I. A. Walmsley and J. H. Eberly, “Continuous frequency entanglement: Effective finite Hilbert space and entropy control”, Phys. Rev. Lett., 84, 5304 (2000)

5. R. Erdmann , D. Branning, W. P. Grice and I. A. Walmsley, “Restoring disperson cancellation for entangled photons produced by ultrafast parametric downconversion”, Phys. Rev. A, 62, 053810 (2000).

6. C. Iaconis, E. Mukamel and I. A. Walmsley, “Multimode quantum state measurement of ultrashort optical pulses” , J. Opt. B, Quant. Semi. Opt. 2, 510 (2000)

7. A. Kuzmich, I. A. Walmsley and L. Mandel, “Observation of phase-space nonlocality by generalized EPR states using homodyne detection”, Phys. Rev. Lett., 85, 1349 (2000)

8. W. P. Grice, A. U’Ren and I. A. Walmsley, “Eliminating frequency and space-time correlations in multiphoton states”, Phys Rev. A, 64, 063815 (2001)

9. A. Kuzmich, I. A. Walmsley and L. Mandel, “Violation of a Bell-type inequality in the homodyne measurement of light in an Einstein-Podolsky-Rosen state”, Phys. Rev. A, 64, 063804 (2001)

10. M. Beck, C. Dorrer and I. A. Walmsley, “Joint quantum state measurement using unbalanced array detection”, Phys. Rev. Lett., 85, 253601 (2001)

11. K. Banaszek , A. B. U'Ren and I. A. Walmsley, “Generation of correlated photons in controlled spatial modes by downconversion in nonlinear waveguides”, Opt. Lett., 26, 1367-1369 (2001)

12. K. Banaszek and I. A. Walmsley, “Photon counting with a loop detector”, Opt. Lett., 28, 52 (2003)

13. E. Mukamel, K. Banaszek , I. A. Walmsley and C. Dorrer, "Direct measurement of spatial Wigner function with area-integrated detection", to appear in Opt. Lett. 2003.

(2) Scientific Personnel

Principle Investigator: Ian Walmsley
Post-doc(s): Matthew Anderson, Konrad Banaszek
Graduate student(s): Reinhardt Erdmann, Alfred U'Ren, Manuel De La Cruz Gutierrez

(3) Report of inventions

None filed

(4) Scientific Progress and Accomplishments

We have completed this phase of our study and development of bright sources of biphotons with engineered entanglements in the space-time degrees of freedom. The detailed theory of entanglement via interference is outlined in Refs.[2] and [3], which identifies as well the places where theory and experiment diverge. Several such experiments in the recent past, in our group as well as others, have observed disagreements of one kind or another, and this suggests that a rethinking of the theoretical approach to the problem is perhaps warranted.

We have developed a method to precisely quantify the degree to which particles correlated in continuous variables (such as their frequency, as in this case) are entangled. (Ref. [4]) This work was a collaborative effort with the Rochester Center for Quantum Information (C. K. Law) and the Rochester Theory Center (J. H. Eberly). The basis of this work is the definition of a set of perfectly correlated modes (that represent single photon wave packets of short duration and broad spectrum) which transform the problem to a discrete basis, to which standard techniques for measuring entanglement can be applied. We believe that it is possible to devise methods for detecting these peculiar mode functions and to develop a method of secure communications based upon them. The advantages of this approach are two fold: First, there are many more of this type of mode than the two associated with the polarization degree of freedom. Second, the broad band nature of these modes may allow quantum CDMA-type teleportation schemes for multi-user access.

Other analyses relevant to the problem of Bell-state detection based on photon interference have been undertaken. Specifically we have examined how the continuous variable correlations between photons affects entanglement swapping, and proposed schemes for suppressing the distinguishing information at the source. (Ref.[2]) Also, experiments are currently underway to explore the effects of non-local dispersion cancellation for these modes, the analysis of which is found in ref.[5]. We have already observed the restoration of interference between entangled photons by balancing the dispersion of two long lengths of glass. This implies that balanced dispersion does not pose a problem for communication schemes using entangled photon pairs. Currently we are working on a scheme to compensate for lateral walk-off in the down-conversion crystal, which we believe leads to increased visibility and reduced count rates in collinear Type-II processes.

A new approach to the generation of entangled photons makes use of quasi-phase matching rather than birefringent phase matching. We have shown theoretically (in ref.[8]) that states of almost arbitrary degree of spectral correlation (including zero correlation pairs, necessary for multiple source experiments). One difficulty with this approach is that the photons cannot be separated using their polarization. Instead, one must make use of the spectral anticorrelation that is present in the laboratory source. Our experimental demonstration (ref. [11]) of PDC in a QPM waveguide structure showed greatly enhanced single- to coincidence count ratios than are usually available from bulk crystals. This is a crucial advance for conditional state preparation as is required for linear optical quantum computing.

In a different vein, we predicted in ref.[1] with the group of Prof. Mandel a novel quantum interference effect when a single photon is coincident on a beamsplitter with a weak coherent state. In a series of experiments, we have demonstrated this effect, and in refs.[7] and [9] showed for the first time a violation of local realism for the EPR state generated in parametric downconversion. In contrast to the seminal experiments of Ou and Kimble in this area, we operate in the regime of very small parametric gain, and use weak local oscillators and photon-counting detectors to perform homodyne detection of the two-mode EPR state. In this regime the arguments made by Bell and echoed by Kimble concerning the non-violation of local realism by the EPR state do not apply, and the positivity of the Wigner function of the light does not abrogate the observation of such a violation. The important point of our observation is to show that non-locality does appear in experiments using unentangled or only weakly entangled beams of light, provided the local measurements are of the appropriate type – generally of the class of POVM rather than projective measures. We expect in the future to explore the application of this type of arrangement to quantum communications schemes, following similar ideas to those proposed by Ekert for entangled photons.

We have also proposed and demonstrated a novel method for quantum state measurements of radiation fields using array detectors. A detailed analysis of a multi-temporal-mode detection scheme has been given in ref.[7], and the experimental implementation in ref.[10]. An important feature of array detection is that the homodyne arrangement does not require balanced detectors. This is because the array of detectors allows the relevant information to be encoded into a spatial fringe pattern, whose noise mimics that of the appropriate modes of the field. We expect such a detector to be of use in quantum imaging applications.

The problem of generating single photons and entangled photon pairs for applications in quantum information processing has led us to consider the major sources of low detection efficiency in the proposed schemes. Aside from the use of filters to eliminate distinguishing information (a problem that the source engineering described above is intended to eliminate) the other major loss is that of mode matching. Thus we have developed a unique method for the complete characterization of the spatial mode and demonstrated it experimentally in ref. [13]. Our method makes optimal use of the available signal in regimes when array detectors are not readily available, which makes it particularly advantageous in measurements of single-photon signals.

The mode matching issue is also critical generating non-classical states via conditional detection of ancillary photons. Moreover, the inability to distinguish one, two and three photons precludes the successful application of such conditional state preparation schemes. Thus we have proposed a novel design (ref.[12]) for a photon-number resolving detector that makes use of currently available technology and can be assembled quite cheaply.

We are pursuing several of the ideas developed under this grant with new funding from the ARDA.

(5) Technology Transfer

None undertaken.