REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
MAR 2012	Journal Article Post Print	OCT 2009 – SEP 2011

4. TITLE AND SUBTITLE

COMPENSATED CRYSTAL ASSEMBLIES FOR TYPE-II ENTANGLED PHOTO GENERATION IN QUANTUM CLUSTER STATES

5a. CONTRACT NUMBER IN-HOUSE QIS0PROJ

5b. GRANT NUMBER N/A

5c. PROGRAM ELEMENT NUMBER N/A

6. AUTHOR(S)

Michael Fanto, Thomas McEwen, Reinhard Erdmann, Enrique Galvez

5d. PROJECT NUMBER QIS0

5e. TASK NUMBER PR

5f. WORK UNIT NUMBER OJ

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

AFRL/RITA
525 Brooks Road
Rome NY 13441-4505

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFRL/RITA
525 Brooks Road
Rome NY 13441-4505

10. SPONSOR/MONITOR'S ACRONYM(S)
N/A

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-RI-RS-TP-2012-001

12. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED. PA #: 88ABW-2010-1848
DATE CLEARED: 5 APR 2010

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Spontaneous downconversion yields photons for Quantum-Optical-Gate development though their generation is probabilistic. Optimized efficiency requires control over the spectral wavefunction, generally achieved via spectral filtering which sacrifices most downconverted photons. Selecting crystal parameters to address the issue has been demonstrated, but no natural media enable this for 800 nm applications with optimal detection. Synthesizing parameters with super-lattices of known crystals was also analyzed but two-crystal experiments were insufficient to exploit it. Prototype twelve-crystal-assemblies have now been fabricated and the first results are reported here. We review implications for further work and discuss how methods described here enhance efficiency in applications of entangled photons requiring multi-crystal sources, such as cluster states, entanglement swapping, and teleportation.

15. SUBJECT TERMS
quantum, entangled photons, joint spectral function, spontaneous parametric downconversion

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	9	PAUL M. ALSING
					19b. TELEPHONE NUMBER (*Include area code*) N/A

Compensated crystal assemblies for type-II entangled photon generation in quantum cluster states

Michael Fanto, Thomas McEwen, Reinhard Erdmann
Air Force Research Laboratory, Rome, NY (USA)
Enrique Galvez, Colgate University, Hamilton, NY (USA)

1. ABSTRACT

Spontaneous downconversion yields photons for Quantum-Optical-Gate development though their generation is probabilistic. Optimized efficiency requires control over the spectral wavefunction, generally achieved via spectral filtering which sacrifices most downconverted photons. Selecting crystal parameters to address the issue has been demonstrated, but no natural media enable this for 800 nm applications with optimal detection. Synthesizing parameters with super-lattices of known crystals was also analyzed but two-crystal experiments were insufficient to exploit it. Prototype twelve-crystal-assemblies have now been fabricated and the first results are reported here. We review implications for further work and discuss how methods described here enhance efficiency in applications of entangled photons requiring multi-crystal sources, such as cluster states, entanglement swapping, and teleportation.

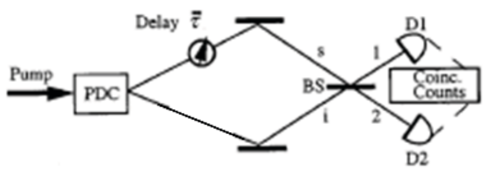
Key Words: quantum, entangled photons, joint spectral function, spontaneous parametric downconversion

2. INTRODUCTION

Spontaneous parametric downconversion (SPDC) in nonlinear crystals has provided the source of groundbreaking foundational and applications work in quantum optics (QO) for the last two decades. Experimental demonstrations of entanglement in photon pairs has more recently become of interest in quantum computational architectures that operate by principles entirely distinct from any based on classical physics. In contrast with other applications such as two-photon interference in Hong-Ou-Mandel Interferometers (HOMI) or quantum cryptography/key distribution, all of the applications the applications listed first require ***multiple crystal sources*** for entangled photons, while a HOMI and some others entail a single source, and most quantum cryptography implementations require only single photons, not entangled photons. It has been found moreover that multi-crystal sources of entangled pairs are not feasible with the CW pump lasers that were used throughout the original QO developments; short pump pulses are essential for the multiple interference effects to be realized. The temporal-spectral information inherent in pulses however affects and constrains the quantum interference; the effects must be clearly understood to enable and optimize the performance in practical applications.

The organization is briefly outlined as follows: We first describe multi-crystal interference particularly for type II SPDC, with key implications of separable quantum states. Next the significance of group velocity matching (GVM) in such states is discussed. Prototypes of new methods for implementing GVM it are designed and assembled so that initial spectral tests could be performed. Finally brief mention is given of how the methods can be generalized to increase control of the SPDC spectral function, to enable applications in regions that have not been accessible with other methods.

Quantum Information and Computation VIII, edited by Eric J. Donkor, Andrew R. Pirich, Howard E. Brandt,
Proc. of SPIE Vol. 7702, 77020H · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.852641



Add amplitudes that yield coincidence count events in single photon detectors in the most general case

$$(\omega_1\ in\ D_1)\quad and\quad (\omega_2\ in\ D_2)$$

Two paths that lead to to this event via Tx-Tx OR Rx-Rx are indistinguishable, and exhibit quantum interference by nulling the coincidence counts . (i.e. photons go to same detector.) NOTE that high spectral entanglement here, does NOT produce any distinguishing path information!

Figure 1. Hong-Ou-Mandel Interferometer_Single SPDC Source.

In an application of photon entanglement it is essential to designate which photon properties (momentum, energy (spectral), polarization, path, or time etc) in a given configuration are to be entangled, and to ensure that no others yield information to degrade the desired entanglement. Quantum interference relies on indistinguishable amplitudes ("Feynman paths") leading to an event; which in this case will be photon pair detection in coincidence counting modules. To illustrate first with the HOMI (Fig. 1) where two photons "meet" at a BS and always strike the same detector, to null the coincidence counts. An 'event' may be reached by two 'pathways' that cannot be distinguished and the calculation predicts destructive interference. Such a simplified single mode treatment based on photon's bosonic symmetry is sufficient for conceptual analysis, but not to describe an actual experiment. SPDC photons are far from single mode, even when the pump beam is CW and nearly single spectral mode. The photons in SPDC are in fact emitted as "wavepackets," with finite spectral and temporal bandwidths that can be Fourier transform limited. Each photon can exhibit any spectral value within its envelope! Thus to explain the HOMI effect with such wavepackets, it must be clear that the spectral properties cannot provide distinguishing information as to the noted Feynman event paths. (Fig. 2)

CW pump laser photons "infinitely" long; time of SPDC events is unknown.
BUT SPDC photons are wave-packets with finite temporal and spectral width

CW photons: long in time implies narrow spectrum: delta function $\delta(\omega)$

Entangled pair photons each have finite spectral - temporal width (e.g. 10 fs <–> 10 nm) YET narrow JOINT spectral width due to exact conservation of photon energy. Thus the JOINT SPECTRAL FUNCTION of photon pair is given as

$$F(\omega_1,\omega_2)=\delta\left(\omega_1+\omega_2-\omega_p\right)=\delta\left(\nu_1+\nu_2\right)$$
$$\text{where } \nu_{1,2}=\omega_{1,2}-\tfrac{1}{2}\omega_p$$

Figure 2. Photon wavepackets generated with CW Pump.

It is emphasized that it is not relevant whether the ***spectral*** detections are carried out, it matters only that the measurements could in principle be made; i.e. it is *possible* events and not actual ones that determine the quantum amplitudes used to calculate (probabilistic) experimental results. Spectrally resolved single photon detection is cumbersome and seldom carried out, but it *could be* using dispersed arrays of single photon counters.

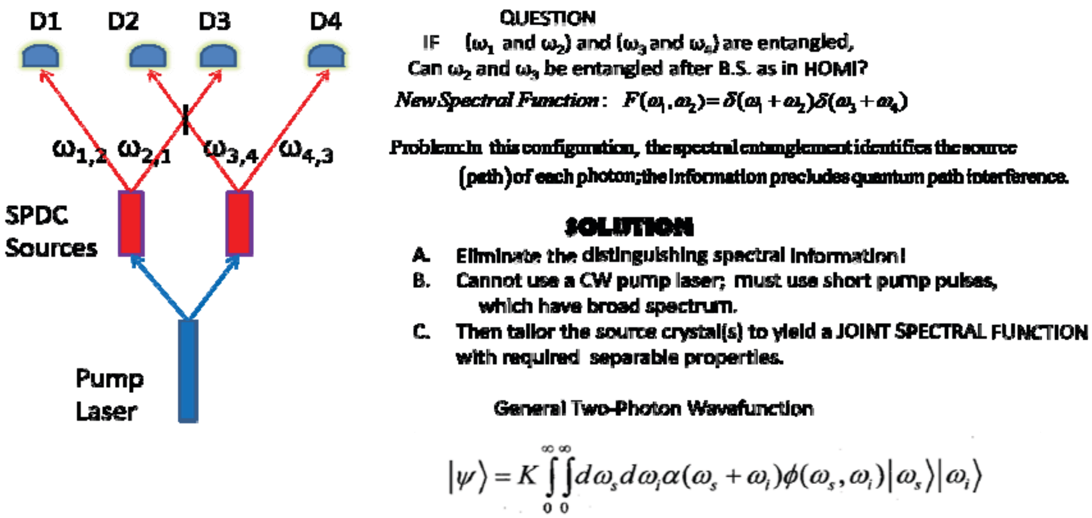


Figure 3. Spectral distinguishalitty in multi-source entangled photon interference.

We return to the problem of critical interest; how to make use of **many independent** photon sources, essential to producing more than two entangled photons or two qubits! A first step is to replace a CW pump source with short pulses that have a broad spectrum and well defined pair-creation time intervals, which can effectively overlap from many sources. This approach enables but does not yet optimize the process efficiency and purity of quantum interference. For that an analysis of distinguishing information is required, particularly the photons' spectral state function. To eliminate path distinction, spectral state information regarding A must yield no identifying information regarding B. This is the case as explicitly shown by Grice [1], when the two-photon state probability distribution is separable into a product state for each photon i.e. $F(\nu_s \nu_i) = f(\nu_s) g(\nu_i)$. In that case knowledge of the value of ν_s provides no influence the value of ν_i ! This contrasts (Fig. 3) with a CW pump spectral function $\delta(\nu_s + \nu_i)$, where knowledge of ν_s determines ν_s exactly; this state is ***not separable*** in frequency. Thus the issue becomes: how to generate separable spectral states that can be realized in SPDC? The most direct example would be the product of spectral bandpass filters placed before the detectors, to contribute spectral response of the form $f(\nu_s) g(\nu_i)$. However this is only realizable in practice if the spectral form contribution of the pump photons and the crystal contributions are neglected, since the latter two are in general not separable! However if the filters are sufficiently narrowband, their form factor predominates and makes the (separable) Gaussian filter product a good approximation to the experimental distribution.

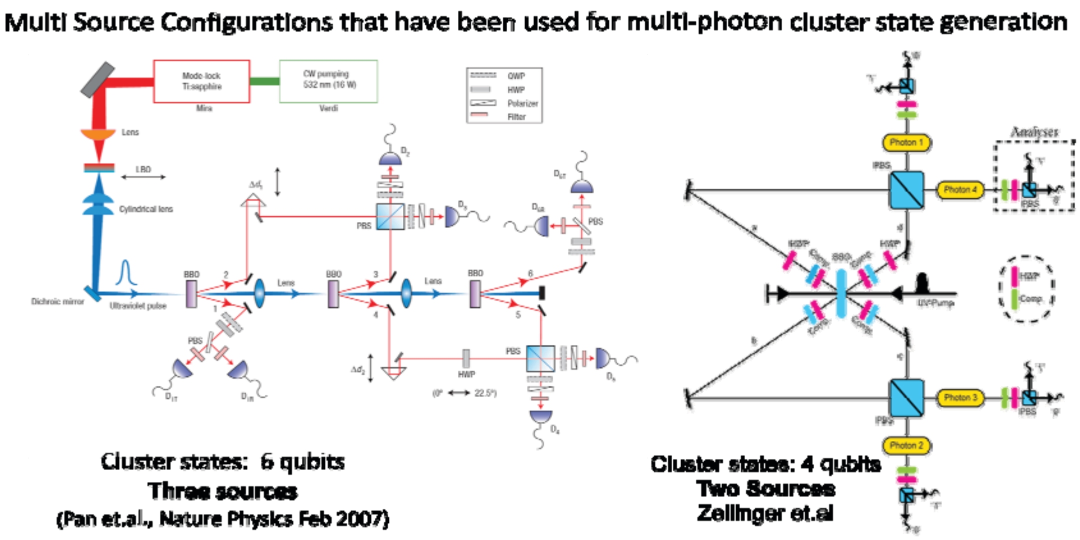


Figure 4. Experimental configuration for the generation of entangled photon cluster states.

This is indeed how nearly every multi-source experiment (Fig. 4) to date has achieved the required separability, sometimes without explicit awareness thereof [2, 3]. Unfortunately the vast majority of entangled photons are necessarily discarded in this process. There is however another way to achieve the desired results without any spectral filtering, and avoid the losses entailed. It was also shown [4] in the analysis that if the crystal spectral function has a particular form then its product with the pump spectral function can become separable, though neither of the two alone meets that condition. A simplified calculation is illustrated (Fig. 5).

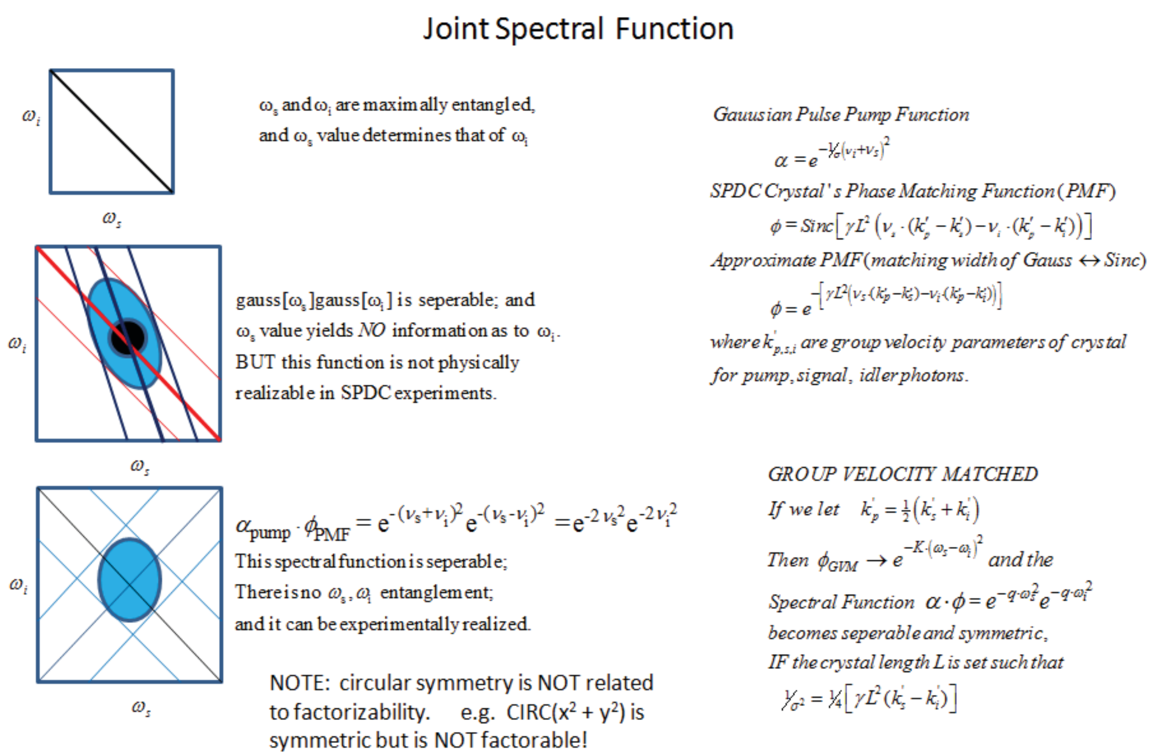


Figure 5. Joint spectral functions for CW pump, BBO under broadband pump and ideal GVM case.

Rather than the most general case we consider the central one only that of exact group velocity matching. This means simply that the crystal dispersive parameters are such that the pump pulse velocity matches that of the (type II) photon pair's (average) velocity. Since then several experiments [1] were able to demonstrate such states with selected non linear crystals in the 1.5 um regime. No known crystals enable GVM for applications at ~ 800 nm or shorter wavelengths, where much of the quantum optics work is centered and where photon detectors exhibit the highest quantum efficiency (>90%) without cryogenic operation. Accordingly, the focus of this work is to demonstrate how GVM crystals at ***arbitrary wavelength ranges*** can be "synthesized" by properly combining segments of ***known*** crystals.

3. MUTLI-CRYSTAL LATTICES

The illustration Fig 3 bears some resemblance to 'quasi-phase matching' (QPM), but it is crucial to understand difference as well as similarity to the methods pursued in this work. In QPM calibrated periodic poling reverses the sign of the nonlinear coefficient such that the periodicity effect can compensate for the phase mismatch, in a medium which otherwise could not exhibit 'non-critical' phase-matching. But here the NL (BBO) crystals are already phase matched; it is the group velocities which must be made to match as well. This can be viewed as a generalization of phase matching to include overlap of the photon propagation vectors $\vec{k}_{e,o.p} = \frac{2\pi}{n\lambda}$ with the phase being the zero order term in that Taylor expansion, and (inverse) group velocity the first order term. Unlike QPM however, GVM cannot be synthesized in a single medium, two or more media with proper complementary properties are required for a "compensated assembly" [5, 6]. Though physical difficulties delayed earlier investigations, progress in crystal fabrication has brought the feasibility and cost within reasonable range (Fig. 6).

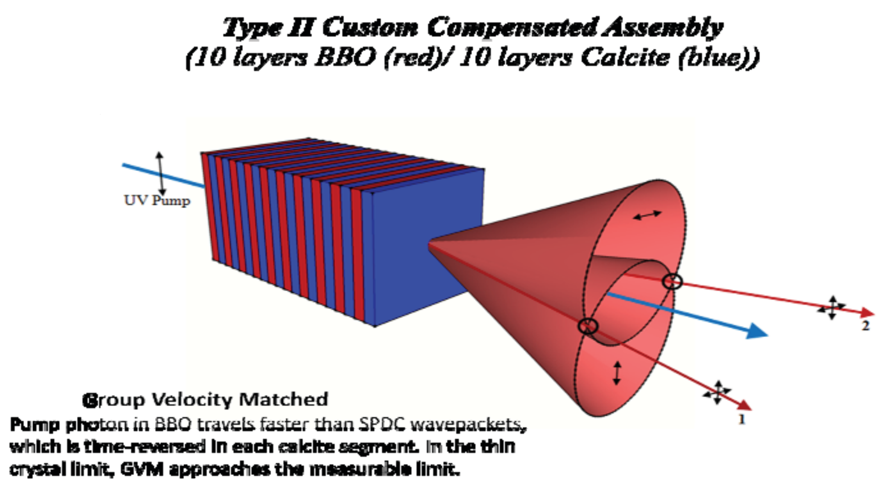


Figure 6. Type-II custom assembly showing alternating BBO and calcite segments.

The orientation of the crystal phase matching function (PMF) is determined by conservation of momentum for the propagation components along the respective crystal axes. Note that for a photon the momentum in a medium is simply P=nk where the index of refraction n embodies the medium's propagation effect. The width or spread in this case is inversely related to the crystal length and is orthogonal to that of the pump function. A special case of GVM can be met when the slope of the crystal function becomes exactly orthogonal to that of the pump function and the widths of the pump and crystal functions are engineered to be equal so as to yield a separable state. The more general conditions (Fig.7) involve symmetry about a vertical (or horizontal) axis. Any asymmetry means that a spectral detection of one photon (e.g. signal) provides spectral information regarding the idler photon. To modify the orientation (or shape) of this distribution one could add components (spectral filters), select a different source, or modify the effective source.

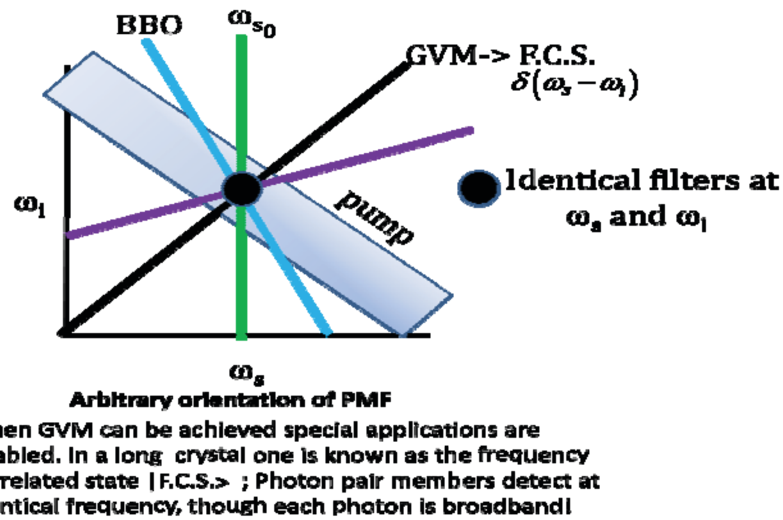


Figure 7. Arbitrary possible orientations of the crystal function with crystal assembly configurations.

The method we develop in this work makes use of custom crystal assemblies (Fig. 6). Each thin (nonlinear) BBO segment is alternated with a (linear) medium, which is also birefringent but *not* phase matched hence does not generate SPDC. Its purpose is to reverse the effect of pump pulse velocity mismatch in BBO compared with that of the SPDC two-photon wavepacket. Calcite has been identified as one of very few crystals which meets this condition for this effect at 800 nm (400 nm pump and shorter). For sufficiently thin segments, GVM is nearly satisfied throughout the assembly, and deviation from the ideal case can be calculated from the actual thickness used.

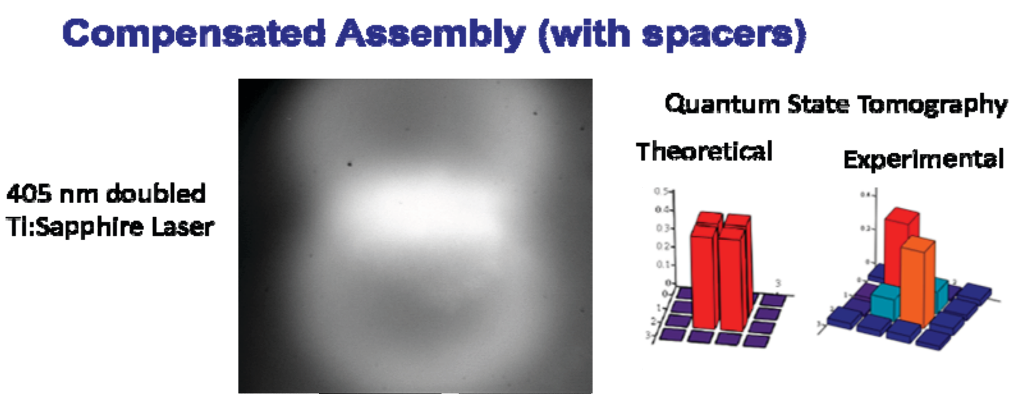


Figure 8. Output entangled rings and tomography for initial custom assembly under broadband pumping.

Our initial measurements of the polarization state tomography illustrated in Fig. 8 deviated from the theoretical expectation. Further measurements on these prototype assemblies will be required to resolve this in future work.

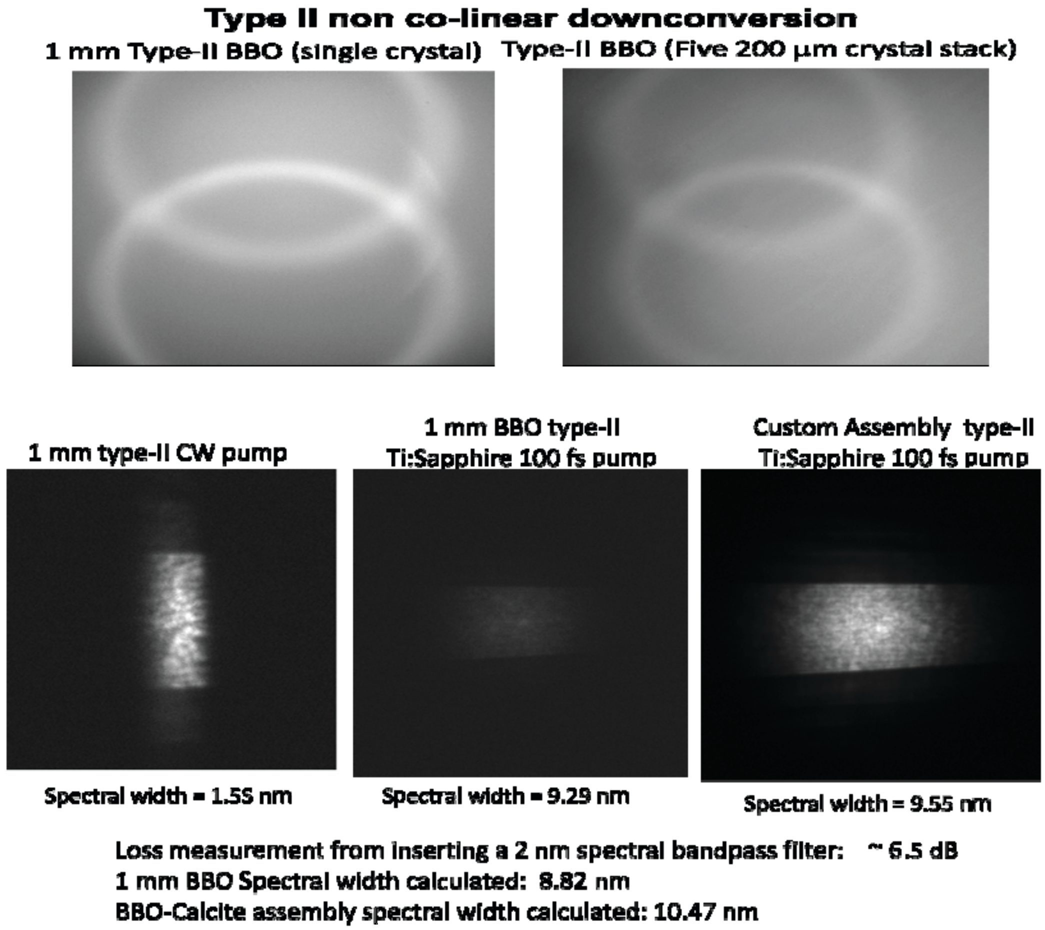


Figure 9. Images of Type II polarization entangled photons and spectral data.

3.1 ARBITRARY CONTROL OVER PHASE MATCHING FUNCTION ORIENTATION

We have focused on the establishment of GVM because of its wide utility, but the flexibility of the segmented methods can be also extended to other application, in fact it can produce arbitrary orientations of the PMF (Fig. 7). To define this we may view the GVM condition as a special case of a spectral function oriented at 45 degrees. Note that pump orientation is always about – 45 degrees. The PMF orientation can be rotated to any angle by simply adjusting the ratio of segment length between BBO and Calcite, something which cannot be done with other known methods for which special applications have already been identified in prior work [5, 6].

3.2 FREQUENCY CORRELATED STATE

When GVM can be achieved in practice other applications are enabled, one such is known as the frequency correlated state. In this case the photon pairs are always detected with identical frequency, although each photon is broadband. Several applications have been identified [6, 7]. In the case of type II, the GVM crystal must be made relatively long, since the value of L determines the joint spectral width. Single crystal experiments have been performed at 1.55 nm, but none at 800 nm for the reasons mentioned, that no such crystals exist. The multi-crystal assembly offers an in principle approach to attempt this results in Fig. 8, 9, but the number of crystal segments required is quite large. In comparison about 12 have been demonstrated in this work, whereas at least 50 would be needed for a high fidelity GVM and well over 100 would be needed for a FCS.

4. SUMMARY

- The effects of various types of photon entanglement must be understood before optimizing SPDC sources for applications.

- Pulsed pump sources are essential for multi-source applications of entangled photons. Control over spectral entanglement (and disentanglement) can enable order of magnitude improvement in efficient yield entangled pairs.

- Properly designed multi-crystal sources enable Group Velocity Matching to be synthesized in regimes where no natural media are available.

- Generation of "Frequency-correlated photon states," is also enabled by GVM assemblies, not presently feasible with other methods near 800 nm.

Acknowledgements: Warren Grice (ORNL, Oak Ridge, TN) and Alfred U'Ren (Institute Ciencias Nucleares de México) for theoretical foundations and technical discussions. Nicholas Noga (AFRL Summer Student); AFOSR for research funding, Inrad Corp. for constructing the crystal assembly.

5. REFERENCES

[1] W. Grice et.al. Eliminating frequency and space-time correlations in multi-photon states, PRA 64, 063815, 2001

[2]A. Zeilinger et.al. Experimental One-way computing Nature 434, 169, 2005

[3] J.Pan et.al. Six photon six qubit cluster states, nature Physics, (2007)

[4] A.U'ren et.al. Synthesis of time-bin entangled states via tailored group velocity matching, JMO 52, 2197, 2005

[5] A. U'Ren et.al. Generation of two-photon states with an arbitrary degree of entanglement via nonlinear crystal super lattices, PRL 97, 223602, 2006

[6] R. Erdmann et.al. Restoring dispersion cancellation for entangled photons produced by ultrashort pulses, PRA **62**, 053810 (2000)

[7] F. Wong et.al. Two-Photon coincident frequency entanglement via extended phase matching, PRL **94,** 083601, (2005)