Triple photons : from nonlinear generation to quantum correlations

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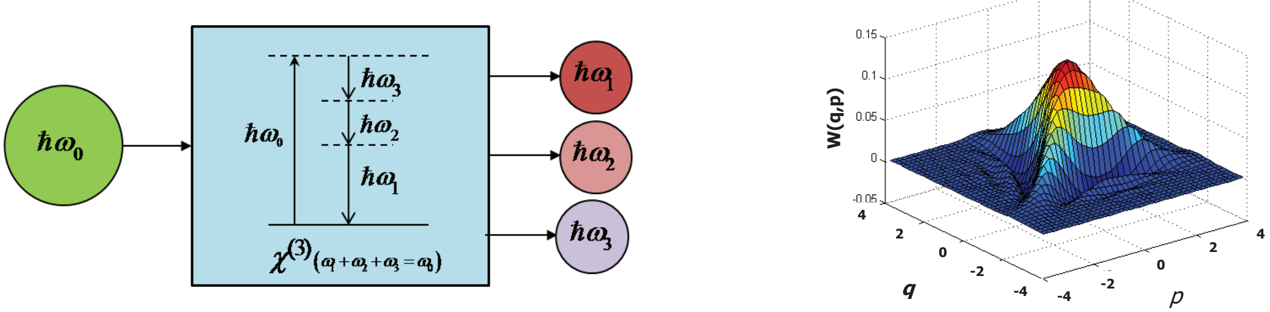
Abstract

We implemented an experiment using a KTP crystal pumped at 532 nm that allowed the first generation of triple photons. It corresponds to the creation of three correlated photons from the splitting of a single photon from a pure third order down conversion parametric process. We gave prominence to the experimental and theoretical demonstrations of quantum correlations of these triple photons. We considered several protocols, including the recombination of the three photons and the three possible recombinations by pairs. These original results open the way to new fundamental quantum optics studies that should have applications in quantum information and cryptography.

1. Introduction

We consider the generation of triple photons where a pump field gives birth simultaneously to three photons in a nonlinear material. During this process governed by a third order electric susceptibility $\chi^{(3)}$, three highly correlated photons, with the energies $\hbar\omega_1$, $\hbar\omega_2$ and $\hbar\omega_3$, are created from the annihilation of a photon at $\hbar\omega_0$ as shown in figure 1(a).



(a) **(b)**

Figure 1. (a) Photonic diagram corresponding to triple photons generation. (b) Wigner function in the phase space corresponding to degenerate triple photon generation, *i.e.* with $\omega_1 = \omega_2 = \omega_3$ and the same polarization for the three corresponding waves.

Quantum mechanically, triple photons generation (TPG) is the most direct way to produce pure quantum states of light, whose statistics goes beyond the usual Gaussian one associated with coherent sources and optical parametric twin-photon generators. Indeed calculations showed that the simultaneous birth of three photons is at the origin of intrinsic three-body quantum properties such as three-particle Greenberger-Horne-Zeilinger (GHZ) quantum entanglement [1]. It also leads to Wigner functions, *i.*e :

$$W(q,p) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{ipx}\left\langle q - x/2 \right| \hat{\rho} \left| q + x/2 \right\rangle dx \qquad (1)$$

where q and p are the amplitude and phase quadratures, and $\hat{\rho} = |\psi\rangle\langle\psi|$ is the density matrix of the state, presenting quantum interferences and negativities as shown in figure 1(b) [2, 3]. The experimental alternatives to GHZ light generation that have been reported until now concerned two entangled pairs of photons produced by two processes governed by the second-order electric susceptibility $\chi^{(2)}$. This scheme is interesting since it led in particular to a new way of testing the Bell theorem [4]. However it has two main limitations : the correlations are observed by destructive selection, so that the triple photons cannot be *a posteriori* manipulated, and the scheme is a conditional protocol, generating a small amount of triple photons.

Our objective was then to get beyond these limitations by directly generating triple photons using the third order electric susceptibility $\chi^{(3)}$. In 2004, we made the first experimental demonstration of triple photon in a KTP crystal pumped at λ_0 = 532 nm. However, it was necessary to stimulate the nonlinear process by using two incident photons at $\lambda_2 = \lambda_3$ = 1665 nm [5, 6]. Few attempts had been made in the past ten years prior to our work, but without any success : these failures were due to the weak magnitude of the third order electric susceptibility, and to the fact that the corresponding processes cannot be simply deduced from a simple analogy with second order interactions [7].

Here we describe the current triple photon generator and the protocols for studying the quantum correlations based on the recombination of the photons of the triples in a nonlinear crystal through a second order or third order nonlinear sum-frequency generation (SFG), and on the study of the recombination-born field.

2. Nonlinear generation

The triple photon generator (TPG) is described in Figure 2. The pump beam at λ_0 = 532 nm is the second harmonic of a 10 Hz repetition rate Nd:YAG laser (CONTINUUM Leopard D -10) with a full width at half maximum (FWHM) pulse duration of 15 ps. The stimulation beam at $\lambda_2 = \lambda_3$ = 1665 nm is generated by an Optical Parametric Generator (Topaz-355, T3P1N1). TPG is realized in a 13-mm-long KTP crystal cut in the *X*-axis, *i.e* in the (θ = 90°, φ = 0°) direction. The temporal coincidence between the 532 nm and 1665 nm pulses is ensured by a delay line, which accuracy is better than 3 ps. The beam at 532 nm is ordinary polarized (o), *i.e.* along the *Y*-axis, and the beam at 1665 nm is polarized at 45° of the *Z*-axis at the entrance of the TPG KTP crystal in order to give rise to ordinary (o) and extraordinary (e) polarizations inside the crystal. According to phase-matching, the generated beam at λ_1 = 1474 nm is extraordinary polarized. When the crystal is pumped with $1.2\text{x}10^{15}$ photons (450 µJ) per pulse at 532 nm, a maximal value of $4.5\text{x}10^{13}$ triples (6.1 µJ) can be generated when seeding with $8.0\text{x}10^{14}$ photons (90 µJ) at 1665 nm. The spectral bandwidth (FWHM) at 1665 nm and 1474 nm are 12 nm and 30 nm1474 nm, respectively.

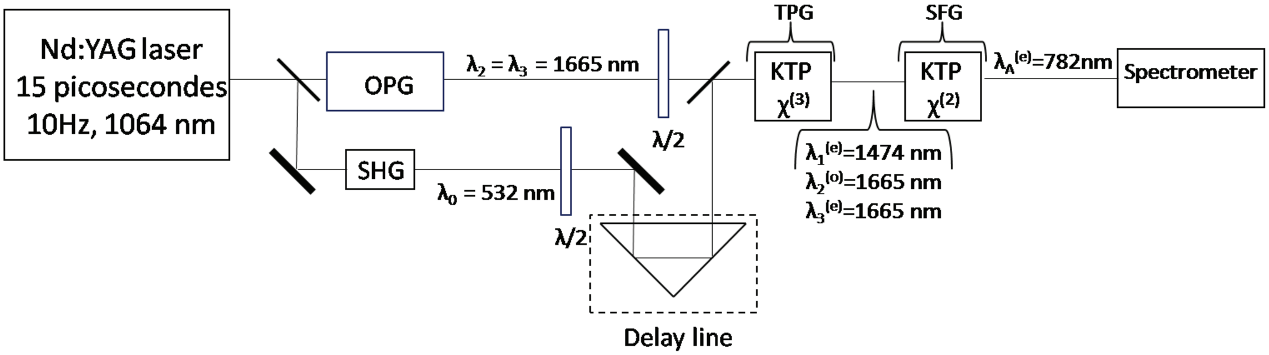


Figure 2. Experimental setup for the correlation study of triple photons ; OPG is an optical parametric generator ; the half wave plates (λ/2) allow the pump and stimulation beams to be properly polarized : (o) and (e) stand for the ordinary and extraordinary polarizations respectively ; TPG corresponds to triple photon generation ; SFG stands for sum-frequency-generation used for the study of the quantum correlations.

3. Quantum correlations

The chosen protocols for the study of the correlations should allow the discrimination of the triplet photons from the seeding. For that, we consider experiments based on the recombination of the generated photons in a nonlinear crystal using second order or third order SFG, as shown in figure 2 where a KTP crystal cut in the proper phase-matching direction is used for performing the chosen recombination. This protocol is the transcription for triplets of the one proposed and demonstrated for twin photons correlations and is also applicable in the fluorescence generation scheme [8, 9]. In our case, it is possible to consider several *scenarii*, including the recombination of the three photons, $\omega_1 + \omega_2 + \omega_3 \rightarrow \omega_0$, by using a third order sum-frequency-generation (SFG), and the three possible recombinations by pairs, $\omega_1 + \omega_2 \rightarrow \omega_A$, $\omega_1 + \omega_3 \rightarrow \omega_B$ and $\omega_2 + \omega_3 \rightarrow \omega_C$, thanks to different second order SFG. For each scheme, the generated beam can be temporally or spectrally analyzed : (i) measurement of the intensity at ω_0, ω_A, ω_B and ω_C as a function of the delays applied between the triple beams ; (ii) measurement of the spectrum around ω_0, ω_A, ω_B and ω_C when no delay is applied. All of these two – and three – photon recombination schemes are able to reveal different aspects of the quantum character of the triples.

We performed the calculations by quantifying all the fields, and by assuming the plane wave and low gain approximations. We analytically resolved the equations of motion for broadband quantum fields, to obtain the field operators of the triple photons in all points of the nonlinear crystal, in the Heisenberg representation. We then recombined these fields by defining the proper sum-frequency operator. The recombination-born field has different characteristics depending on the fields-recombination schemes and on the amount of seeding photons. In any case, the quantum calculations feature different behaviours from the case of calculations with classical fields, which would correspond to recombination-born fields from independent fields.

As example, in figure 3 is plotted the spectral shape of the recombination-born field from a three-field recombination with a TPG injected with 10^5 photons, the crystal (KTP) being pumped with 10^{15} photons. The pump field, at 532 nm, is considered as monochromatic, and the two seeding fields, both centred at 1665 nm, have a FWHM of 10 nm.

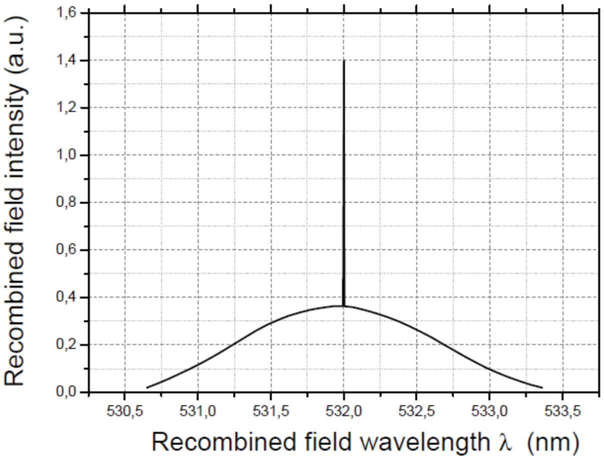


Figure 3. Spectrum of the recombined field arising from the three triple fields.

The narrow peak is the exact spectrum of the pump field, issued from the recombination of all the photons that "recognize" one each other from the same triple, evidencing the quantum link they share. The Gaussian background is issued from random recombination of non-linked photons, which is equivalent to the classical three-field recombination. The spectrum of figure 3 is close to what is found in the case of twin photons [8, 9].

4. Conclusion

The calculations corresponding to all the possible *scenarii* described above have been led, both at high and low energies, corresponding to experiments in progress. Experimental and theoretical results will be presented. All of them reveal different aspects of the quantum character of the triples.

These original studies open the door to new fundamental results in quantum optics, all the more as triple photons are promising for the use of announced pair of photons instead of a single photon in quantum information protocols.

5. References

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