Evolution of spatio-spectral coherence properties of twin beam states in the high gain regime

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ABSTRACT

We present the experimental investigation of the coherence properties of the light produced by parametric down conversion in the macroscopic regime, also including pump depletion. In particular, we compare the results obtained in very similar geometric conditions by using two nonlinear crystals having different lengths. We observe that the number of generated photons, the size of spatio-spectral coherence areas, and the number of modes in the photon number statistics exhibit a similar behavior in the two crystals as a function of pump mean power, even if we notice that the absolute values are different. The available theory of parametric down conversion cannot account for these differences.

Keywords: Nonlinear optics; Parametric down conversion; Photon statistics; Coherence properties; Photodetectors

1. INTRODUCTION

Parametric down conversion (PDC) is a well-known nonlinear process extensively investigated for the production of entangled states of light, which can be useful for applications ranging from the fundamental tests of quantum mechanics to the implementation of quantum state engineering, quantum information and quantum communication protocols.[1–3] To better exploit the nonclassical nature of such states, during the last few decades many investigations were devoted to the study of correlations and coherence properties at different intensity regimes and as functions of different parameters. In particular, the two factors that play a key role in the behavior of spatial and spectral properties of PDC light are the pump field properties (spectral bandwidth, spatial profile, power and pulse-duration) and the nonlinear medium. It is worth noting that, under the assumption of an infinite plane-wave pump beam, the relation among the above parameters and the PDC features is quite simple and analytical expressions exist.[4,5] Nevertheless, in realistic situations, the plane-wave model is not sufficient to explain the experimental results. Such a problem has been addressed in some recent papers[6,7] aimed at investigating the angular spectrum of PDC light at the single-photon level as a function of crystal length.

In this work we present the results of recent experimental investigations performed in the macroscopic domain, also including pump depletion. We achieved such a condition by pumping either a 4-mm-long or a 8-mm-long nonlinear crystals with the third-harmonic pulses of a ps-Nd:YLF laser amplified at 500 Hz. The coherence properties of the generated twin beam (TWB) states were studied by sending the far-field pattern of PDC radiation to an imaging spectrometer, at whose output an electron-multiplying CCD (EMCCD) camera was used to register single-shot images. In particular, we determined the value of parametric gain from the evolution of the mean number of photons. In addition, we investigated the widths of spatial and spectral profiles as well as the number of modes close to frequency degeneracy and collinear-interaction geometry. Even if the general behavior of coherence properties as a function of pump mean power is the same for both crystals, some differences arise, especially in the absolute values, which deserve further investigations.

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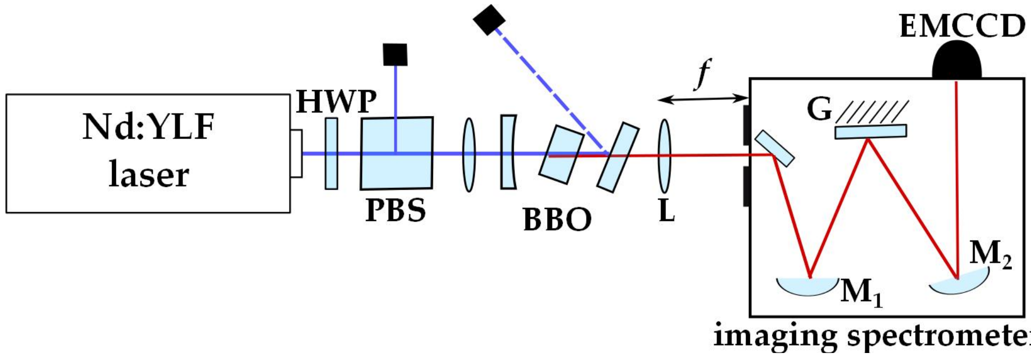

Figure 1. (Color online) Sketch of the experimental setup used to compare the coherence properties of PDC light in two crystals having different lengths. HWP: half-wave plate; PBS: polarizing cube beam splitter; BBO: β-Barium Borate crystal; L: lens with focal length f = 60 mm; G: grating; M_j: spherical mirrors; EMCCD: electron-multiplying CCD camera.

2. EXPERIMENTAL SETUP AND METHODS

A sketch of the experimental setup is shown in Fig. 1. The third-harmonics (349 nm, 4.5-ps pulse duration) of a mode-locked Nd:YLF laser (High-Q-Laser), regeneratively amplified at 500 Hz, was used to produce PDC either in a β-Barium-Borate (BBO) crystal 8-mm long (cut angle = 37 deg) or in one 4-mm long (cut angle = 33.8 deg). Each crystal was tuned to have phase-matching at frequency degeneracy in a slightly non-collinear configuration geometry. The full width at half maximum (FWHM) of the pump beam, collimated by means of a telescope in front of the BBO, was $\sim 380\mu$m at the lowest pump power. The PDC light was focused by a 60-mm focal length lens on the plane of the vertical slit of an imaging spectrometer (Lot Oriel) having a 600 lines/mm grating. The (ϑ, λ) far-field radiation was then recorded in single shot by a synchronized EMCCD camera (iXon Ultra 897, Andor), operated at full frame resolution (512x512 pixels, 16-μm pixel size). The resulting resolution of the system composed of the imaging spectrometer and the EMCCD camera was 0.2 nm in spectrum (horizontal direction) and 0.015 deg in angle (vertical direction). In order to make a systematic comparison between the spatio-spectral coherence properties of PDC light generated in the two crystals, in both cases we saved sets of single-shot images (1000 images) at different pump mean power values. The pump power was changed by a half-wave plate followed by a polarizing cube beam splitter. Single-shot images display a clear speckle pattern, which is a manifestation of coherence properties of TWB.

As already explained in Ref. [8], the evolution of the structure of PDC patterns registered by our detection system at different pump mean powers, and hence at different PDC gains, can be investigated by calculating the intensity correlation coefficient between a single pixel at coordinates (i,j) and all the pixels (k,l) contained in a single image

$$\Gamma^{(i,j)}_{k,l} = \frac{\langle I_{i,j} I_{k,l} \rangle}{\langle I_{i,j} \rangle \langle I_{k,l} \rangle}, \quad (1)$$

Here I is the intensity value of each pixel expressed in digital numbers and upon subtraction of the mean value of the noise measured with the camera in perfect dark, whereas $\langle ... \rangle$ indicates the averaging over a sequence of 1000 subsequent images. The procedure was applied to a statistical ensemble of pixels having abscissa i close to frequency degeneracy and ordinate j in the quasi-collinear direction. The function $\Gamma^{(i,j)}_{k,l}$ defined in Eq. (1) is a matrix having the same size as the original images and containing both the intensity autocorrelation and the cross-correlation areas. The horizontal section of these correlation areas is related to spectrum, whereas the vertical section gives information about the angular dispersion. Moreover, from the value of autocorrelation coefficient it is possible to extract the number of spatio-spectral modes[9, 10]

$$K = \frac{1}{\Gamma^{(i,j)}_{i,j} - 1}. \quad (2)$$

We notice that such a relation yields the number of modes contained in a single pixel of the camera, which represents the best resolution we can achieve with our detection apparatus.

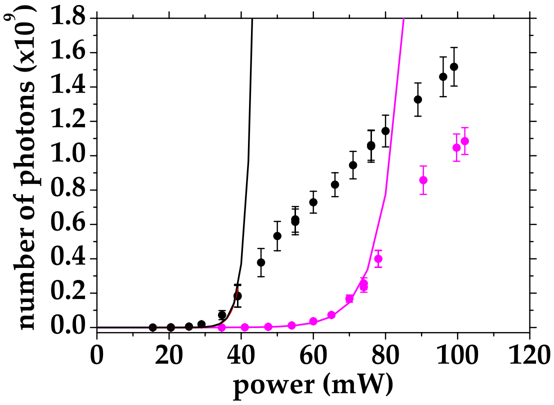

Figure 2. (Color online) Mean number of photons detected in an area close to frequency degeneracy and in the quasi-collinear interaction geometry by taking into account the actual transmittance coefficients of the neutral density filters. The data are shown as functions of the pump mean power for long (black dots) and short (magenta dots) crystals. A hyperbolic sine-squared function, shown as colored line, is superimposed to the first part of each data set.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The most immediate characterization of TWB can be performed in terms of the number of generated photons. To this aim, in Fig. 2 we plot the mean number of photons detected in an area close to frequency degeneracy and in the quasi-collinear interaction geometry as a function of the pump mean power for long (black dots) and short (magenta dots) crystals. To obtain these two plots, we have taken into account the calibration of the camera sensitivity (5.4 electrons per digital number), its detection efficiency ($\sim$ 90% at 698 nm) and all the optical losses. It is clearly evident that for both crystals the mean number of photons shown in Fig. 2 starts increasing exponentially, as expected for high-gain PDC under the hypothesis of un-depleted pump beam. Actually, this initial behavior is well fitted by the function $y = A \sinh^2(Bx)$, shown as line (black for the long crystal and magenta for the short one) in Fig. 2. As already explained in Refs. [8,11], this fitting curve represents the expected behavior under un-depleted pump-beam approximation. In this condition, the gain of the process would vary from 5.3 up to 13.4 in the long crystal and from 5.8 up to 10.7 in the short crystal, but the occurrence of a progressive depletion process prevents the exponential growth in both cases. On the contrary, the evolution of the second part of the data, corresponding to the condition in which also the pump beam evolves, exhibits a linear dependence on pump power with roughly the same slope.[12] Not surprisingly, the change in the behavior of the number of photons as a function of pump power occurs at a different pump mean power value in the two crystals. We note that to superimpose the data obtained with the long crystal to the data corresponding to the short one, we should multiply the pump power value by a factor of 2, which is quite unexpected. In fact, according to the infinite plane-wave model the relevant quantities that describe PDC light, such as the number of generated photons, are all functions of $\sqrt{P}\,L$, in which P is the pump power and L is the length of the crystal. However, we have already shown in Ref. [13] that such a model is unable to effectively describe the richness of the nonlinear phenomenon because it does not take into account the finite spectral amplitude of pump beam, the effective length of the crystal, and possible walk-off effects. In addition, we have already demonstrated that this model fails in the presence of pump depletion.[8]

To better investigate such a problem, we also studied the coherence properties of PDC light. In Fig. 3 we show the behaviors of the spectral (left panel) and spatial, *i.e.* in angular domain, (right panel) widths, FWHM, of the intensity autocorrelation and cross-correlation areas, as functions of the input pump mean power for long and short crystals. In both panels, we can observe that, for each nonlinear medium, the sections of autocorrelation and cross-correlation areas exhibit an initial growth, reach a maximum and then decrease. We have already demonstrated that the trend of the first part of the data can be explained by the infinite plane-wave model according to which the evolution of autocorrelation and cross-correlation areas can be described by a fourth-root function of pump power.[5] On the contrary, the second part of the data (including the peak and

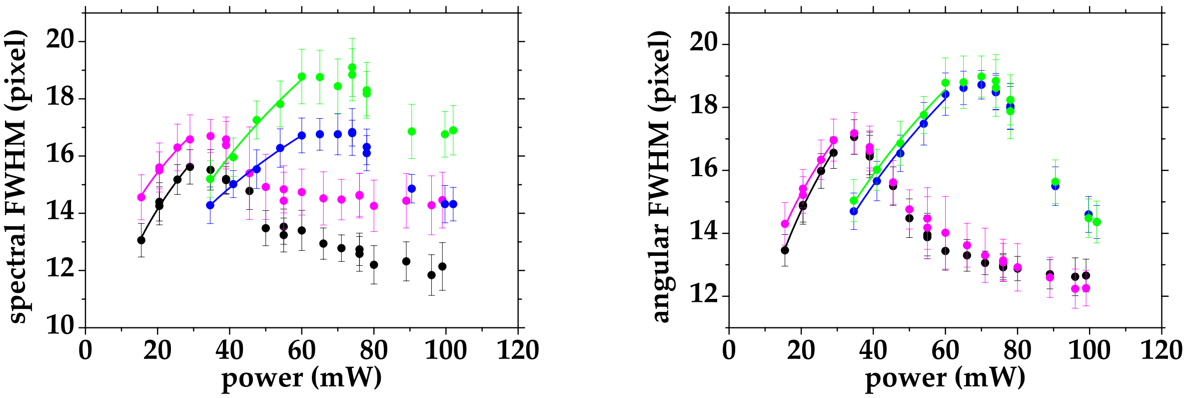

Figure 3. (Color online) Spectral (left panel) and spatial (right panel) FWHM widths of the autocorrelation and cross-correlation areas for long (black symbols: autocorrelation, magenta symbols: cross-correlation) and short (blue symbols: autocorrelation, green symbols: cross-correlation) crystals. The fourth-root fitting functions to each data set are shown as colored lines. See the text for details.

the decrease in the FWHM) can be understood only by assuming that for such power values pump depletion occurs. Nevertheless, it is clearly evident that the pump power values at which depletion starts is different for the two crystals. This is quite obvious, since at a fixed pump power value in the long crystal the PDC process is expected to gain more than in the short one. Moreover, because of the different range of explored pump mean power values, we can notice that in the case of the short crystal the evolution of the sections of autocorrelation and cross-correlation areas is smoother than for the long crystal. This behavior is quite expected as the short crystal is more tolerant than the long one to the phase-matching conditions.[5] The same reason partly explains why the value of the peak (both in spectrum and space) is higher for the short crystal than for the long one. Of course, this also depends on the absolute values of pump power, that are higher for short crystal. Furthermore, apart from the absolute values, by comparing the evolution of each data set in Fig. 3 for long crystal with the corresponding data obtained with the short one, we can notice that, as already observed in Fig. 2, the slopes of the curves (increasing part and decreasing one) are very similar.

This behavior can be also observed in Fig. 4, where we plot the number of modes K, obtained from autocorrelation, as a function of pump mean power for long (black dots) and short (magenta dots) crystals. Also in this case, we can notice that the evolution of K testifies the occurrence of pump depletion in the presence of a minimum value followed by a further increase. We have already explained in Ref. [8] that when the PDC process occurs at gain values leading to depletion, also the pump beam evolves in the nonlinear interaction and the dynamics of the system becomes more complex. In particular, the number of effectively populated signal and idler radiation modes depends on pump power. As the pump power increases, the PDC gain profile becomes narrower and narrower, and thus signal and idler fields are dominantly emitted into a smaller and smaller number of modes that gain energy to the detriment of the others.[10, 14] For sufficiently high values of the pump power, the process of mode selection reverts as the pump profile undergoes depletion. For this reason, the gain of the initially high-populated modes is on the one side reduced, whereas the gain of low-populated modes is on the other side supported.

Finally, we notice that also in this plot the pump mean power value at which the minimum appears is double in short crystal than in the long one. In principle, the most unexpected result is the absolute value of the minimum that is smaller for the short crystal than for the long one. This fact is at first sight counterintuitive since, as explained above, a shorter crystal is more tolerant to phase-matching. However, in the short crystal the depletion condition appears at higher pump power values and thus the number of modes is allowed to evolve more and especially decrease till the occurrence of such a depletion.

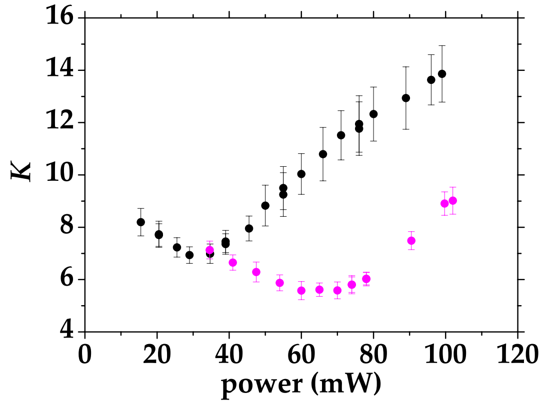

Figure 4. (Color online) Number of spatio-spectral modes K obtained by Eq. (2) for long (black symbols) and short (magenta symbols) crystals.

4. CONCLUSIONS

We have presented the experimental investigation of the spatial and spectral coherence properties of PDC light generated in two BBO crystals with different lengths. In both cases the evolution of the main quantities describing the field, such as the mean number of photons, the FWHM of autocorrelation and cross-correlation areas, and the number of modes, testify the occurrence of pump depletion at a certain pump mean power value. By comparing the behaviors of all these quantities in the two crystals, we can conclude that they are qualitatively the same, even if the absolute values are different, especially because the tolerance of phase-matching condition is sensitive to crystal length. For this reason, the evolution of the coherence properties in the short crystal is quite smooth, whereas it is sharper in the long crystal. At present we cannot give a quantitative explanation of the difference between the results obtained in the two crystals as it seems that the infinite plane-wave model is not sufficient to describe the complexity of the system under investigation and in particular it is unable to indicate which is the exact relation between the pump mean power and the length of the crystal. Numerical simulations should be considered to confirm the experimental observations.

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