Spectral coherence of twin beams by single-shot measurements with a fiber spectrometer

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ABSTRACT

We observed the spectral coherence structure of twin beam states generated by spontaneous parametric down-conversion by using a simple fiber spectrometer synchronized with a pulsed laser source. The recorded single-shot spectra exhibit a well-defined peak structure, where the peak wavelengths change values from shot to shot. We studied the number and the width of the peaks as a function of the different parameters in the experimental setup (pump power, iris size, iris distance from the BBO crystal). Moreover, we evaluated the number of modes in the intensity distribution of the light in different portions of the spectrum. The experimental results indicate that the number of modes from statistics and the number and width of the peaks evolve differently with the parameters.

Keywords: Parametric down conversion, coherence, spectral properties

1. INTRODUCTION

Spectral and spatial coherence properties of twin beam states (TWB) generated by spontaneous parametric down-conversion (PDC) can be measured in different intensity regimes from single-photon up to very high values of parametric gain with different kinds of detectors. Typical setups to investigate spectral properties involve spectrometers and either single-photon detectors[1] or CCD cameras[2–4] and fiber spectrometers in averaging mode.[5,6]

Recently,[3,4] we have explored the spatio-spectral coherence properties from the single-photon level up to pump depletion by means of an intensified CCD camera (iCCD) and an electron-multiplying CCD camera (EMCCD) coupled to an imaging spectrometer. We found that in the high intensity regime the size of the coherence areas evaluated from intensity autocorrelation evolve at increasing pump power and display a peculiar evolution in pump depletion conditions. The properties demonstrated with the cameras have been also confirmed by further measurements of autocorrelation performed with photon-number-resolving detectors (HPD).[7] Since our PDC source is able to produce high-intensity TWB at a repetition rate (500 Hz) that allows the registration of single-shot spectra, we decided to investigate the spectral properties of PDC with a commercial fiber spectrometer.

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The recorded single-shot spectra show a well defined peak structure whose properties can be connected and compared with those obtained from correlations. In this paper we show that the analysis of the PDC emission with a rather simple setup made of a fiber spectrometer is able to reveal the spectral properties of PDC.

2. EXPERIMENTAL SETUP

We consider TWB states generated by pumping a 8-mm-long ($\theta_{\text{cut}} = 37\,\text{deg}$) BBO crystal with the third-harmonics (349 nm) of a ps-pulsed mode-locked Nd:YLF laser amplified at 500 Hz (High-Q Laser) at different values of pump powers. The experimental setup is displayed in Fig. 1. A long-pass filter (cut-off at 400 nm) is located beyond the BBO crystal to select a portion of the PDC light.

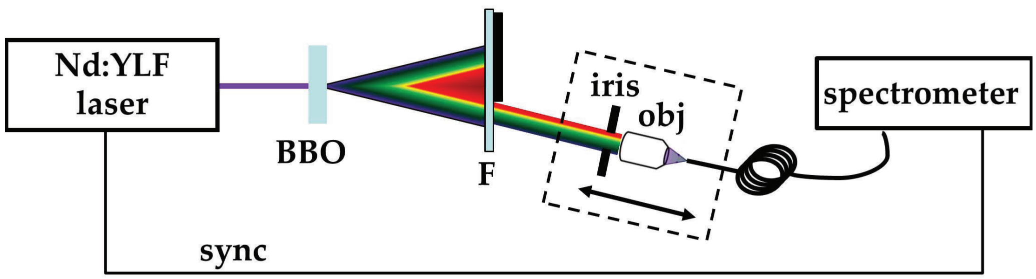

Figure 1. Sketch of the experimental setup. BBO: nonlinear crystal; F: cut-off at 400 nm; iris: variable aperture; obj: 10× microscope objective.

The measurements were performed by selecting a portion of the PDC light by a variable-size iris located at different distances from the BBO. The light was focused in a 300 μm-diameter fiber by using a 10× microscope objective and the fiber was connected to a spectrometer (AvaSpec-ULS2048L, Avantes, 0.6 nm resolution). Iris, microscope objective and fiber were mounted together on a rail to be moved along the propagation direction minimizing misalignment. In Fig. 2(a) we show the mean spectra (average over 1000 single shots of the laser) recorded by the spectrometer through a 4-mm-diameter iris at different distances from the BBO crystal. We can see that the collected spectra have fixed central wavelength at about 550 nm, while their shape and their intensity change slightly at various distances.

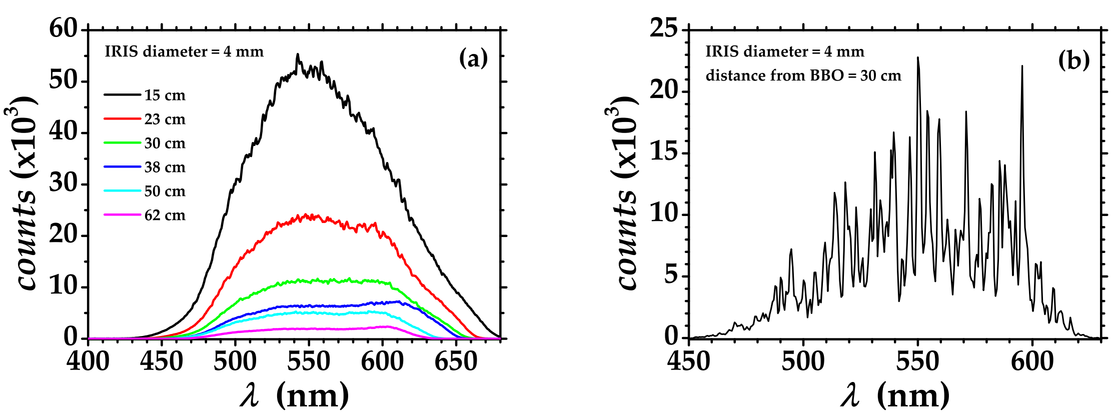

Figure 2. (a) Average spectra total intensity, expressed as counts of the spectrometer, recorded through a 4 mm wide iris at different distances from the BBO crystal (14-62 cm). (b) Typical single-shot signal spectrum recorded at 30 cm distance through a 4 mm wide iris.

The intensity of the down-converted light was high enough to allow the recording of single-shot spectra (see Fig. 2(b)). To this aim, the spectrometer was synchronized to the laser source and the exposure time was set to

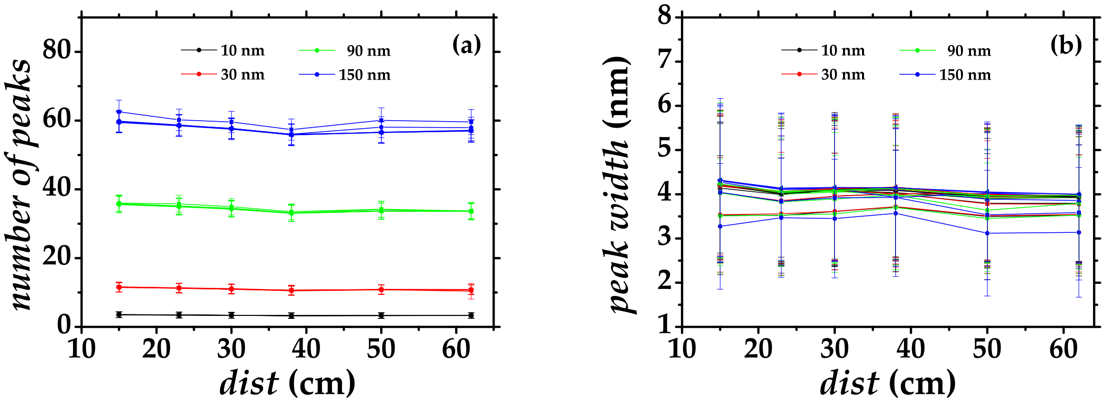

Figure 3. (a) Mean number of peaks as a function of the distance from BBO in the different wavelength intervals indicated in the figure through irises of different diameters: 1 mm (squares), 2 mm (circles), 3 mm (upward triangles), 4 mm (downward triangles), 5 mm (diamonds) and 6 mm (leftward triangles). (b) Mean widths of the peaks in the same conditions as in (a).

1.8 ms to prevent the registration of more than one pulse at a time. Single-shot spectra exhibit a well-defined peak structure, where the peak wavelengths change value from shot to shot but the overall number of peaks is rather constant. This can be interpreted as the existence of a coherence structure in the PDC output. We decided to investigate the distribution of the number of peaks measured in the single shots. Each spectrum was processed to find number, position, maximum value and width of the peaks in given wavelength intervals from 10 to 150 nm. In Fig. 3 we show the mean number of peaks (a) and the mean value of the width of the peaks (b) measured in the different wavelength intervals (indicated in the figure) through irises of different diameters (see symbols in Fig. 3) as a function of the distance from the crystal. As expected, the number of peaks depends proportionally on the width of the considered wavelength interval but their widths are quite independent of it.

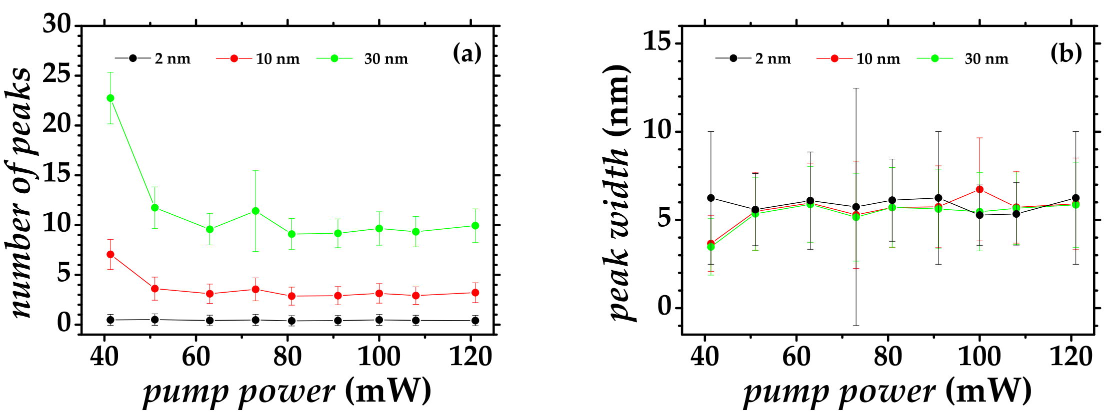

Figure 4. (a) Mean number of peaks in the different wavelength intervals indicated in the figure through a 0.5 mm wide iris as a function of pump power. (b) Mean widths of the peaks in the same conditions as in (a).

Moreover, both the number of peaks and their widths are rather constant with respect to the parameters describing the light collection (iris size and distance from BBO). This indicates that the spectral coherence structure of PDC is independent of propagation, at variance with spatial structure that evolves from near field to far field.[4,8,9] We note that the indetermination of the widths of the peaks is quite large due to the employed algorithm, which is based on the assumption of a gaussian shape for the peaks and on the estimation of the peak widths from the second derivative around the peak maximum.

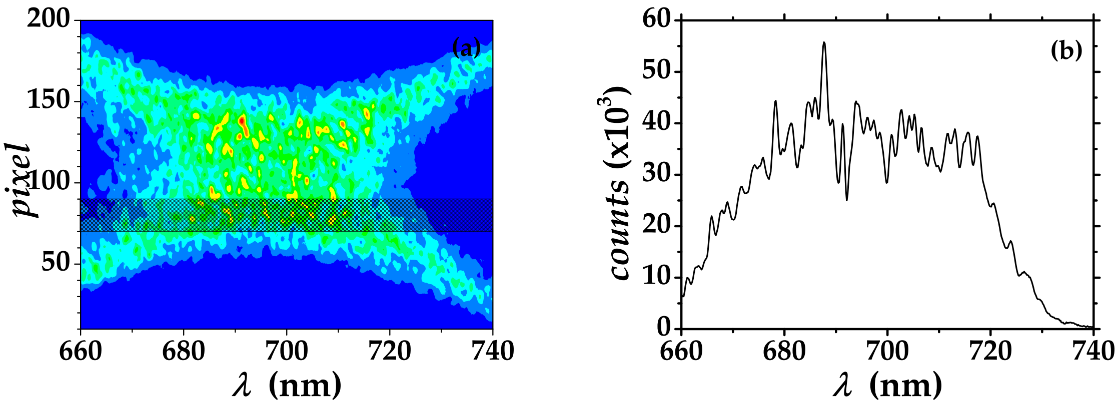

Figure 5. (a) Typical (θ, λ)-spectrum registered by an EMCCD camera at the output of an imaging spectrometer in far-field configuration. (b) Spectral profile obtained by integrating over 20 lines of the (θ, λ)-spectrum (see marked area in (a)).

We also studied the number and the widths of peaks as a function of pump power (see Fig. 4): The mean values of the number of peaks decreases at increasing power, while the peak widths seem to remain constant even with a quite large indetermination (see above).

Since the spectral resolution of the fiber spectrometer is limited to 0.6 nm and the indetermination of the peak widths is much larger, to confirm the obtained results we decided to compare the present measurements with others obtained with the system described in Ref. [4]. In the mentioned experiment, TWB states were generated in the same conditions as those adopted in the present paper, that is same crystal, pump and interaction parameters but the measurement apparatus was completely different. Synthetically, the experimental setup included a converging lens, producing the far field of the PDC light on the input slit of an imaging spectrometer, and an EMCCD camera registering the 1:1 image of the input light at the output of the spectrometer. The spectrometer gave wavelength dispersion in the horizontal direction. The typical output of this experimental setup is an image recording the so-called (θ, λ)-spectrum, in which the horizontal axis represents the wavelength and the vertical axis the angular position of the PDC light (see Fig. 5). The overall recorded spectrum was 80 nm wide and spectral resolution of the system was 0.16 nm.

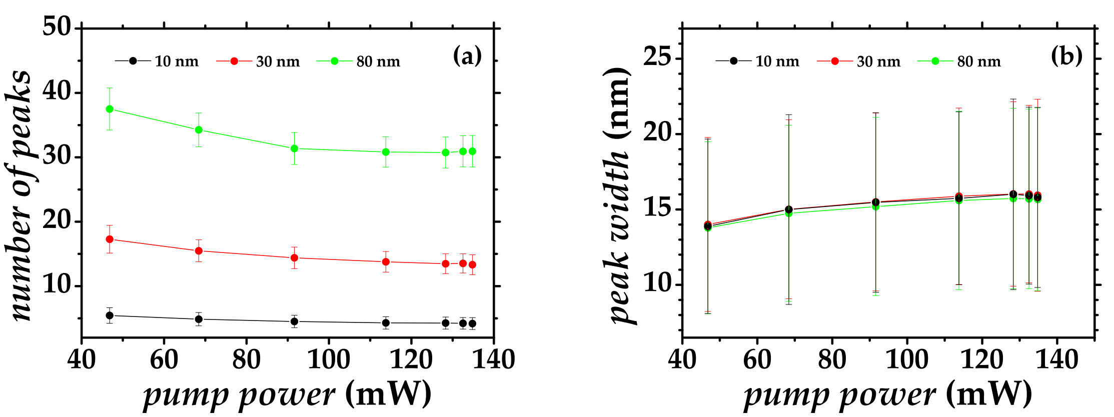

Figure 6. (a) Mean number of peaks as a function of pump power in the different wavelength intervals indicated in the figure evaluated from (θ, λ)-spectra. (b) Mean widths of the peaks in the same conditions as in (a).

To simulate the operation of the fiber spectrometer, we integrated the (θ, λ)-spectrum over 20 lines (see marked area in Fig. 5(a)), thus obtaining a spectral profile like the one shown in Fig. 5(b). By applying the same

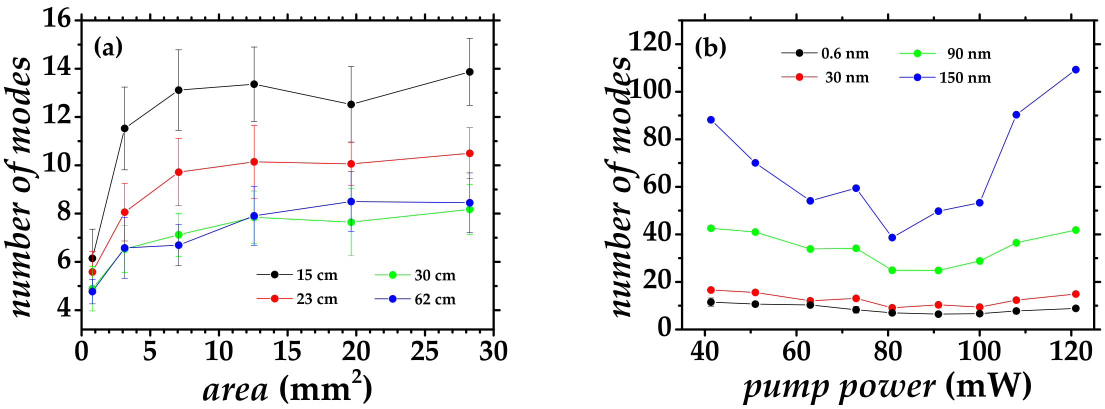

Figure 7. (a) Number of modes, evaluated from counts statistics in a number of single pixels (0.6 nm bandwidth) as a function of the area of the collecting iris for different distances from BBO. (b) Number of modes, evaluated from counts statistics in the wavelength intervals indicated in the figure, as a function of pump power through a 0.5-mm-wide iris located at 19 cm distance from BBO.

algorithm used for the other spectra to these data we obtained the behaviour of the number and widths of peaks as functions of pump power displayed in Fig. 6. The number of peaks shows the same behavior as in Fig. 4(a), while the widths of the peaks shows a more regular trend than in Fig. 4(b), due to the better resolution of this second experimental setup. The increase of the peak width as a function of pump power is consistent with the increase of the size of coherence area evaluated from intensity autocorrelation coefficient and already presented in Ref. [4].

Note that the data measured as a function of power were taken in different experimental conditions with respect to those taken as a function of the distance from BBO: for this reason, the absolute values of the data in panels (a) and (b) of Figs. 4 and 6 are not to be compared.

Finally, as a further characterization of the system we evaluated the number of modes in the intensity distribution of the light in different portions of the spectrum. This quantity is connected to the Schmidt-mode decomposition of the twin-beam states[4, 7, 10] and takes into account both the spectral and spatial structure of the field. In fact, experimental results indicate that the behavior of the number of modes evaluated from statistics evolve differently from the number and width of peaks. In particular, given a selection of a wavelength interval and at a fixed distance, the number of modes increases at increasing iris size till the iris size becomes larger than the entire downconverted cone (see Fig. 7(a)). This result is expected from the geometry of the PDC interaction and TWB propagation. Less obvious is the behavior of the number of modes as a function of pump power. In Fig. 7(b) we see that the number of modes decreases at increasing pump power down to a minimum value and then it increases again. This non-trivial behaviour is explained in terms of the evolution of Schmidt-mode structure of the PDC field. At increasing pump power, the modes corresponding to the peak of the pump gain more than the others, thus causing a reduction of the number of effective modes in the statistics and a progressive depletion of the pump. As soon as the depletion becomes important, the central modes stop gaining intensity and other modes become relevant, thus increasing again the overall number of effective modes in the statistics. We remind that we have already observed this effect in PDC with different kinds of detectors (EMCCD[4] and HPDs[7]).

3. CONCLUSIONS

We have demonstrated that the spectral coherence structure of TWB generated by PDC can be investigated by using a simple fiber spectrometer, provided the TWB intensity is high enough to allow single-shot registration of the spectra. The measured single-shot spectra display a well defined peak-structure that we can interpret as the emergence of the spectral coherence in TWB, which depends on pump spectrum, phase-matching conditions and pump power. The presented results are consistent with those obtained by using more complex experimental apparatuses, such as imaging spectrometers connected with EMCCD cameras.

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