Observation of Image Transfer and Phase Conjugation in Stimulated Down-Conversion

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We observe experimentally the transfer of angular spectrum and image formation in the process of stimulated parametric down-conversion. Images and interference patterns can be transferred from either the pump or the auxiliary laser beams to the stimulated down-converted one. The stimulated field propagates as the complex conjugate of the auxiliary laser. The phase conjugation is observed through intensity pattern measurements.

The cavity-free stimulated down-conversion is a three-wave mixing (TWM) process. TWM has been viewed as a nonlinear optical process, with promising applications for correcting wave front distortions. However, when this process was described by a quantum theory [1], new possibilities were opened. The importance of the quantum approach is closely related to the great success of the spontaneous parametric down-conversion in quantum optics [2] and the connection between the stimulated and the spontaneous processes. The quantum properties of the stimulated down-conversion light has not yet been the subject of intense investigation. It was experimentally observed and studied by Mandel and co-workers [3]. Special attention was given to its coherence properties, presenting characteristics of thermal and coherent states [1,3,4], but its individual quantum state was never put forward.

In this Letter, we study experimentally the transfer of angular spectrum and image formation in the stimulated down-conversion, as predicted in Ref. [5]. It was also predicted that the stimulated field propagates as the complex conjugate of one of the input fields. The understanding of the angular spectrum transfer has allowed the observation of the phase conjugation by direct intensity measurements. Our results have a classical counterpart (except for the spontaneous emission part) in the framework of the TWM, but they support the quantum theory of Ref. [5]. The relation between the angular spectrum of the pump, auxiliary (signal), and stimulated (idler) beams has not been demonstrated thus far, to the best of our knowledge. These relations are important because they will help us to separate the spontaneous from the stimulated emission contributions in the total idler field which will help us understand phase conjugation at the quantum level [6].

A laser pumps a nonlinear crystal, producing twin photon pairs. Another laser is aligned with one of the down-converted modes so that they overlap. The second laser, which we will refer to as the auxiliary laser, will stimulate the emission in those modes that best overlap, enhancing their intensities. As a result the conjugate twin beam, which will be called the stimulated beam, has its intensity enhanced and its spectral characteristics changed in the way it was discussed theoretically in Ref. [5]. The stimulated beam is generated from the superposition of the pump and auxiliary beams, under the restrictions imposed by the phase matching on a particular nonlinear medium. Its field depends on the product of the pump and auxiliary laser fields. Its angular spectrum is given by the convolution between the angular spectrum of the pump and the auxiliary lasers.

According to Ref. [5], the intensity distribution of the stimulated (idler) beam is given by

$$I(\boldsymbol{r}_i) \propto \left\{ \int d\rho \, |\mathcal{W}_p(\boldsymbol{\rho})|^2 + \left| \int d\rho \, \mathcal{W}_p(\rho) \mathcal{W}_s^{\star}(\rho) \exp\left[i|\rho_i - \rho|^2 \frac{k_i}{2z} \right] \right|^2 \right\}, \tag{1}$$

where $\boldsymbol{r}_i = (\boldsymbol{\rho}_i, z)$ is the position in the plane transverse to the idler beam propagation at a distance z from the crystal. $\mathcal{W}_p$ and $\mathcal{W}_s$ are, respectively, the pump and auxiliary lasers' transverse field distributions at the crystal, and k_i is the idler wave number.

In our experiment, the spontaneous emission is much smaller than the stimulated emission so that the first term in Eq. (1) can be neglected. We will analyze two particular situations. In the first situation, the auxiliary laser amplitude distribution at the crystal can be considered constant. Therefore, the resulting idler intensity is given by

$$I(\boldsymbol{r}_i) \propto \left| \int d\boldsymbol{\rho} \, \mathcal{W}_p(\boldsymbol{\rho}) \exp\left[i|\boldsymbol{\rho}_i - \boldsymbol{\rho}|^2 \frac{k_i}{2z} \right] \right|^2. \tag{2}$$

This intensity distribution is the same as the pump's after it has propagated to a plane situated at a distance z from the crystal. The only difference is that the propagation goes with the idler wave vector.

In the second situation, the pump beam amplitude distribution at the crystal can be approximated by a constant. In this case, the idler intensity is given by

$$I(\mathbf{r}_i) \propto \left| \int d\boldsymbol{\rho}\, \mathcal{W}_s^\star(\boldsymbol{\rho}) \exp\left[i|\boldsymbol{\rho}_i - \boldsymbol{\rho}|^2 \frac{k_i}{2z} \right] \right|^2. \quad (3)$$

In analogy to the previous case, the intensity distribution of the idler should follow the auxiliary laser distribution after propagation to a plane situated at a distance z from the crystal. However, now it depends on the complex conjugate of the auxiliary laser field amplitude at the crystal. The above equations were derived within the Fresnel approximation. In this regime, the phase conjugation does not affect the transferred image in a simple way and it resembles that on the auxiliary laser. However, if the Fraunhofer limit can be taken, the image will be inversed, as we shall see. In the Fraunhofer limit the phases can be written as

$$\exp\left[i|\boldsymbol{\rho}_i - \boldsymbol{\rho}|^2 \frac{k_i}{2z} \right] \rightarrow \exp\left(i\boldsymbol{\rho}_i \cdot \boldsymbol{\rho} \frac{k_i}{z} \right), \quad (4)$$

and Eq. (3) turns into

$$I(\mathbf{r}_i) \propto \left| \int d\boldsymbol{\rho}\, \mathcal{W}_s^\star(\boldsymbol{\rho}) \exp\left(i\boldsymbol{\rho}_i \cdot \boldsymbol{\rho} \frac{k_i}{z} \right) \right|^2. \quad (5)$$

Taking the complex conjugate of the argument of the square modulus, the result remains unchanged:

$$I(\mathbf{r}_i) \propto \left| \int d\boldsymbol{\rho}\, \mathcal{W}_s(\boldsymbol{\rho}) \exp\left(-i\boldsymbol{\rho}_i \cdot \boldsymbol{\rho} \frac{k_i}{z} \right) \right|^2. \quad (6)$$

It is easy to see that the intensity profile of the idler beam will have the same shape as the auxiliary laser beam, but with $\boldsymbol{\rho}_i$ replaced by $-\boldsymbol{\rho}_i$. That is to say, the image on the idler beam is inverted with respect to that on the auxiliary laser beam.

A sketch of the experimental setup is shown in Fig. 1. The vertically polarized He-Cd laser pumps a BBO (β-barium borate) crystal. Spontaneous parametric down-conversion takes place and twin photons converted from the pumping wavelength 442 nm, to the signal 845 nm, and idler 925 nm are produced. Because of the type-II phase matching, the signal beam is vertically polarized and the idler is horizontally polarized. We utilize photon counting modules (EG&G-SPCM-AQ151) for detecting signal and idler photons in coincidence. In the signal side of the detection, a 10 nm bandwidth interference filter centered at 845 nm is utilized, while in the idler side the bandwidth is 50 nm centered at 920 nm. This is the first step for obtaining stimulated down-conversion.
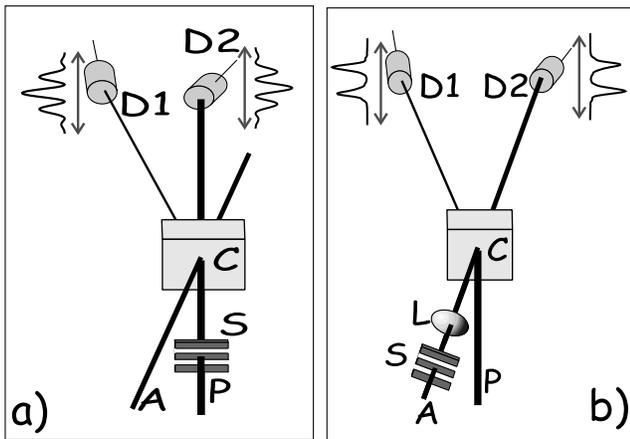
The second step is to carefully align an auxiliary diode laser with the 845 nm signal beam. The diode laser wavelength can be tuned from 840 to about 850 nm, by temperature and current control. When the alignment is good enough, the intensity of the idler is immediately multiplied by a large factor, indicating the amplification of the emission in this particular mode. The factor of amplification is determined by the coupling between the auxiliary and signal down-conversion modes. In our setup it was about 300.

The experiment consists of placing masks on the pump (or auxiliary) beam before the crystal and observing the relationship between pump (or auxiliary) and idler intensity distributions on a plane situated at the same distance from the crystal for both beams. First, a double slit is placed on the pump beam, about 15 cm before the crystal, so that its spectrum carries the information of the passage through the slits during the nonlinear interaction; see Fig. 1(a). After the crystal, the double-slit interference pattern is formed on the pump beam. We measured this pattern on a plane situated about 80 cm from the crystal. This is shown in Fig. 2A. According to Eq. (2), if the field amplitude of the auxiliary laser beam can be approximated by a constant, the interference pattern of the pump beam is transferred to the stimulated idler beam. Note that, while the shape of

FIG. 1. Sketch of the experiment. P is the pump beam, A is the auxiliary beam, S is the double slit, L is the lens, C is the nonlinear crystal, and D1 and D2 are detectors. (a) Slits inserted in the pump beam. (b) Slits and lens inserted in the auxiliary beam.
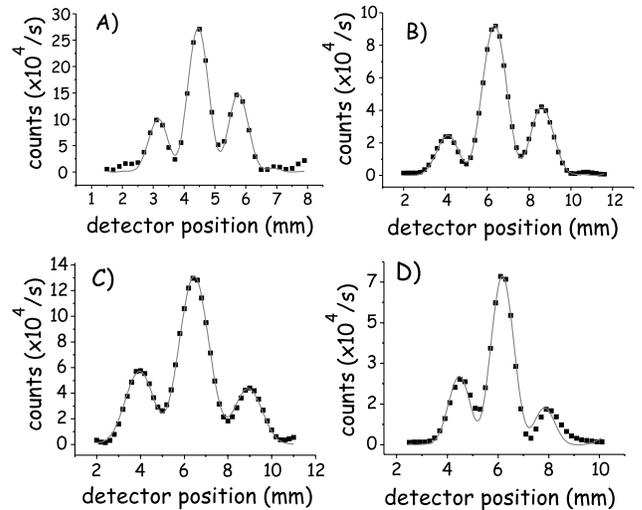
FIG. 2. Vertical intensity profile for (A) pump beam with a double slit inserted 15 cm before the crystal and (B) stimulated idler beam. (C) Auxiliary beam with a double slit inserted 15 cm before the crystal and (D) stimulated idler beam. The solid lines are fits to typical double-slit pattern functions.

the intensity distribution of the idler should *perfectly* (in the ideal case) follow that of the pump, the propagation of the field from the crystal to detection depends on the idler wavelength. As a result, the pattern is about 2 times larger than that of the pump. We also measured it on a plane placed about 80 cm from the crystal. It is shown in Fig. 2B.

In a second set of measurements, we placed the double slit in the path of the auxiliary laser 15 cm before the crystal. The pattern formed on the auxiliary beam, 80 cm after the crystal, is shown in Fig. 2C. Once again, the intensity pattern is transferred to the stimulated idler beam, according to Eq. (3), for a constant pump field amplitude distribution. The measured pattern for the idler beam on a plane 80 cm from the crystal is shown in Fig. 2D. The pattern follows that of the auxiliary beam without inversion of the image, because this is the Fresnel diffraction. These results show that the angular spectrum from the pump and auxiliary lasers is transferred to the stimulated down-conversion. Note that, as the double slit is small (about 0.4 mm width and separated by 0.2 mm) and is placed 15 cm before the crystal, the field inside the crystal is not an image of the slits with two bright spots which illuminate the crystal during the interaction, but is rather a more complicated spatial distribution.

If the angular spectrum is transferred from the pump and auxiliary lasers to the stimulated idler beam, images rather than interference patterns observed on the intensity profile of those laser beams should also be transferred to the stimulated beam. In order to test it, we have projected the double-slit image on the detection plane, when it was inserted in both the pump and the auxiliary beams.
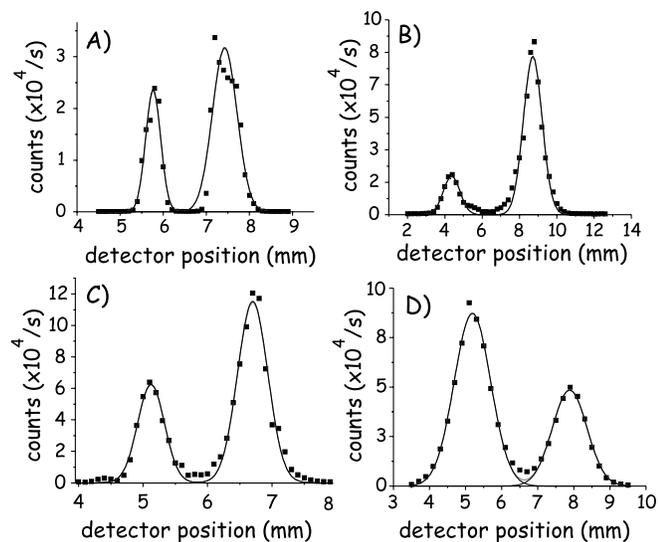
FIG. 3. Vertical intensity profile for (A) pump beam when a double-slit image is focused in the detection plane 80 cm after the crystal and (B) stimulated idler beam. (C) Auxiliary beam when a double-slit image is focused in the detection plane 80 cm after the crystal and (D) stimulated idler beam. The solid lines are guides for the eye.

Figure 1(b) shows the case where the slits and the lens were inserted in the auxiliary beam. This is the simplest one-dimensional image we could utilize. The double slits are now larger than before. For the image pattern we utilized slits of about 1 mm width separated 1 mm from each other. The pump intensity distribution in the vertical direction at the image plane is shown in Fig. 3A, when the slits and the lens are inserted in the pump beam. In Fig. 3B the transferred image can be observed at the idler stimulated intensity profile. As before, the image formed on the idler beam is larger than that on the pump beam because of the influence of the wavelength on the propagation. The intensity peaks were made asymmetric so that we can see how the image is transferred from the pump and auxiliary lasers to the idler beam.

The same procedure was repeated placing the slits on the auxiliary beam and obtaining its image after the crystal, through focalization by a lens. Its intensity distribution is shown in Fig. 3C. However, the image transferred to the idler stimulated beam does not exactly repeat the profile of the auxiliary beam. Since the intensity of the peaks is different in Fig. 3C, it is possible to see that the transferred image is inverted in Fig. 3D. This is a consequence of the phase conjugation, as predicted by Eq. (6). Now, the focalization of the auxiliary beam inside the crystal has taken us to the Fraunhofer limit because its larger dimension ($\rho_{max} \sim 0.1$ mm) is much smaller than the distance between the crystal and the detection plane ($z \sim 1$ m) $\rho_{max}^2 \ll \lambda z$, with $\lambda \sim 10^{-6}$ m. Another consequence of the phase conjugation is that the propagation of the idler goes as the time reversal propagation of the auxiliary laser. While the auxiliary laser converges after the crystal, the idler diverges yielding a pattern about 2 times larger than that of the auxiliary laser.

We performed other measurements, supporting the predictions of Eq. (6). A sharp blade was placed on the auxiliary beam before the crystal, so that about half of the beam was covered by the blade. Using a lens, the image of the half beam was projected onto the detection plane, placed 80 cm from the crystal. The intensity distributions of the auxiliary and idler beams were measured with and without the presence of the blade. This is shown in Figs. 4A and 4B for the auxiliary and idler beams, respectively. The effect of the phase conjugation is then confirmed by the displacement of the intensity peaks in opposite senses. In other words, the dark half of the beam, due to the presence of the blade, appeared on opposite sides of the image formed on the auxiliary beam and the transferred image formed by the conjugate field on the idler beam.

The results presented above can be understood in terms of Eq. (1). The equation shows that the intensity profile of the idler stimulated down-conversion is given by the product of the pump and auxiliary lasers' amplitude distributions at the crystal, propagated by a Fresnel propagator to the observation plane after the crystal. The propagation is performed through the idler wave vector as it should be,
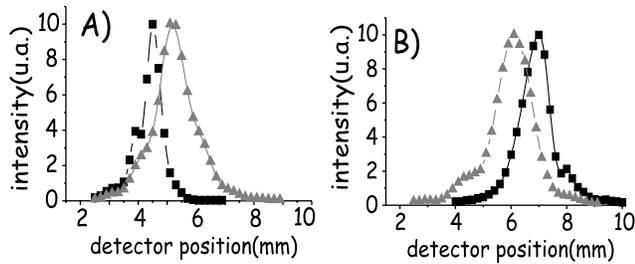
FIG. 4. Vertical intensity profile for (A) auxiliary beam with (squares) and without (triangles) an inserted blade before the crystal and (B) the stimulated idler beam with (squares) and without (triangles) the blade in the auxiliary. The solid lines are guides for the eye.

but when the pump (auxiliary) field amplitude at the crystal is constant the transverse intensity distribution of the idler will follow that of the auxiliary (pump) after propagation to the same observation plane.

We would like to emphasize two points. First, the idler intensity depends on the complex conjugate of the auxiliary field. Even though the dependence comes on the intensity, so that the square modulus of the auxiliary field is calculated, the phase conjugation has observable effects in the idler intensity. This is because the conjugation changes the propagation of the field. In the above-reported case, it has been responsible for the inversion of the idler image compared to the auxiliary laser image, as predicted by Eq. (6). However, this equation is valid only in the Fraunhofer limit, far enough from the source (crystal). In the Fresnel limit the image is not inverted because the propagation depends on $\exp(i|\boldsymbol{\rho}_i - \boldsymbol{\rho}|^2 \frac{k_i}{2z})$.

The second point is that the theoretical treatment adopted is fully quantum mechanical. We are not exploring the quantum aspects of the process in this Letter, but the process can be used to study the quantum aspects of the image formation and phase conjugation in the stimulated parametric down-conversion. In this case weaker auxiliary beams and correlation detection schemes should probably be used.

In conclusion, we have observed experimentally the transfer of the angular spectrum from the pump and auxiliary lasers to the idler beam in the process of cavity-free stimulated down-conversion. The transfer of the angular spectrum is observed through the transfer of images and interference patterns. The experimental results are in agreement with the theoretical predictions of Ref. [5].

We also demonstrated experimentally that the idler field propagates as the complex conjugate of the auxiliary laser field, even though they are completely different modes with different wavelengths and polarizations. The demonstrated properties can lead to applications where images coded by a random medium (key) may be transferred from the auxiliary beam to the idler. The decoding may be achieved by propagation of the idler through the key, for example. They have also been shown to be useful for studying the process of phase conjugation at the quantum level.

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