Observation of Pattern Formation in Optical Parametric Oscillators

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We have observed transverse pattern formation in a near-confocal, type II, triply resonant optical parametric oscillator (OPO) operating close to frequency degeneracy for the signal and idler modes. In the region of observation of these patterns, the OPO oscillation threshold increases. Complex ring patterns and latticelike structures are observed. These patterns are due to the nonlinear coupling of many transverse modes (on the order of 25). The transverse distribution of the light is different in the signal, idler, and transmitted pump modes.

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The phenomenon of spontaneous pattern formation in optical systems [1] has been the object of intense studies in the last 20 years, by both theoreticians and experimentalists, in relation to similar phenomena that can be observed in other parts of physics, such as hydrodynamics or chemistry [2]. So far, these studies have concentrated mostly on optical systems having third-order nonlinearities, like Kerr media, liquid crystals, photorefractive crystals, atomic vapors, or laser media [1], and to the case where the nonlinearity concerned a monochromatic, or nearly monochromatic, electromagnetic field. Stripes, rings, hexagons, or even more complicated patterns have been predicted and observed in these systems.

Second-order nonlinear effects, such as parametric down-conversion or frequency doubling, have been studied in this respect only recently. They provide at the same time a very simple nonlinear mechanism and a rich variety of possible phenomena allowed by the coupling between electromagnetic waves of different frequencies. On the theoretical side, various transverse instabilities have been predicted, especially in the case of optical parametric oscillators (OPOs), in the degenerate or nondegenerate configuration [3–10]. On the experimental side, patterns have been observed in parametric amplifiers [11,12], but, to the best of our knowledge, no experiment has been so far reported concerning patterns in OPOs, except [13], which describes a photorefractive oscillator mimicking in some respect a true parametric oscillator. We present here what we believe to be the first experimental observation of spontaneous pattern formation in a $\chi^{(2)}$ medium, more precisely in a cw nearly confocal, nondegenerate OPO.

The experimental setup, sketched in Fig. 1, is the following: a high power cw Nd:YAG ring cavity laser, injected by a single mode ultrastable monolithic Nd:YAG laser and stabilized by means of HF-sideband modulation technique, produces 3.6 W of 1064 nm light, which is used for second harmonic generation in a linear semimonolithic cavity containing a $LiNbO_3$ crystal, stabilized with the same RF-sideband modulation. One gets 1.8 W of green light at 532 nm of high spectral purity and stability which is used to pump a triply resonant OPO. The pump beam has a waist radius close to 100 μm inside the OPO, which consists of a temperature-stabilized KTP crystal inserted in a linear optical cavity of great mechanical stability. Ordinary and extraordinary polarization optical fields, respectively called signal and idler modes, are generated through the $\chi^{(2)}$ parametric interaction with the pump beam, polarized on the extraordinary direction. In order to minimize the walk-off effects between the signal, pump, and idler beams which would complicate the analysis of transverse effects in the system, the crystal is walk-off compensated: it consists of two optically contacted KTP crystals disposed in such a way that they give rise to opposite walk-off angles [14]. This ensures that the walk-off is compensated outside the crystal, but not inside. The crystal has a total length of 10 mm and has a 5 mm wide square aperture. It is inserted between two mirrors having a radius of 5 cm, and its center is located 19 mm after the first mirror, M_1, which has reflection coefficients of 0.900 at 532 nm and 0.999 at 1064 nm. The second mirror, M_2, has reflection coefficients of 0.990 at 1064 nm and 0.999 at 532 nm. As the bandwidth of the reflection coating for signal/idler is 2 nm, the OPO always operates in a near frequency degeneracy configuration.

The cavity is operated close to its confocal position. Its length can be changed by a few millimeters around the confocal geometry by means of a translation plate on which M_2 is mounted. This change will be called "coarse length change" in the following. It can also be changed by a few micrometers by means of a piezo translator in order

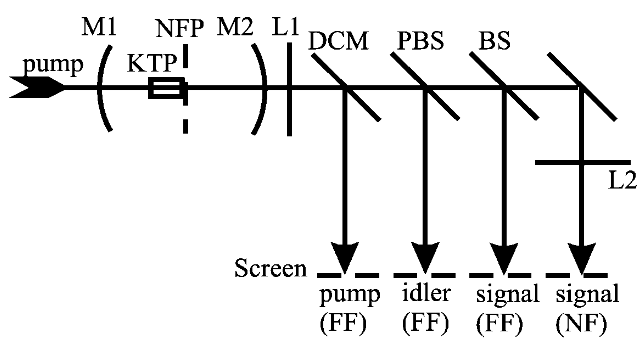

FIG. 1. Sketch of the experimental setup.

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to reach the exact resonance positions for the different modes. The latter change will be called "fine tuning" throughout this Letter. The cavity fine tuning either can be scanned at low frequency (up to a few 10 Hz) over one free spectral range or can be maintained on a given resonance for a few seconds.

As seen in Fig. 1, the pump beam transmitted through the OPO is separated from the signal/idler with a dichroic mirror (labeled DCM). The signal and idler beams are separated from each other by means of a polarizing beam splitter (PBS). The output surface of the crystal, defined as the near field plane (NFP), is imaged by two lenses L1 and L2 on an observation screen. The transverse intensity distributions of the signal, pump, and idler far field (FF), and of the signal near field (NF), separated by the beam splitter BS, are simultaneously recorded on the screen by means of a CCD camera.

The transverse characteristics of the cavity are determined by using a probe beam at 1064 nm and measuring its transmission as a function of the cavity fine tuning. A beam at 532 nm on the ordinary polarization can also be injected in the cavity at the same time to evaluate the thermal effects arising from the light absorption inside the crystal. Without green light, the OPO is close to confocality for a length labeled $+1.25$ mm in Fig. 2. When the 532 nm beam is injected, the crystal is slightly heated, which creates a lensing effect modifying the transverse characteristics of the cavity. For example, with a pump power of 300 mW, the OPO is "confocal" at a length labeled 0 in Fig. 2. Furthermore, the cavity can be shown to be unstable for lengths slightly smaller than the cold-cavity confocal configuration. This instability range shifts to smaller cavity lengths when the intracavity green power increases.

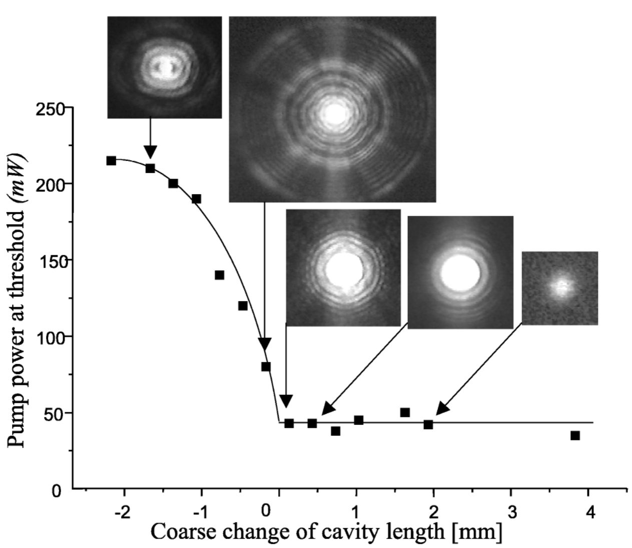

FIG. 2. Pump power threshold as a function of cavity length close to the confocal position, and corresponding signal near field distribution close to threshold.

Our first observation is that, close to the confocal configuration, the cavity length has a very strong influence on the OPO oscillation threshold. Figure 2 shows the pump threshold for OPO oscillation as a function of the coarse length change of the resonator, while the fine tuning is optimized to reach the exact cavity resonance conditions. For positive length changes, the OPO threshold is on the order of 40 mW. For negative length changes, the threshold increases up to 220 mW. Such an increase seems to be due to the great difficulty of a precise alignment of the cavity when it is very close to an unstable region. The different pictures inserted in Fig. 2 show the NF transverse distribution of the signal field for the corresponding cavity lengths, always at exact cavity resonance. One can observe transverse intensity distributions which change quickly with the coarse length change around the confocal position: for positive length changes, and for pump powers ranging between 40 mW and 1 W, the signal field is emitted in a configuration close to the TEM_{00} mode. For negative cavity length changes, where the threshold is much higher, the signal NF always exhibits a ring structure which is qualitatively insensitive to the power of the pump and is very robust with the fine tuning of the cavity. Such an asymmetry of effects with respect to the zero coarse length change is not predicted by the usual model of the OPO [13,15,16]. It might be related to the Kerr-like nonlinearity present in our system because of the light absorption in the crystal. This aspect will be studied in more details in a forthcoming publication.

Figure 3 simultaneously gives the NF and FF configurations of the structure observed on the signal field with a length change of -0.25 mm and a pump power of 300 mW. The NF (Fig. 3a) consists of a saturated center surrounded by wide concentric rings (marked by spots) and thin fringes, looking like high order Laguerre-Gauss modes, extending between the center and the boundaries.

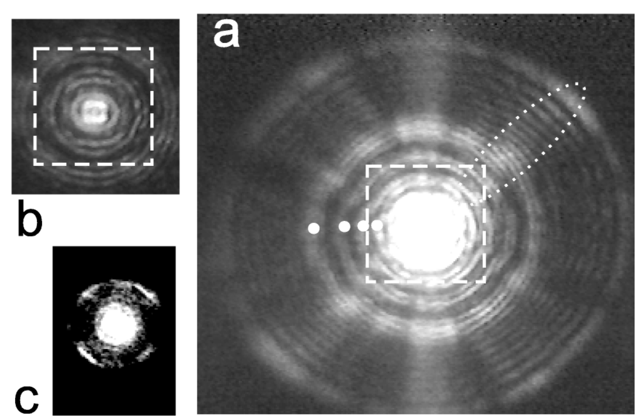

FIG. 3. Transverse structure observed in the signal field: (a) near field with a saturated center, wide rings, and thin fringes (see, for example, inside the dotted ellipse); (b) detail of the central part of the near field (the intensity is reduced by a grey filter); and (c) far field configuration with a saturated center and a bright ring.

When one desaturates the center by using a grey filter (Fig. 3b), one can observe thin rings and a narrow bright spot in the center, much smaller than the TEM_{00} cavity fundamental mode. The FF (Fig. 3c) presents a saturated center inside a bright ring. One can easily check that the FF pattern is, indeed, the Fourier transform of this NF pattern. The existence of qualitative differences between NF and FF, and of very small features in the center, is a strong indication that the signal is a superposition of many transverse modes. As up to 25 concentric rings can be counted in the near field pattern, we tried to simulate the signal transverse distribution as a superposition of 25 transverse Gauss-Laguerre modes $TEM_{0,0}$, $TEM_{1,0}, \ldots, TEM_{24,0}$. We obtained an intensity distribution in good agreement with the experimental results. We are then led to the conclusion that in our experimental configuration and for negative length changes, the OPO oscillates on a coherent superposition of roughly 25 transverse modes. Note that the rings that we observe here are quite reminiscent of the periodic structures predicted for the degenerate OPO [15,16] with a transversely homogeneous broad pump beam.

In order to analyze the longitudinal modes of the OPO, we sent the signal beam in an external confocal Fabry-Pérot cavity. Within its 15 MHz resolution, only one longitudinal mode has been identified in most configurations. In some particular cases, two competing longitudinal modes could be observed. This implies that when the OPO operates in a multitransverse mode configuration, it operates at the same time, at least in most cases, in a single longitudinal mode.

When the signal beam intensity is reduced by a grey filter in order to go below the saturation level of the CCD camera, in the case of a negative coarse change of length and with 360 mW of pump power, we have also observed in the center of the signal FF optical patterns of small size. They can be simple rings, like in Fig. 4, or more complex structures, like in Fig. 5. One observes on this latter figure unexpected latticelike structures, changing with the cavity coarse length change, while the fine tuning is kept on exact resonance (Figs. 5a and 5b), which turn out not to change much when the pump power is increased. We have also observed that the distance between the bright spots increases with decreasing coarse cavity length change. Another remarkable feature of these patterns is that an inversion of intensity maxima and minima takes place (Figs. 5c and 5d) when the fine tuning of the cavity is slightly modified around the exact resonance.

Figure 4 shows another remarkable feature: the signal, idler, and transmitted pump beams have completely different transverse structures. The pump beam remains in a configuration close to a TEM_{00} mode, whereas the signal and idler beams exhibit different complex patterns. This is a strong indication that the transverse structures of signal and idler modes are really caused by the nonlinear interaction, and not by the spatial distribution of the pump beam nor by the aperture of the resonator. As for the difference between the signal and idler mode transverse profiles and their anisotropy, it is certainly due to the birefringence of the KTP crystal [10,17].

In order to determine the influence of the pump beam size on the patterns, we continuously changed its waist radius from 60 μm (size of confocal cavity TEM_{00}

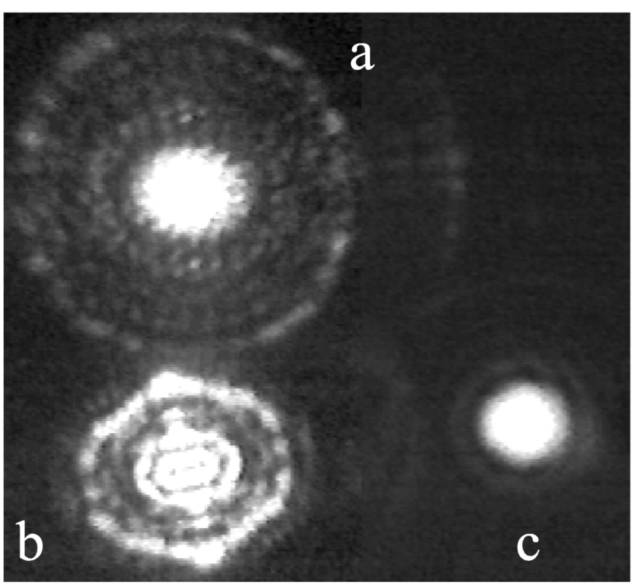

FIG. 4. Intensity distribution in the far field of the idler (a), signal (b), and transmitted pump (c) beams, simultaneously recorded for a pump power of 360 mW and a coarse length change of −0.5 mm.

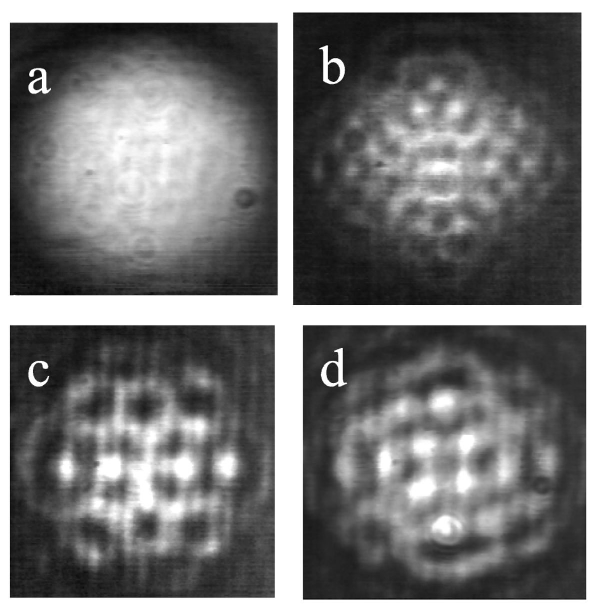

FIG. 5. Center of the signal intensity distribution in the far field for a pump power of 360 mW and a coarse length change of (a) −0.5 mm; (b) −0.4 mm; (c) and (d): −1 mm. (c) and (d) correspond to different fine tunings of the cavity.

eigenmode) to 100 μm. The complex signal and idler structures were observed only when the pump mode was wider than the TEM_{00} mode, and, when present, the patterns did not vary qualitatively with the pump size.

In conclusion, we have reported in this Letter the first observation of optical structure formation in a triply resonant optical parametric oscillator, observed only with negative coarse length changes with respect to the cold-cavity confocal configuration. Let us finally mention that an OPO operating in a highly multitransverse mode configuration is a good candidate to generate light fields with a nontrivial transverse distribution of quantum fluctuations, labeled as "quantum images" [18], and which can be useful to increase the transverse resolution in optical images [19].

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