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Cooperative oscillation of non-degenerate transverse modes in an optical system: multimode operation in parametric oscillators

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We show experimentally that transverse multimode oscillations are ubiquitous in a triply resonant optical parametric oscillator, in agreement with the theoretical prediction by Amon et al. [Phys. Rev. A **68**, 023801 (2003)] that parametric interaction can induce a cooperative oscillation of non simultaneously resonant transverse modes.

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Sources of coherent radiation such as lasers or optical parametric oscillators (OPOs) are based on a nonlinear gain medium enclosed inside an optical cavity, whose purpose is to recycle the generated radiation into the gain medium. The cavity imposes longitudinal and transverse boundary conditions on the radiation field and forces it into a superposition of a discrete set of modes, each associated with an oscillation frequency [1, 2]. An important question is whether an optical oscillator can operate simultaneously on several modes or not. This strongly depends on how different modes compete for gain. When mode competition is weakened by effects such as spatial, spectral or polarization hole-burning, as is often the case in lasers [1, 2, 3], intermode coupling is reduced and multimode operation is common. When instead modes strongly compete for gain, the lowest-threshold mode prevents the onset of other modes (as, e.g., in some homogeneously broadened lasers [1, 2] or optical parametric oscillators [4, 5]) and single-mode operation is the rule (“winner-takes-all” dynamics).

In the latter case, it is generally believed that multimode operation can only be observed when several modes have coincident resonance frequencies [5, 6, 7, 8]. Such coincidences occur in *degenerate cavities* where different combinations of longitudinal and transverse mode indices result in the same oscillation frequency. Except in a few specific configurations including highly degenerate cavities such as the plane-parallel, confocal and concentric two-mirror configurations [1], mode coincidence is generally difficult to achieve and thus multimode operation is generally considered to be accidental and uncommon.

However, this view assumes a kind of superposition principle, namely that modes must oscillate individually before they can interact. In this Letter, we show that even in a “winner-takes-all” system, the nonlinearity of the gain medium can induce simultaneous oscillation of transverse modes with well separated resonance frequencies. More precisely, we experimentally study multimode operation in a continuous-wave triply resonant optical

parametric oscillator (TROPO), where optical amplification relies on three-wave mixing [4]. In this system, intracavity pump power remains clamped at its value at the lowest mode threshold so that this system is generally considered as a single-mode device [4, 5], except in degenerate configurations [6, 7, 8].

Our experiments are motivated by a recent theoretical analysis of a multimode TROPO model, which shows that the quadratic nonlinearity can induce cooperative oscillation of modes with non-overlapping resonance curves even though individual modes are below their monomode threshold [9]. We provide experimental evidence of mode coexistence between two monomode resonances, and we find that contrary to what the mode coincidence principle predicts, multimode operation is common in our TROPO. It is observed in many different geometries, including far from transverse degeneracy, and with dynamical frequencies that can be much higher than cavity resonance bandwidth. As is suggested by recent Faraday experiments in hydrodynamics [10], this effect may more generally occur in systems which combine a strong nonlinear interaction with tight boundary conditions.

In spite of its simplicity, the TROPO has a rich dynamics which is still only partially understood. On the theoretical side, it has been predicted that the monomode TROPO displays a Hopf bifurcation eventually leading to deterministic chaos through a period-doubling cascade [11]. On the experimental side, fast periodic instabilities at frequencies in the range 1–300 MHz have been observed in TROPOs [12, 13]. They occur alone or combined with slow thermo-optic instabilities [14, 15], giving then rise to bursting oscillations [9], and can follow a transition to deterministic chaos [16]. These fast oscillations are not compatible with the monomode instability: they are observed at much weaker pumps and smaller signal frequency detunings than predicted by the monomode model [17], and with dynamical frequencies smaller than the Hopf frequency [13]. As shown below,

these fast oscillations result from the interaction of transverse modes, as previously conjectured [13] on the basis of numerical simulations of a bimode model [6]. This allows us to check whether multimode oscillations are as common as predicted in Ref. [9], even though this theoretical study assumed for simplicity identical signal and idler fields, which is not the case in our system.

More precisely, it was shown in [9] that in a degenerate two-mode TROPO model, two transverse modes with disjoint resonance curves can nevertheless interact when their resonance frequencies approximately add up to the pump frequency. Conversion of a pump photon into two photons in the same mode is then strongly repressed, leaving the cross-conversion channel (one photon in each of the two modes) as the dominant process. Roughly speaking, the OPO views the two combined signal-idler modes as a pair of distinct signal and idler fields, and can thus utilize the fact that parametric interaction only constrains the sum of the generated frequencies, not their individual values.

An important result of Ref. [9] is that an exact expression for the two-mode threshold can be computed, and that it is identical to that of a virtual single-mode regime with an effective coupling constant that depends on mode overlap. This allows one to study the mode selection process in a unified way by considering simultaneously single-mode and two-mode resonances, in which the two neighboring modes oscillate cooperatively (Fig. 1). Because multimode operation is thus allowed to occur without transverse mode degeneracy, it is expected that such regimes can be observed in a large number of cavity configurations. As reported here and in previous works [9, 13], there are indeed many configurations where our TROPO displays fast oscillations at frequencies typically between 1 and 300 MHz.

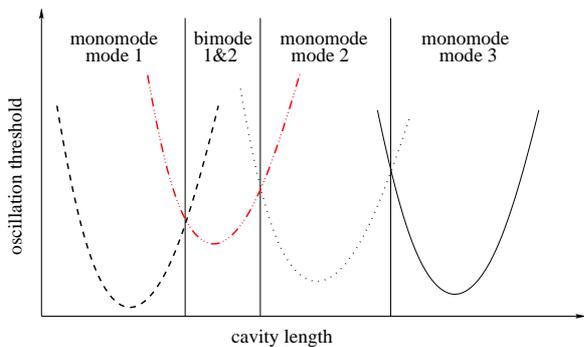


FIG. 1: Schematic representation of the resonance spectrum showing threshold of various regimes as a function of cavity length. Between two single-mode resonances, there exist two-mode resonances where the two modes of the neighboring resonances oscillate cooperatively.

The experimental setup is similar to that used in previous experiments [9, 13, 14, 15, 16]. A 15-mm-long KTP crystal cut for type-II phase matching is enclosed inside

a cavity of length L varying between 30 and 100 mm, delimited by two mirrors with a radius of curvature of 50 mm. Cavity length is not actively stabilized. Cavity finesses at 532 nm, the wavelength of the frequency-doubled Nd:YAG pump laser, and at 1064 nm, near which the signal and idler fields are generated, are 50 and 550, respectively. The regimes discussed here have been obtained at a pump power of 3.5 W, with a parametric threshold ranging from 10 mW to 35 mW depending on cavity length. The output pump beam had a TEM₀₀ structure. In most configurations, scanning the cavity through one free spectral range with a PZT allowed us to observe fast oscillations in the output intensity of the OPO at some cavity lengths, at a frequency f varying typically from 1 to 300 MHz, combined or not with optothermal oscillations (Fig. 2).

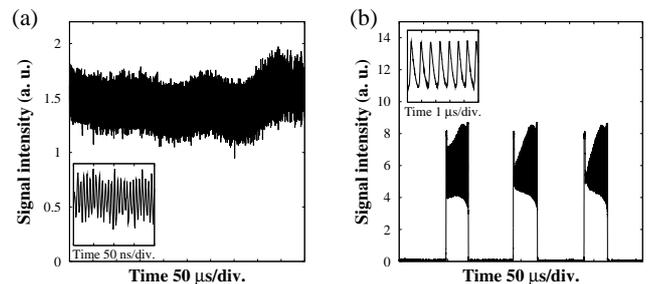


FIG. 2: Signal intensity vs. time in two configurations. (a) $L = 47$ mm; threshold 10 mW, $f = 130$ MHz ; $L = 77$ mm; threshold 33 mW, $f = 1.2$ MHz-2.7 MHz.

The transverse profiles of the output signal beam observed with a CCD camera during fast oscillations clearly suggest the presence of several transverse modes (Fig. 3). However, the pattern displayed by the camera is averaged over 20 ms, which does not allow us to distinguish between true mode coexistence and fast periodic alternation of the type that has been described previously [15].

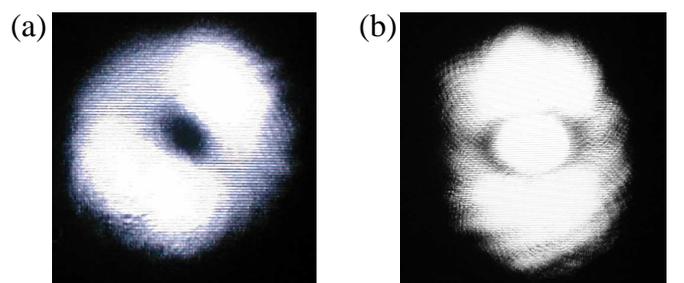


FIG. 3: Transverse intensity profile of the signal field recorded with a standard CCD camera operating at 50 frames/s. (a) $L = 46.3$ mm, $f = 15$ MHz; (b) $L = 37$ mm, $f = 31.5$ MHz.

To obtain convincing evidence of mode coexistence, we have monitored the output intensity of the signal field in two different locations of the transverse plane using fast detectors. A monomode transverse profile can be de-

scribed by a single time-dependent amplitude, and the time traces of the two detectors should then be proportional to each other. Fig. 4 shows the two time traces in a regime where bursts of fast oscillations are observed. The two traces have very different waveforms and are out of phase during the fast oscillations, which shows the presence of at least two modes. This clearly confirms that fast oscillations originate in the interaction of two or more transverse modes.

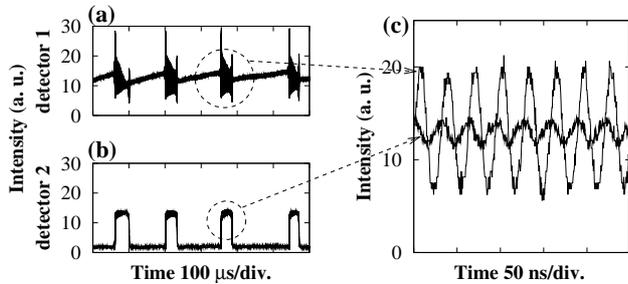


FIG. 4: Time traces recorded by two detectors located at different points of transverse profile. (a) Detector 1; (b) detector 2; (c) superposition of the two out-of-phase time traces during a burst of fast oscillations. $L = 47$ mm.

To study how multimode oscillations are switched on and off when cavity length is varied, we have monitored the evolution of the beam spatial profile as the uncontrolled cavity was slowly drifting due to thermal effects. Sufficient spatial and temporal resolutions could be simultaneously achieved by using a linear CCD array of 256 pixels, with an acquisition rate of 33,000 profiles/second. Fig. 5 shows a typical observation made in the same configuration as in Fig. 4. This allows us to correlate qualitative changes in the total output intensity with modifications in the beam transverse profile.

The following events can be seen from left to right in Fig. 5: first there is a mode hop associated with a sudden jump in the total intensity and the one-hump transverse profile changes to a two-hump one. After the mode hop, the output intensity and the two-hump profile remain approximately constant during $200 \mu\text{s}$. Then, the system switches abruptly to finite amplitude oscillations, with no notable change in the transverse profile. As cavity drifts through the oscillation zone, the transverse profile changes gradually from a two-hump profile to a one-hump one until oscillations disappear through an inverse supercritical Hopf bifurcation. Finally, intensity and the one-hump profile remain constant until the end. This scenario indicates that fast oscillations occur between two cavity lengths where two different transverse modes are dominant, as predicted theoretically [9], and that composite profiles are observed in the unstable zone. A singular value decomposition analysis of these profiles confirms that they are linear superpositions of the two monomode profiles.

A natural consequence of the theoretical findings of

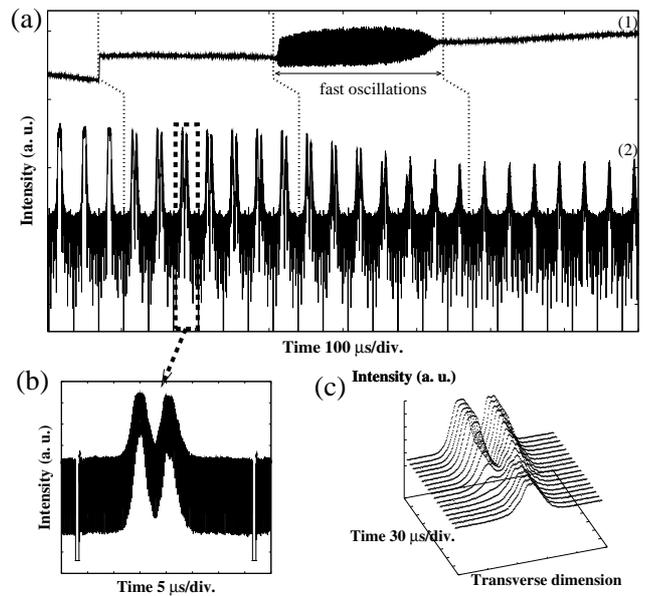


FIG. 5: (a) Traces 1 and 2 show total signal intensity as a function of time and the raw video signal from the CCD array, including interpixel and interframe pulses. Trace 2 is lagging behind trace 1 by the CCD transfer time ($30 \mu\text{s}$), as indicated by dashed lines. (b) The video signal between two interframe pulses displays a one-dimensional section of the beam profile acquired at the beginning of the segment, superimposed with interpixel pulses. (c) Succession of 1D profiles in the oscillation zone, extracted from trace 2 by suitable filtering, showing gradual transition from a two-hump to a single-hump profile.

Ref. [9] is that two-mode regimes should be much easier to observe than if transverse degeneracy were required for mode interaction. In order to estimate the prevalence of fast multimode oscillations in our experimental system, including far from the confocal or concentric geometries, we have thus conducted a systematic search near cavity lengths $L = 46, 63, 71, 77$ mm. Multimode behavior has been easily observed in each case.

For example, Fig. 6 displays the result of several cavity-length scans carried out near the configuration of Figs. 3-5, by increments of $200 \mu\text{m}$ or $500 \mu\text{m}$. For each configuration, cavity detuning was swept over one free spectral range to find whether or not fast oscillations could be observed for some detuning. The data of Fig. 6 clearly show that multimode behavior can be observed in almost all configurations studied. Surprisingly, transverse profiles almost always resemble that of low-order modes. Oscillation frequencies gather around 10–15 MHz, with a few points in the 100–300 MHz range. For cavity lengths $L = 63, 71$ and 77 mm, most probable frequencies were in the 6–15 MHz, the 3–8 MHz and the 1–3 MHz ranges, respectively, but frequencies outside these ranges have also been observed. Thus, lower frequencies are seemingly favored as cavity length is increased but we do not

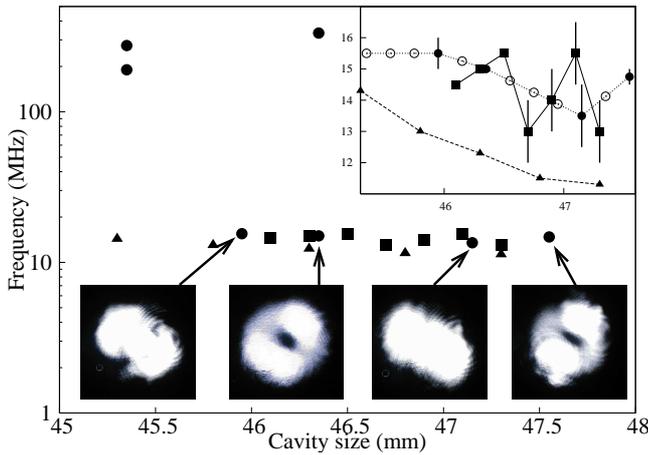


FIG. 6: Frequencies of multimode oscillations observed in three scans (each associated with a different symbol) of cavity length in the 45–48 mm range. Inset shows data points with frequencies between 10 and 15 MHz, with a line passing through data points of a given scan. Filled (open) symbols denote configurations where oscillations were observed (not observed). When different oscillation regimes were observed in the same configuration, the frequency range is indicated by a vertical bar. Transverse profiles observed in the scan associated with circle symbols are also shown.

yet have an explanation for this behavior.

It has to be noted that the degenerate bimode model whose predictions [9, 13] motivated our experiments is in principle not suitable to describe a type-II OPO, where the signal and idler fields have orthogonal polarizations, even though in the monomode case the non-degenerate model reduces to the degenerate one [9]. The study of the non-degenerate multimode model is difficult and is currently in progress. As in the degenerate case, cross-conversion channels involve signal and idler fields with different transverse structures but because the difference between the periods of the signal and idler frequency combs is small, they become resonant in symmetrical pairs.

In conclusion, we have shown that the fast oscillations observed in TROPOs are generated by the coexistence of interacting transverse modes. The surprising prediction made in Ref. [9] that multimode oscillations do not require mode degeneracy, and thus do not depend on the cavity geometry, also holds in our system, as is confirmed by systematic scans of the cavity lengths which have revealed a high probability of occurrence. By monitoring the transverse structure of the beam as cavity length was slowly swept, we have also evidenced the occurrence of fast oscillations due to mode coexistence between two resonances corresponding to two different transverse modes. These findings are important because they show that

two-mode regimes can have a lower threshold than individual modes and thus must be taken into account to determine which operating mode is selected in OPOs [18, 19].

Finally, we expect the phenomena described here not to be specific to OPOs or even to optical systems. More precisely, the similarity of our observations with those reported in hydrodynamical Faraday experiments [10] suggest that the nonlinear mechanism studied here may occur in any system where a parametric nonlinear interaction, or more generally a nonlinear wave mixing, interacts with strong boundary conditions.

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