

# Experimental evidence of spontaneous symmetry breaking in intracavity type-II second harmonic generation with triple resonance

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We describe an experiment showing a spontaneous symmetry breaking phenomenon between the intensities of the ordinary and extraordinary components of the fundamental field in intracavity type-II harmonic generation. It is based on a triply resonant dual cavity containing a type II phase matched  $\chi^{(2)}$  crystal pumped at the fundamental frequency  $\omega_0$ . The pump beam generates in the cavity a second harmonic mode at frequency  $2\omega_0$  which acts as a pump for frequency degenerate type II parametric down conversion. Under operating conditions which are precisely symmetric with respect to the ordinary and extraordinary components of the fundamental wave, we have observed a breaking of the symmetry on the intensities of these two waves in agreement with the theoretical predictions.

Triply Resonant Optical Parametric Oscillators are well-known to have a rich dynamical behavior showing in particular bistability, self-oscillation and chaos [1, 2]. We study here a similar system consisting in a type-II phase matched crystal placed inside a triply resonant cavity but where the pumping is made at the fundamental frequency  $\omega_0$ , not at the harmonic frequency  $2\omega_0$ . In this case, both second harmonic generation and parametric down-conversion simultaneously occur. The pump wave is sent at  $45^\circ$  of the crystal neutral axes and is frequency doubled. The produced harmonic wave acts then as a pump for an OPO inside the same cavity and using the same crystal. This system has been widely studied theoretically for its classical and quantum properties [3, 4, 5, 6, 7]. The system is *a priori* symmetric : the ordinary and extraordinary fundamental waves intensities are in general

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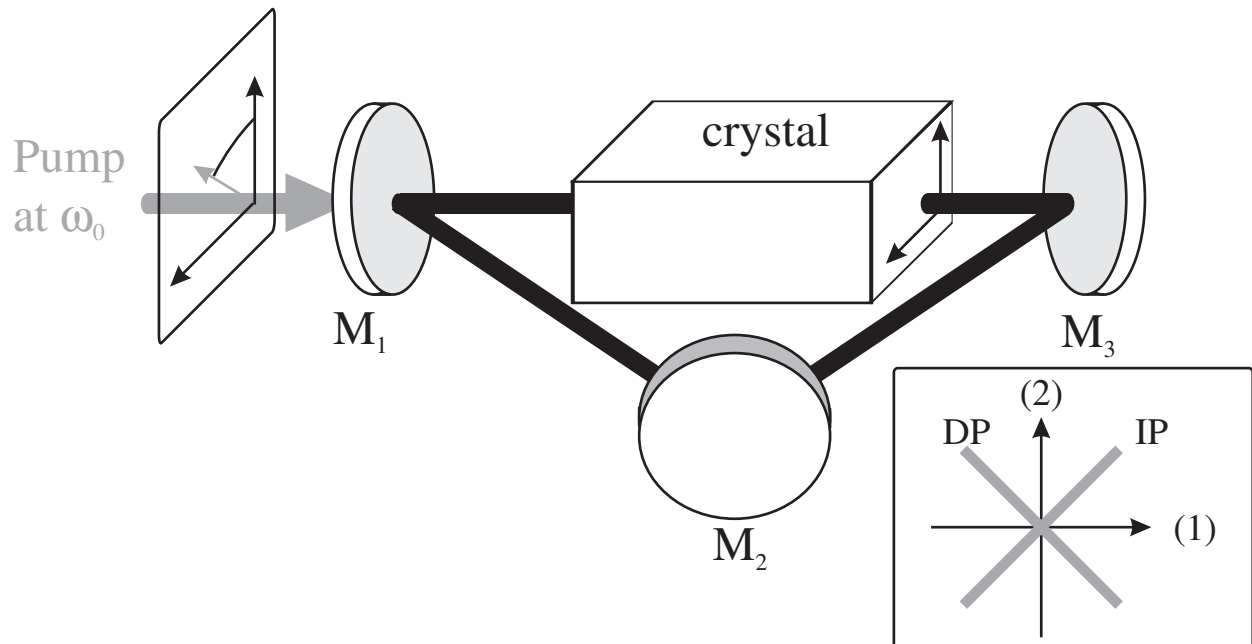


FIG. 1: Scheme of the ring cavity.  $M_1$  : pump coupling mirror;  $M_{2,3}$  : highly reflective mirrors at  $\omega_0$  and  $2\omega_0$ . In the box : input polarization (IP) and down-converted polarization (DP) with the crystal neutral axes (1) and (2).

equal at the output of an OPO. However, a spontaneous symmetry breaking phenomenon is predicted to occur under some circumstances : the intracavity signal and idler intensities may be different. In this letter, we report what is to our knowledge the first experimental demonstration of this phenomenon.

We consider a ring cavity (figure (1)) containing a  $\chi^{(2)}$  crystal with type-II phase matching. This cavity is pumped with a beam at frequency  $\omega_0$  polarized at  $45^\circ$  of the crystal neutral axes, (1) and (2).

Pumped by the intracavity second harmonic field, parametric oscillation takes place on the down-converted fields frequencies  $\omega_1$  and  $\omega_2$  (with  $\omega_1 + \omega_2 = 2\omega_0$ ) which minimize the threshold [8]. The non frequency degenerate case has been considered both theoretically and experimentally [9, 10, 11] and spontaneous symmetry breaking is not predicted in this case. Here, we suppose that the the system is operated at frequency degeneracy ( $\omega_1 = \omega_2 = \omega_0$ ) : the down-converted fields are at the frequency of the input field and interfere with it. We denote  $A_{1,2}$  the intracavity field envelopes at frequency  $\omega_0$  and  $A_0$  the intracavity field

enveloppe at frequency  $2\omega_0$ . The corresponding detunings are denoted

$$\Delta_{1,2} = \frac{\omega_0}{c} (n_{1,2}l + L) [2\pi] \text{ and } \Delta_0 = \frac{2\omega_0}{c} (n_0l + L) [2\pi]. \quad (1)$$

where  $n_{0,1,2}$  are the crystal indices of refraction,  $l$  is the crystal length and  $L$  the free propagation length inside the cavity. When the optical length of the cavity is adjusted so that all fields are close to resonance and the intracavity losses small, the normalized equations for the normalized intracavity field envelopes can be written :

$$(\gamma' - i\Delta_1)A_1 = A_0A_2^* + \sqrt{2\gamma}\frac{A_{in}}{\sqrt{2}} \quad (2)$$

$$(\gamma' - i\Delta_2)A_2 = A_0A_1^* + \sqrt{2\gamma}\frac{A_{in}}{\sqrt{2}} \quad (3)$$

$$(\gamma_0 - i\Delta_0)A_0 = -A_1A_2 \quad (4)$$

where  $A_{in}$  is the pump field,  $\gamma'$  and  $\gamma_0$  correspond respectively to the round trip amplitude losses for the pump and second harmonic wave, while  $\sqrt{2\gamma}$  is the transmission of the coupling mirror  $M_1$  at frequency  $\omega_0$ ). In a standard OPO, the system oscillates on the frequency pairs which verify

$$\Delta_1 = \Delta_2 = \Delta. \quad (5)$$

In our case, the frequencies are fixed by the injected field but we assume, which is experimentally realistic, that the system parameters can be adjusted so that relation (5) is verified. Equation (4) leads to an expression for  $A_0$  as a function of  $A_1$  and  $A_2$  which can be re-injected in equations (2) and (3). One obtains then a system of two nonlinear coupled equations for  $A_1$  and  $A_2$ . From this system, one can obtain the following relation :

$$\left( (\gamma'^2 + \Delta^2) - \frac{1}{\gamma_0^2 + \Delta_0^2} I_1 I_2 \right) (I_1 - I_2) = 0 \quad (6)$$

where  $I_i = |A_i|^2$  is the intensity of the corresponding field. This equation has two solutions, one symmetric ( $I_1 = I_2 = I$ ) and another dissymmetric.

In the symmetric case, the intracavity intensity  $I$  of both fields at the fundamental frequency is a solution of a third degree equation :

$$\left( \gamma'^2 + \Delta^2 + \frac{I^2}{\gamma_0^2 + \Delta_0^2} + 2\frac{\gamma\gamma_0 - \Delta\Delta_0}{\gamma_0^2 + \Delta_0^2} I \right) I = \gamma|A_{in}|^2 \quad (7)$$

In the dissymmetric case,  $I_1$  and  $I_2$  verify :

$$I_1 I_2 = (\gamma_0^2 + \Delta_0^2)(\gamma'^2 + \Delta^2) \quad (8)$$

$$I_1 + I_2 = \frac{\gamma|A_{in}|^2}{\gamma'^2 + \Delta^2} - 2(\gamma\gamma_0 - \Delta\Delta_0) \quad (9)$$

It can be shown by a linear stability analysis [4] that the symmetric solution is stable for :

$$I_{in} < I_{threshold} = \frac{2(\gamma'^2 + \Delta^2)}{\gamma} \times \left( \sqrt{(\gamma_0^2 + \Delta_0^2)(\gamma^2 + \Delta^2)} + \gamma\gamma_0 - \Delta\Delta_0 \right) \quad (10)$$

while the dissymmetric solution is stable in the opposite case ( $I > I_{threshold}$ ). The symmetry-breaking phenomenon can be understood in the following way : above  $I_{threshold}$ , frequency degenerate parametric oscillation takes place. The generated subharmonic field can be shown [4] to be polarized the direction (DP) of figure (1), *i.e.* orthogonally to the pump polarization (IP). The total field at frequency  $\omega_0$  is therefore no longer at  $45^\circ$  from the crystal axes, leading to the symmetry breaking phenomenon. Furthermore, because of the well-known  $\pi$  phase indeterminacy of the subharmonic field in the degenerate OPO, the vectorial sum of the fields at frequency  $\omega_0$  can take two different values : as a result, the lower and upper values of  $I_1$  and  $I_2$  can be taken by any of the two polarizations (1) or (2), and the system may switch from one solution to the other. Equations (7) and (9) allow one to plot the intracavity intensities as a function of the various parameters of the system. The corresponding plots are shown in fig. 2.

The top graph shows a pitchfork bifurcation phenomenon as a function of the input intensity : below a critical value, the system is symmetric and above this value it is asymmetric. The bottom graph gives the same phenomenon as a function of cavity detunings. For large values of  $|\Delta|$ , the fundamental frequency waves are far from resonance and  $I_{threshold}$  is large : the intracavity intensities are symmetric and follow the usual cavity resonance shape. Under a certain value of  $|\Delta|$ , the harmonic frequency intensity becomes larger than the OPO oscillation threshold, parametric reconversion occurs and the harmonic intensity decreases : this is the phenomenon of pump depletion which occurs in standard OPOs. In our case, the spontaneous symmetry breaking occurs : the fundamental frequency intensities are no longer equal as is the case in a standard harmonic-pumped OPO or in a non-degenerate system.

We will now describe the experimental set-up. As mentioned previously, we need to be able to control independently  $\Delta$  and  $\Delta_0$ . In order to achieve this, we use a dual-cavity set-up (fig. 3) : this also adds a degree of freedom which allows the verification of relation (5). The intensity reflection coefficient are shown in table I. The fundamental frequency beam is produced by a Nd:YAG laser ( $\lambda = 1064 \text{ nm}$ , Lightwave 126-1024-700) which is

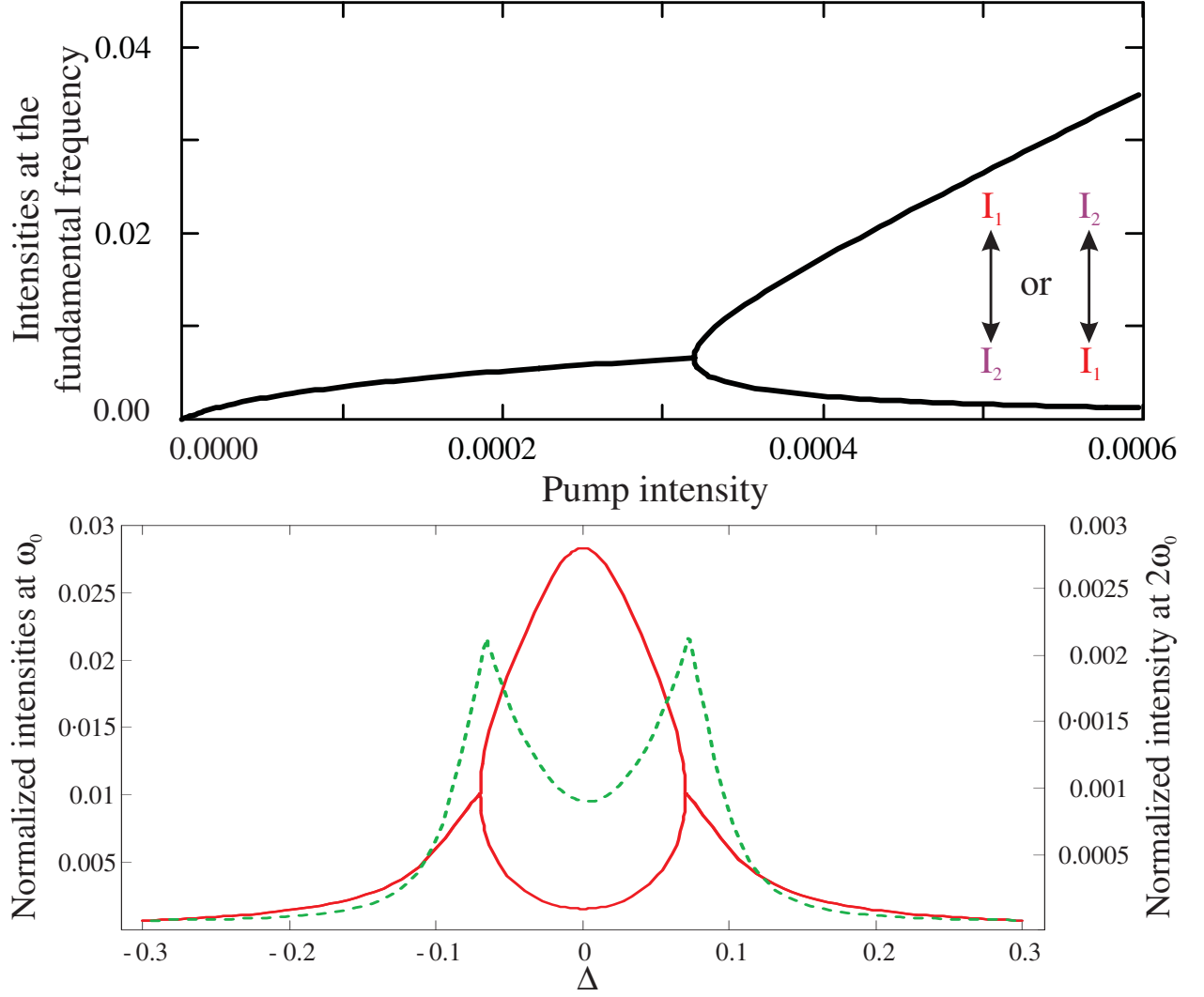


FIG. 2: Top : normalized intensities of the fundamental frequency as a function of  $I_{in}$  with  $\Delta = 0$ . Bottom : normalized intensities of the extraordinary and ordinary fundamental frequency (continuous line) and harmonic frequency fields (dashed line) as a function of  $\Delta$  with  $I_{in} = 0.001$ . The other parameters are  $\gamma_0 = 0.06$ ,  $\gamma' = \gamma = 0.11$ ,  $\Delta_0 = 0$ .

mode-matched to the cavity and linearly polarized at  $45^\circ$  of a KTP crystal neutral axes (Cristal Laser).

The crystal is shared by the two cavities, one resonant for the fundamental frequency (IR cavity), the other for the harmonic frequency (green cavity). The green cavity length is kept approximately fixed but not locked to a well defined value of the detuning  $\Delta_0$  while the IR cavity length is scanned via the PZT ceramic. The intracavity intensities are monitored

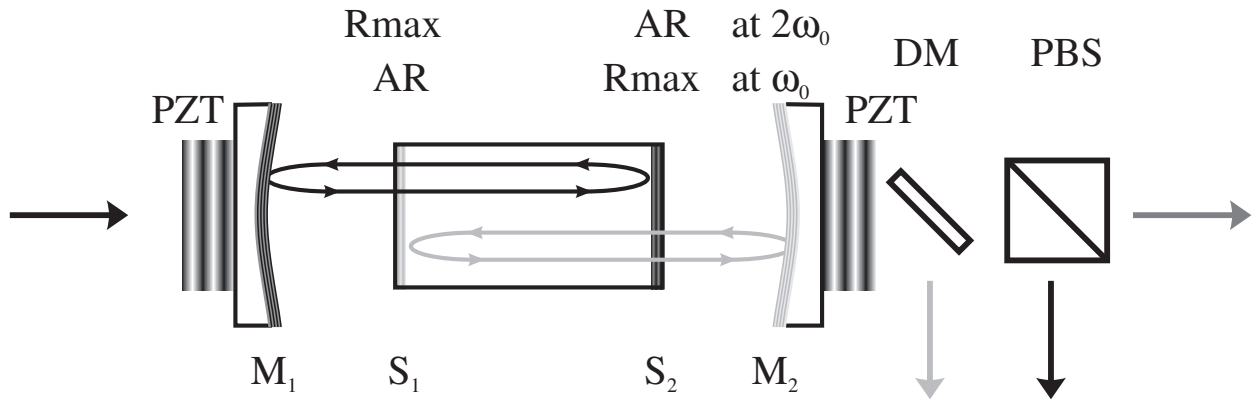


FIG. 3: Principle of the dual-cavity. DM : dichroic mirror; PBS : polarizing beamsplitter; PZT : piezo-electric ceramic.

TABLE I: Intensity reflection coefficients.

	$M_1$	$S_1$	$S_2$	$M_2$
$R(1064 \text{ nm})$	95 %	0.11 %	99.96 %	99.8 %
$R(532 \text{ nm})$	> 99.9 %	99.3 %	5.25 %	95 %

via the small transmission of the green cavity and we are able to measure independently the intensities along the crystal neutral axes.

A spontaneous symmetry breaking is observed for certain values of the IR cavity length (fig. 4). Experimental values of the various parameters governing the system behavior vary from one recording to the other. In some recordings, one observes that  $I_2 > I_1$  (fig. 4, top), in others that  $I_2 < I_1$  (B region of fig. 4, bottom). In both cases, one observes pump depletion as predicted on fig. 2, bottom. Pump depletion is also observed in the region A of fig. 4, but without symmetry breaking between  $I_1$  and  $I_2$  : this region of the parameter space corresponds to the non frequency degenerate operation, which does not lead to symmetry breaking.

In conclusion, we have developed a dual-cavity set-up which has allowed us to observe the spontaneous symmetry breaking predicted in intracavity frequency generation with triple resonance. To our knowledge, this is the first experimental evidence for this behavior.

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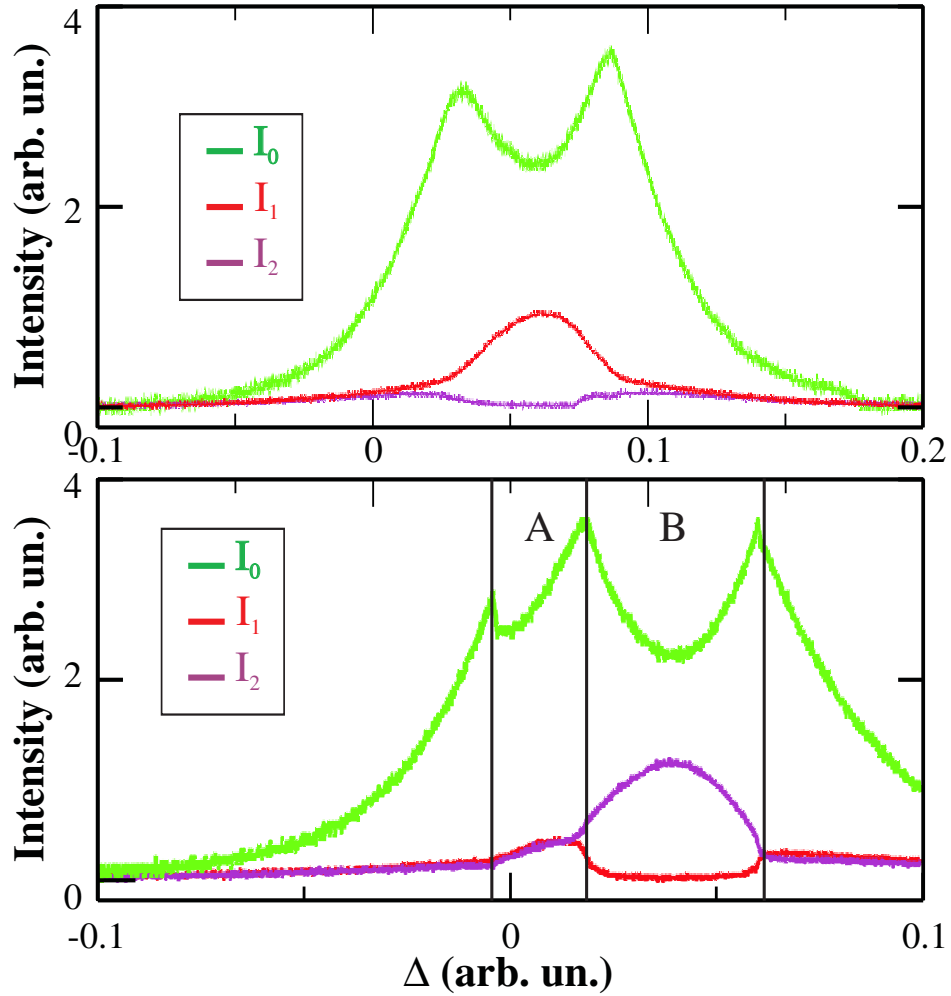


FIG. 4: Experimental recordings of the intracavity intensities as a function of the cavity length scanned in time.

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