Periodic mode hopping induced by thermo-optic effects in continuous-wave optical parametric oscillators

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We show that thermal effects can lead to periodic mode hopping in cw optical parametric oscillators (OPOs). This mode hopping may occur as soon as two modes have different intensities at the point where they exchange their stability; this condition is easily fulfilled in OPOs that are triply resonant, or doubly resonant with a weakly resonant pump. We have observed such oscillations experimentally in a type II OPO in both configurations. A simple thermo-optic multimode model reproduces well the experimental regimes.

We expect that multimode instabilities based on this mechanism can be observed with various aspects in many experimental setups at high pumping rate. © 2001 Optical Society of America

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Because of their wide tunability, optical parametric oscillators (OPOs) are promising sources of coherent optical radiation. To lower the oscillation threshold of cw OPOs, researchers commonly set them up as doubly resonant oscillators (DROs) or triply resonant oscillators (TROs), with the signal and idler fields resonant in the cavity.1 Because of the multiple resonance conditions, however, such configurations are known to suffer from mode and cluster hopping when a control parameter is varied or randomly fluctuates.2,3

In this Letter we show that thermo-optic effects can lead to periodic mode hopping in cw OPOs: We have observed thermally induced oscillations at a few kilohertz between two different longitudinal modes in type II OPOs, in both the DRO and the TRO configuration. At high pump power, this instability occurs over wide ranges of detunings, thus severely affecting tunability.

As shown below, this phenomenon can be understood in the same framework as a recently described monomode self-pulsing instability4: It involves a feedback loop linking the fast optical fields and the crystal temperature. Unlike in the monomode case, however, the mechanism of oscillations observed does not rely on the presence of a bistability cycle. Thus, the phenomenon occurs over a much larger parameter region than for the monomode case and can be observed even if the pump is only weakly resonant, as in many configurations generally considered as DRO. For brevity, we focus here on the TRO case, which is the natural context for the theoretical analysis, but we also present examples of instabilities observed in our DRO.

The experimental setup is a TRO similar to that previously described.4 The TRO is based on a KTP crystal cut for type II phase matching. Crystals of length \( l_c = 7 \) or \( l_c = 15 \) mm have been used, with similar results. The 5-cm-long Fabry–Perot cavity consists of two mirrors with a radius of curvature of 3 cm and is resonant at the frequencies of the Nd:YVO\(_4\) pump laser (Coherent Verdi; maximum power, 5 W, operating at 532 nm) and of its subharmonic, so that the signal and idler wavelengths are close to 1064 nm. The mirrors have maximal reflectivity, except at 532 nm, where the input mirror (R = 90%) and at 1064 nm for the output mirror (R = 99%), and correspond to a finesse of 45 for the pump and 550 for the signal and idler fields, taking into account absorption by the crystal.4 Under these conditions, the pump power at threshold is \( \sim 20 \) mW. The three fields oscillate in the TEM\(_{00}\) mode. The signal and idler display similar time evolution. The DRO is identical to the TRO, except that (i) the input mirror has R = 15% at 532 nm, corresponding to a finesse of 3 for the pump; (ii) mirrors with a radius of curvature of 5 cm were used; and (iii) only the 15-mm-long crystal was used, with a threshold of \( \sim 180 \) mW. We used no active stabilization to avoid interfering with the intrinsic dynamics of the OPO.

Figure 1 shows typical examples of the regimes studied in this Letter, observed in a TRO and a DRO. These oscillations can be stably observed for up to a few minutes. They are similar to the periodic regimes presented previously5: The oscillation period (270 \( \mu \)s) is of the order of the estimated thermal-diffusion time scale,6 i.e., \( \tau_{th} = 230 \mu \)s, and depends markedly on cavity detunings; and the time signals display intervals of slow evolution, separated by sudden jumps in the pump and signal intensities. Yet the present instability cannot be interpreted as

\[ \text{Fig. 1. Experimental self-pulsing regimes: (a) signal and (b) pump intensity in a TRO (} l_c = 7 \text{ mm, } P_{\text{pump}} = 1.5 \text{ W}) \text{ and (c) signal and (d) pump intensity in a DRO (} l_c = 15 \text{ mm, } P_{\text{pump}} = 3.6 \text{ W}). \]
oscillations around the bistability cycle of a single mode, because the signal intensity never goes to zero. In fact, the system is exploring the resonance curves of two different longitudinal modes, as we show below.

The output of a confocal Fabry–Perot spectrum analyzer for a typical regime is shown in Fig. 2. The spectrum analyzer was purposely misaligned so that the broadened resonance curve for a given longitudinal mode of the OPO would be swept in a time that is long compared with the oscillation period of the instability.

Two series of peaks, corresponding to two resonances, can easily be seen in Fig. 2. The two resonances are separated by 3 GHz, which is exactly the frequency difference between two adjacent longitudinal modes of the OPO. This clearly confirms the two-mode hypothesis. Moreover, if we look closely at the first resonance and compare the input of the Fabry–Perot analyzer [Fig. 2(b)] with its output [Fig. 2(c)], we can see that mode 1 oscillates only during the first phase of the period and completely vanishes during the second phase. Similarly, mode 2 oscillates only during the second phase (not shown) and thus is in antiphase with mode 1.

This result clearly shows that the instability consists of periodic hopping between two longitudinal modes of the OPO, which is consistent with the fact that two modes with different frequencies cannot oscillate simultaneously in a cw OPO. The same analysis was carried out for the DRO instabilities and led to the same conclusion.

Accordingly, we extended the simple thermo-optic model described previously to multimode operation. The extension is based on the usual two-mode mean-field model of a degenerate TRO:

\[
\dot{A}_p = \gamma\{-[1 + i\sigma_p(\theta)]A_p - A_1^2 - A_2^2 + E\},
\]

\[
\dot{A}_1 = -[1 + i\sigma_1(\theta)]A_1 + A_pA_1^* + \eta,
\]

\[
\dot{A}_2 = -[1 + i\sigma_2(\theta)]A_2 + A_pA_2^* + \eta,
\]

where \(A_p, A_1, A_2\) are the complex amplitudes of the pump and the two subharmonic modes. The frequencies of the subharmonic modes are assumed to be well separated so that there is no cross coupling between \(A_1\) and \(A_2\). The time unit is the cavity decay time of the signal, \(\gamma\) is the cavity decay rate of the pump, and \(E\) is the input pump. The small constant \(\eta\) is an artificial source term that mimics parametric fluorescence.

The core ingredient in our model is that the cavity detunings \(\sigma_p, \sigma_1, \sigma_2\) of the three fields depend on a slow variable \(\theta\), which describes changes in the optical length of the crystal as a result of thermal effects. We choose \(\theta\) so that, to first order, the cavity detunings are given by \(\sigma_{1,2}(\theta) = \Delta_{1,2} - \theta\) and \(\sigma_p(\theta) = \Delta_p - 2\theta/\gamma\), where \(\Delta_{1,2}\) and \(\Delta_p\) are the detunings of the fields in the cold cavity (at \(\theta = 0\)). Conversely, the influence of the optical fields on the dynamics of \(\theta\) is described by the following equation:
period and the amplitude in \( \theta \) is not straightforward and requires a singular perturbation analysis.

It is easy to see that self-pulsing can appear near the stability exchange as soon as the two modes have different intensities at the point where they exchange their stabilities, so \( \theta \) has opposite signs on the two branches. In the case of two longitudinal modes discussed here, it suffices that both the pump and the signal modes are slightly detuned \( [\sigma_p(\theta_c) \sigma_1(\theta_s) \neq 0] \). The larger the intensity difference, the larger the region in which instability will occur: In some configurations operated at a high pumping rate, we have observed oscillations for approximately half the detuning range.

Although this qualitative description is similar to that of the monomode instability described in Ref. 4, the condition obtained above is much less stringent: It does not depend on the presence of a bistability cycle, which requires that \( \sigma_p(\theta_c) \sigma_1(\theta_s) > 1 \). This explains why the bimode instability can easily be observed in an OPO in which the pump is weakly resonant [Fig. 1(b)], provided that the pump detuning, even when small, is nonzero. A nonzero pump detuning is possible as soon as the pump is at least double pass, which is the case in many configurations that are classified as doubly resonant.

This conclusion has been confirmed by numerical simulations of the model (1)–(4) in the limit \( \gamma \gg 1 \) for small values of \( \Delta_p \). Another very important result of our simulations is that instability can occur at pump rates as small as twice the threshold (e.g., for \( E = 1.5, \Delta_p = -0.6, \Delta_1 = 2, \Delta_2 = 2.9, \alpha = 0, \beta = 12, \gamma = 40, \text{ huey } \eta = 10^{-40} \), which indicates that the range of operating conditions that can be affected by the instability is large.

The mechanism discussed here seems very general. For example, it can also induce oscillations between two transverse modes. In this case the fields need not be detuned, as the intensity difference at the exchange of stability is ensured by the difference in the effective nonlinear coefficients. We have also observed oscillations among three modes or more, as well as fast oscillations superimposed on the thermally induced ones, similar to those reported by Richy et al. Finally, we have found numerical solutions of our model with smooth waveforms. Thus the present instability cannot be ruled out when no sudden jump is observed.

These observations lead us to believe that the instability presented here should be observable in many cw DROs or TROs, especially as high-power pump lasers become increasingly available. In particular, it might explain the slow periodic behaviors observed in different cw OPOs by Richy et al. and Douillet et al. This Letter certainly provides motivation for further study of multimode instabilities, both from a dynamic point of view and with a view to achieving stable operation of cw OPOs at high pump power.

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