Entanglement in Multimode Devices with Photonic Crystals

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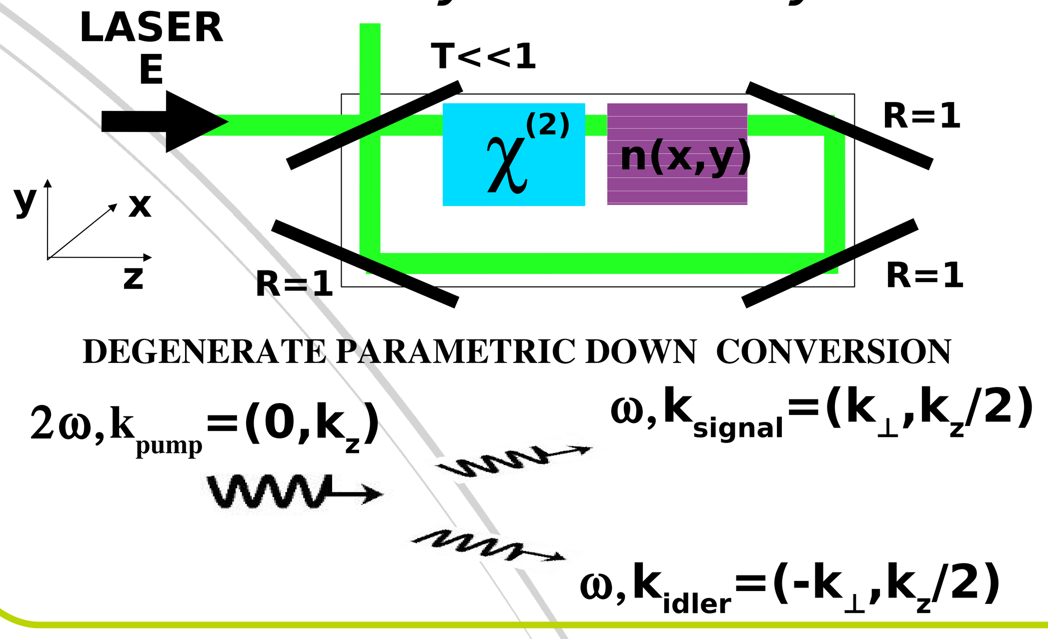
Abstract

There have been two decades of intense research on photonic crystals to control spontaneous-emission in different devices [1]. In this work we show that photonic crystals (PC) can be used also to tune quantum fluctuations in the context of *spontaneous pattern formation* in optics. Extended nonlinear optical devices are developed instabilities towards spatially multimode structures and it was recently proposed and experimentally confirmed the use of PC to inhibit such modulation instabilities in presence of photonic band-gaps [2]. Moreover, nonlinear optical devices are common sources of non-classical light beams. In particular, multimode optical parametric oscillators emit light exhibiting sub-Poissonian fluctuations, squeezing and entanglement between frequency, polarization and spatial components. In the last decade, *spatial* quantum correlations have found applications in quantum information and imaging [3].

Our analysis predicts the possibility to control the signal emission threshold of a type I degenerate OPO with intracavity PC (PCOPO) when the unstable wavelength is in the band-gap. The instability can be inhibited (as in [2]) but also stimulated. When considering quantum fluctuations, we find that PC can be used to tune spatial squeezing leading also to EPR entanglement above threshold [4].

Quantum fluctuations in PCOPO

Type I degenerate OPO with Intracavity Photonic Crystal



Spatial Instabilities in OPOs

NON-LINEARITY
LOSSES
DIFFRACTION
NEGATIVE Δ_1

↓

PATTERN FORMATION IN THE TRANSVERSE PROFILE ABOVE THRESHOLD AT k_c

Langevin equations in the Q representation

pump (ordinary polarization):

$$\partial_t \alpha_0(\vec{x},t) = -\left[(1+i(\Delta_0 + M_0 \sin k_p x) - i\,\nabla^2\right]\alpha_0(\vec{x},t) + E - \frac{1}{2}\alpha_1^2(\vec{x},t) + \sqrt{\frac{2}{a}\frac{g}{\gamma}}\xi_0(\vec{x},t)$$

signal (extraordinary polarization):

$$\partial_t \alpha_1(\vec{x},t) = -\left[(1+i(\Delta_0 + M_1 \sin k_p x) - i\,\nabla^2\right]\alpha_1(\vec{x},t) + \alpha_0(\vec{x},t)\alpha_1^*(\vec{x},t) + \sqrt{\frac{2}{a}\frac{g}{\gamma}}\xi_1(\vec{x},t)$$

LOSSES — DETUNING — PHOTONIC CRYSTAL — DIFFRACTION — MULTIPLICATIVE WHITE NOISE

MULTIMODE & NON-LINEAR

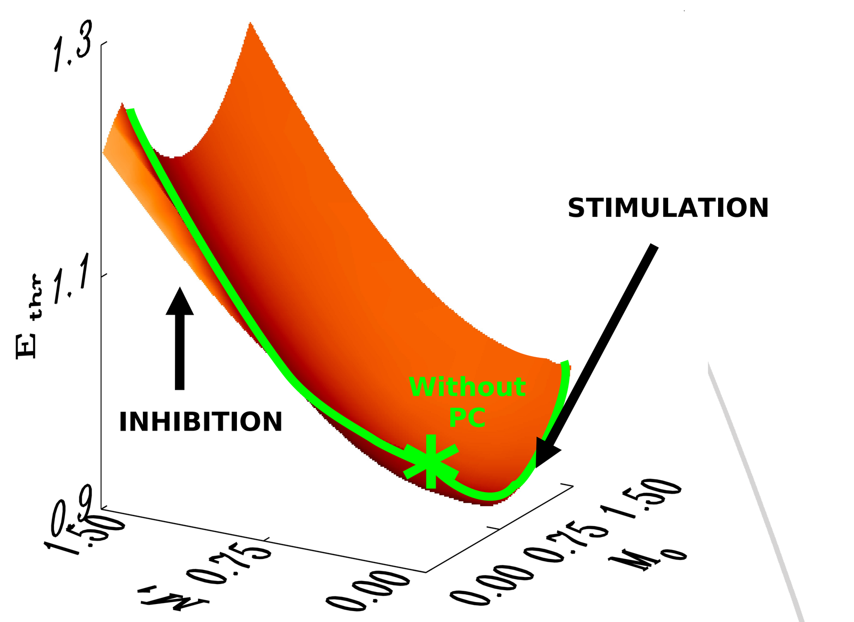
$$\hat{H}_{int} = i\hbar\frac{g}{2}\int dx\left[\hat{A}_0(x,t)\hat{A}_1^{\dagger 2}(x,t) - \hat{A}_0^\dagger(x,t)\hat{A}_1^2(x,t)\right]$$

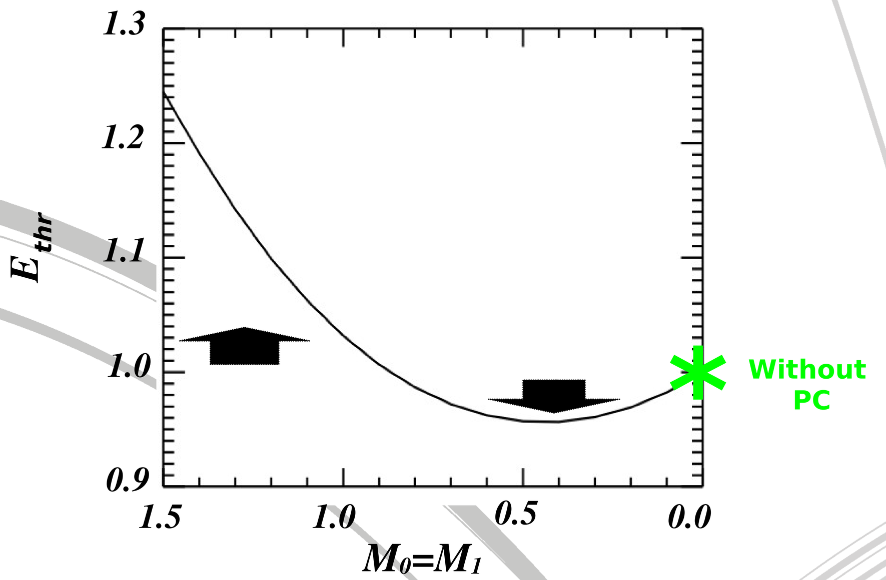
TWO IMPORTANT SPATIAL SCALES → k_c and k_p in the following $k_p=2k_c$ (Band-gap)

Parametric and Instability Threshold Control

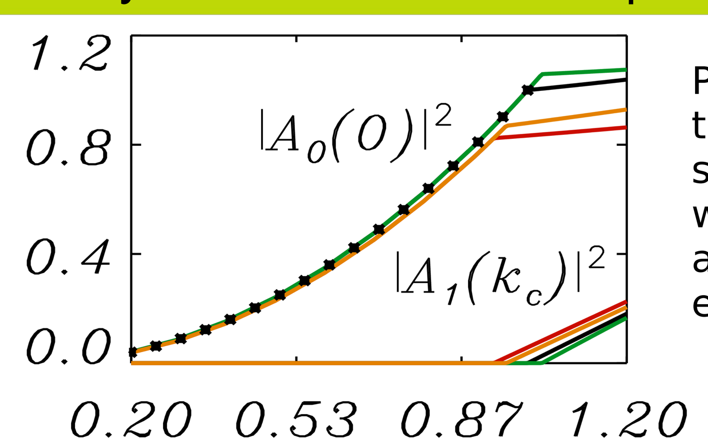
PHOTONIC CRYSTALS can either

STIMULATE or INHIBIT the pattern



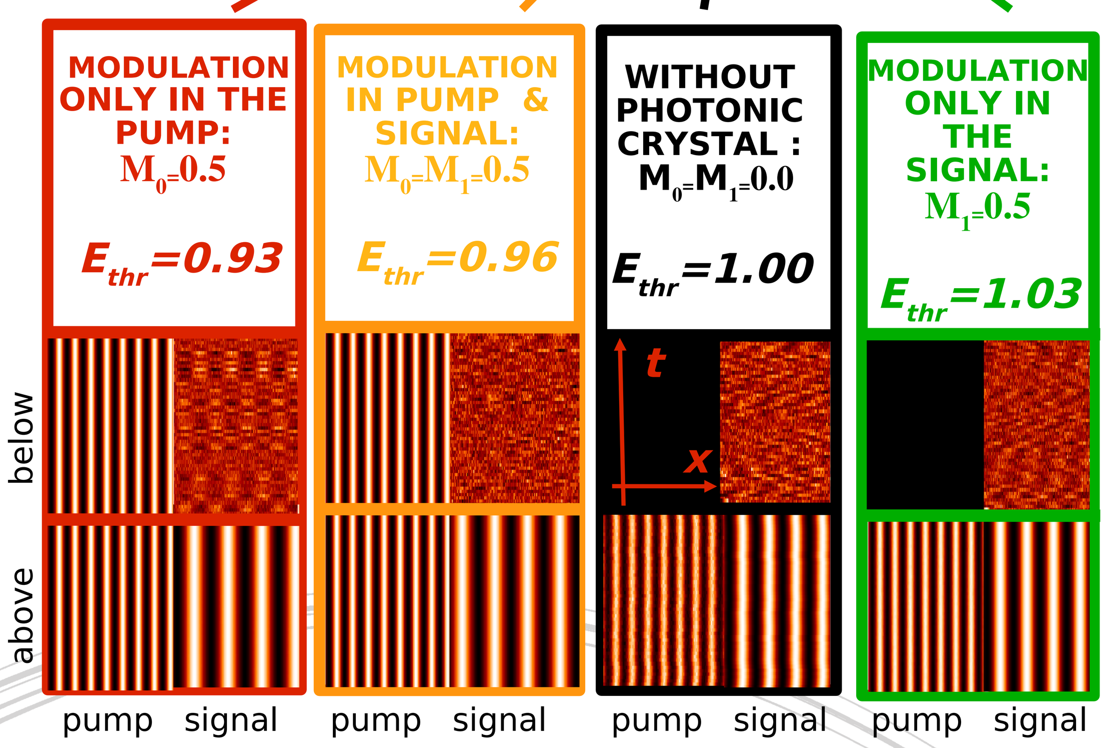


Efficiency of down conversion process



PC breaks translational symmetry without affecting efficiency

dots [5] $|A_0^{st}|^2 = \dfrac{E^2}{1+\Delta_0^2}$



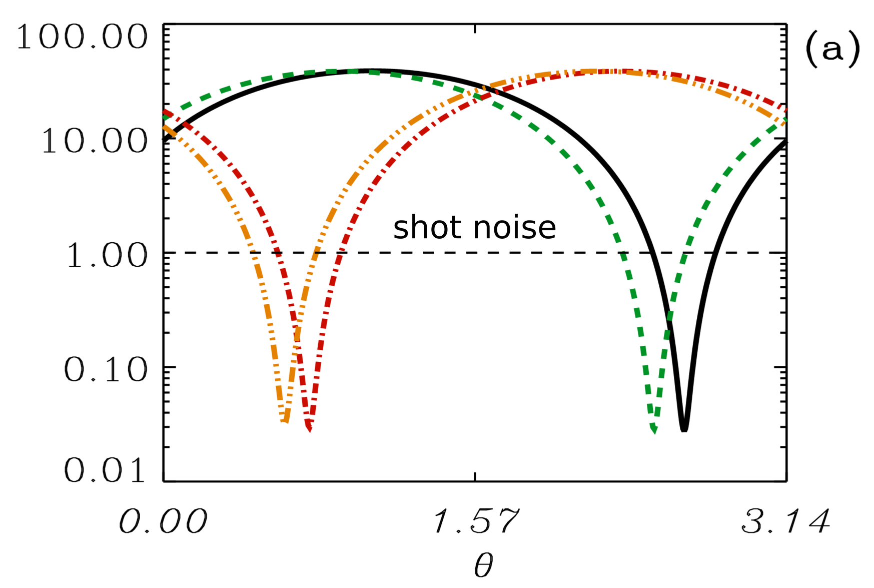
In presence of PC noisy precursors have a fixed phase.

Two modes squeezing in PCOPO

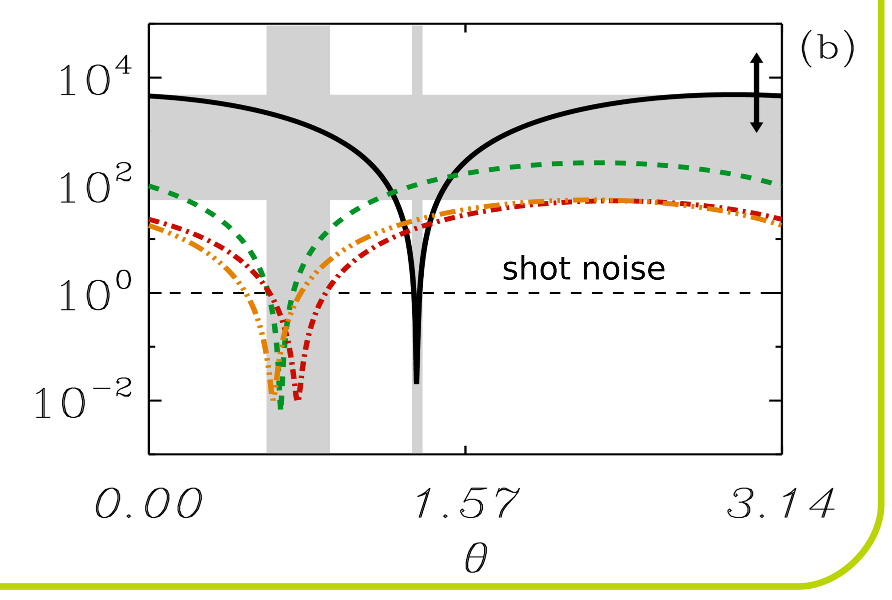
$$\Sigma_{\theta\phi}(k,-k,t) = (\hat{A}_1(k,t) + \hat{A}_1(-k,t)e^{i\phi})e^{i\theta} + h.c.$$

Variance of the quadrature superposition in log scale for the superposition angle that minimizes the variance

5% below threshold. We find that squeezing achieves similar values in the OPO (black line) and in the PCOPO modulating pump and/or signal detuning, as shown in Fig. a (same legend as before).



2% above threshold. A strong noise reduction in the PCOPO: in Fig. b there are two orders of magnitude between the variances of the unsqueezed quadrature in the PCOPO for modulated Δ_0 and the OPO (black line), as highlighted by the horizontal grey line.



Einstein-Podolski-Rosen entanglement in PCOPO

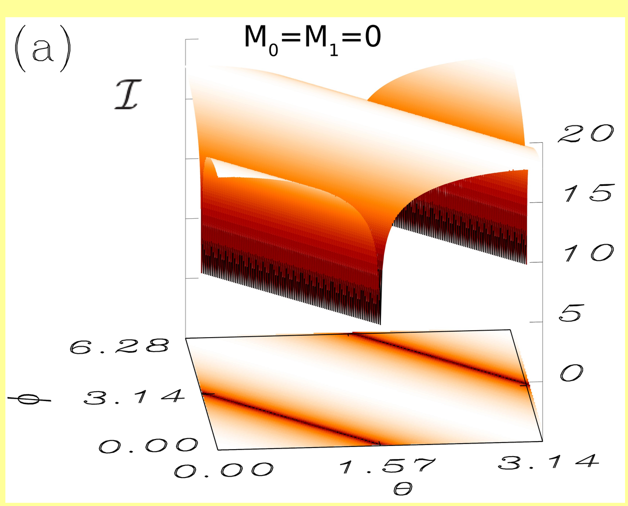
PHOTONIC CRYSTAL CREATES SIGNIFICANT REGIONS (limited by white dashed lines) WHERE EPR PARADOX AND STATE SEPARABILITY [4] CONDITIONS ARE FULFILLED

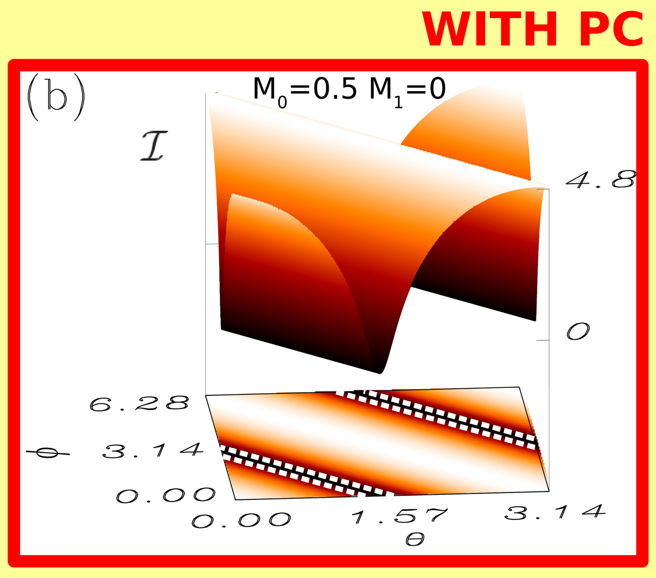
Duan *et al.* non separability criterion

$$\mathcal{I} = \Delta^2\tilde{\Sigma}_{\theta_0,\phi_0} + \Delta^2\tilde{\Sigma}_{\theta_0+\frac{\pi}{2},\phi_0+\pi} \le 2(a^2 + \frac{1}{a^2})$$

parameter $a > 0$

WITH PC

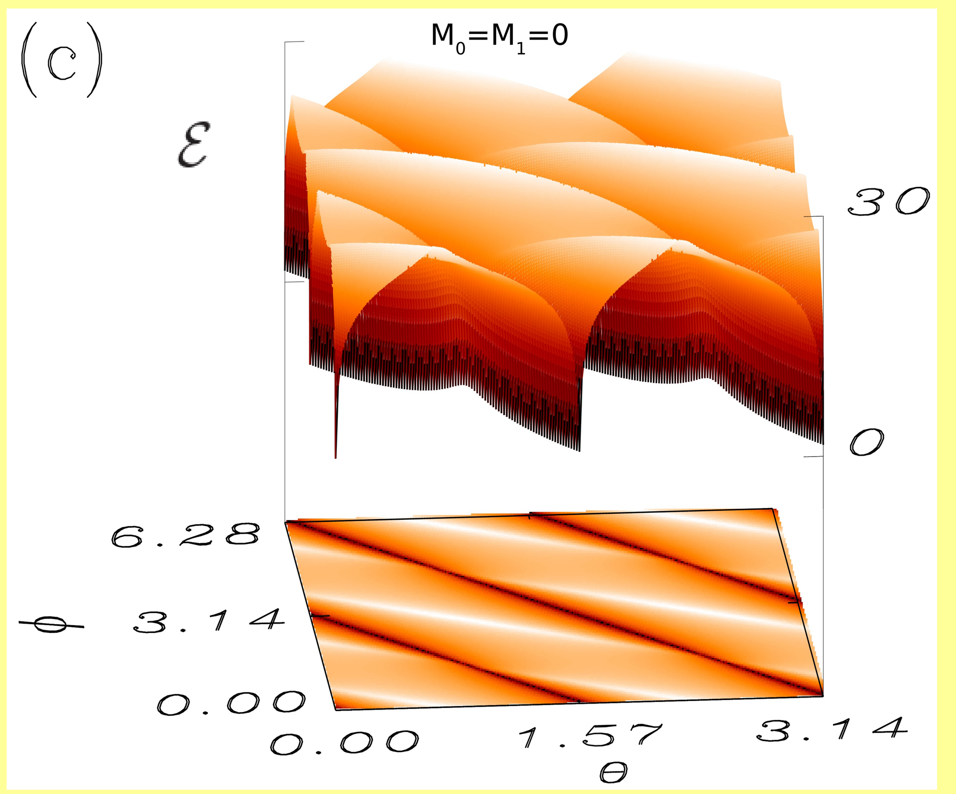


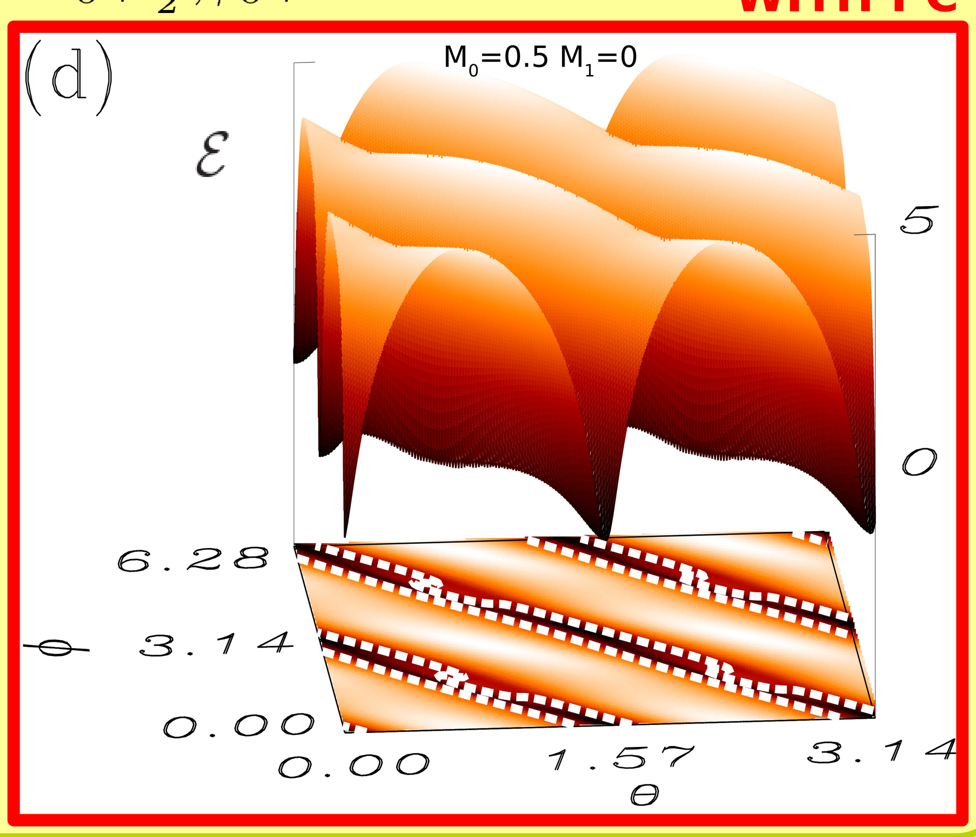


Reid *et al.* EPR entanglement criterion

$$\mathcal{E} = \Delta^2\Sigma_{\theta_0,\phi_0}\Delta^2\Sigma_{\theta_0+\frac{\pi}{2},\phi_0+\pi} \le 1$$

WITH PC





Conclusions

- Photonic Crystals allow to tune parametric and modulational instability threshold in optical parametric oscillators. They are a versatile tool to control the pump energy needed to obtain signal emission.
- Squeezing above threshold is improved: quadrature squeezing appears over a wider angular range in presence of Photonic Crystals due to translational symmetry breaking.
- For a not translational invariant system, we find significant regions in which both EPR paradox and state inseparability [4] are predicted. Spatial entanglement appears due to the introduction of the PC in the OPO.

References

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