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ScienceDirect
Superlattices and Microstructures 41 (2007) 297–300
Superlattices and Microstructures
www.elsevier.com/locate/superlattices

Vortices in the microcavity optical parametric oscillator

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Available online 23 April 2007

Abstract

A theoretical treatment is presented for a novel from of optical vortex state, in a microcavity optical parametric oscillator (OPO). The state comprises a vortex/anti-vortex pair in the signal and idler beams, with a Gaussian pump. A numerical solution of the microcavity OPO equations shows that such a vortex can be stable.

Keywords: Optical parametric oscillator; Optical vortex; Theoretical modelling

The phenomenon of the microcavity optical parametric oscillator (OPO) is well established: when a planar microcavity is pumped at a finite angle (10°–20°) to the surface normal, coherent signal and idler beams are generated, with one, defined as the signal, always close to the normal direction, and the idler on the high angle side of the pump [1,2]. This is a rather unusual type of OPO, in that the underlying excitonic non-linearity is $\chi^{(3)}$ rather than $\chi^{(2)}$, so the phase matching conditions on the frequencies and wave-vectors are $2\omega_p = \omega_s + \omega_i$ and $2k_p = k_s + k_i$.

Vortices can be formed in many systems with two-dimensional scalar fields; they are states where the phase of the field winds about a point, the vortex core. Typical systems where vortices are found include bosonic condensates, such as dilute gases, liquid helium and superconductors. However, they also occur in classical systems, particularly electromagnetic fields, with examples including optical vortex beams [3], and vertical cavity lasers [4]. This latter case is probably the closest to the present study, as it corresponds to a non-linear dissipative system, though it is electrically, not optically, driven, and involves only one coherent field. The vortices in the microcavity OPO are thus more complicated, in that they involve three coherent fields; the pump

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0749-6036/$ - see front matter
doi:10.1016/j.spmi.2007.03.032

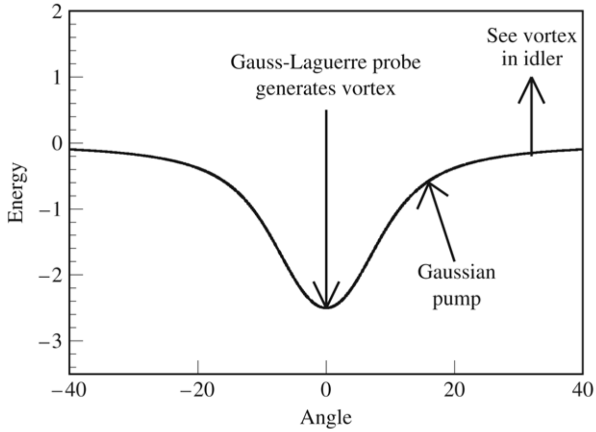

Fig. 1. Schematic diagram of the microcavity OPO dispersion, showing the proposed method for generating a vortex, using a Gauss–Laguerre probe beam to ‘stir’ the signal. The corresponding anti-vortex should appear in the idler. The probe could be continuous wave or pulsed.

is in a state of zero angular momentum, $m_p = 0$, while the signal and idler carry a vortex–anti-vortex pair, $m_s = -m_i$, so that angular momentum is conserved in the non-linear scattering process: $2m_p = m_s + m_i$.

The microcavity OPO has been treated theoretically both in a microscopic quantum [5] model and as a classical [6,7] non-linear optical effect, though in the former case, mean field approximations mean that the equations developed are essentially the same in the two descriptions. Details of the numerical treatment of these equations have been described elsewhere [8]. Briefly, the numerical solution is obtained in the time domain on a two-dimensional spatial grid, using an alternating-direction implicit algorithm. For the results presented here, the grid comprised $2^9 \times 2^9$ points. Time resolved images of the pump, signal and idler polariton populations are obtained by filtering short time sequences of data in the frequency domain to separate the different modes.

The proposed method of introducing vortices into the OPO, shown in Fig. 1, is to use a probe pulse to ‘stir’ the signal state. The pulse is chosen to have an energy and angle matching those of the signal, and has a Gauss–Laguerre spatial profile with finite angular momentum, m_s. Driving the system like this causes it to behave as a parametric amplifier, generating an idler containing an anti-vortex with $m_i = -m_s$, which conserves angular momentum in the scattering process. The probe pulse could be continuous, in which case a steady vortex would be obtained, or it could be a short pulse, in order to investigate issues such as the stability and dynamics of the vortex state.

Fig. 2 shows a vortex created in the OPO state using the stirring method described above. Comparison of the phase plots for the signal and idler demonstrates that $m_i = -m_s$, as expected. The image corresponds to a time ∼1 ns after the end of the probe pulse. This is a very long time compared with the characteristic timescales of the system (∼ps), so it is reasonable to claim that the vortex is, within the model, a stable state. It should be noted that it is not always the case that a stable vortex is obtained. In the transient period, just after the probe has been removed, there is a tendency for the vortex core to drift around the spot before settling down. Sometimes, and particularly at powers close to threshold, the core drifts right out of the spot and the vortex disappears. There are, of course, other processes which could destroy the vortex, which are not