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WW5

Vortex Nucleation and Evolution in Parametric Wave Mixing

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Singular light beams, that contain topological wave front dislocations are ubiquitous entities that display fascinating properties with widespread important applications. [1] Screw dislocations, or vortices, are a common dislocation type. They are spiral phase-ramps around a singularity where the phase of the wave is undefined and its amplitude vanishes. The order of the screw dislocation multiplied by its sign is referred to as the winding number, or topological charge of the dislocation. Vortices appear spontaneously in several settings, including in speckle-fields, in optical cavities and in the doughnut laser modes, and otherwise they can be generated with phase masks, or with astigmatic optical components. Vortices also form by self-wave front modulation in nonlinear optical media. In this context, parametric wave mixing of multiple waves propagating in quadratic nonlinear media constitutes a fascinating scenario. In this paper we predict a variety of new phenomena, that includes the spontaneous nucleation of multiple vortex twins, vortex rotation and drift, vortex-antivortex interaction and annihilation, and formation of quasi-aligned patterns of single-charge vortices.

We consider cw light propagation in a bulk quadratic nonlinear crystal under conditions for type I second-harmonic generation. We restrict ourselves to up-conversion geometries with material and light conditions that yield negligible depletion of the pump fundamental frequency (FF) beam. Then, the second-harmonic (SH) beam is dictated by an inhomogeneous linear partial differential equation whose general solution can be obtained by means of the Green function approach. In the case of un-seeded geometries (i.e., no SH input light), and in absence of Poynting vector walk-off between the FF and SH beams, sum- and difference-charge arithmetic operations have been predicted and observed experimentally. [2-4] However, a new range of phenomena is discovered in seeded geometries and with Poynting vector walk-off. In particular, in the case of seeded schemes without walk-off, our numerical and experimental investigations show the spontaneous nucleation of multiple-vortex twins. [5] In such case, the number of vortices present in the SH beam and its total topological charge varies with the propagation distance inside the crystal. Figure 1 shows a typical example of the vortex pattern that is typically obtained.

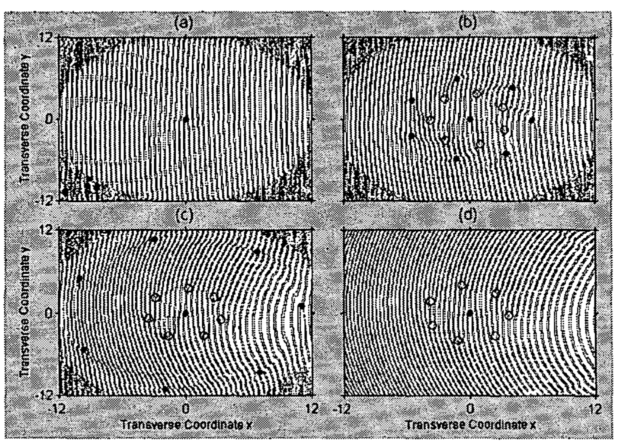

Figure 1: Numerically obtained interferograms for the SH beam at different propagation distances inside the nonlinear crystal. Filled dots: Positive vortices; open dots: Negative vortices. Input conditions are: FF pump peak amplitude A_0=0.1, SH seed peak amplitude A_0^s=.01, width of the two fields $w_{0s}=w_{0v}$=2, and exact phase-matching (β=0). FF charge is 3. SH charge is -1. Propagation distances: (a) ξ=0.5, (b) ξ=1.5, (c) ξ=2. and (d) ξ=3.

Walk-off introduces a new range of phenomena. In the case of un-seeded schemes with a Gaussian pump beam with a single-charge vortex nested, one finds that the generated SH beam is given by the expression [6]

$$a_2(x,y,\xi)=\frac{A_0^2}{(1+j2\xi)^3}\int_0^{\xi}\frac{[x+\delta(\xi-\xi')+jy]^2}{1+j2\xi'}\exp\left\{-2\frac{[x+\delta(\xi-\xi')]^2+y^2}{1+j2\xi}\right\}\exp(-j\beta\xi')d\xi' \qquad (1)$$

Here the transverse coordinates are normalized to the FF beam width η, and the propagation coordinate ξ is normalized to twice the diffraction length of the FF beam $L_{d1}=k_1\eta^2/2$. The parameter β is given by $\beta=k_1\eta^2\Delta k$, where $\Delta k=2k_1-k_2$ is the wave vector mismatch. k_1 and k_2 are the linear wave numbers. The parameter δ stands for the Poynting vector walk-off that occurs in birefringent media when propagation is not along the crystalline optical axes. Its is given by $\delta = \pm 2L_{dl}/L_w$, where $L_w = \eta/|\rho|$ is the walk-off length: ρ is the walk-off angle.

Expression (1) can be evaluated numerically in a mesh of transverse points at each value of the propagation distance. To analyze the presence of screw wave front dislocations in the obtained SH beam, we monitored the interference pattern arising by superposing the obtained SH beams with a reference plane wave tilted slightly relative to the propagation axis. The resulting wave amplitude exhibits a characteristic fork at the position of the dislocation and its topological charge is visually evaluated. The number and precise location of all the dislocations was then determined by numerically harvesting all the complex zeroes of (1).

At short propagation distances and small walk-off parameters, diffraction and walk-off affect weakly the beam evolution. The only effect induced by the presence of walk-off is the splitting of the double-charge vortex into two single-charge vortices.[7] However a new range of phenomena is discovered when both δ and the propagation distance are increased so that the competition between diffraction and walk-off can manifest itself. Figures 2 and 3 show a representative example of the scenario encountered. The plots correspond to δ=2, which stands for material and light conditions where walk-off and diffraction compete on similar footing, and to exact phase-matching.

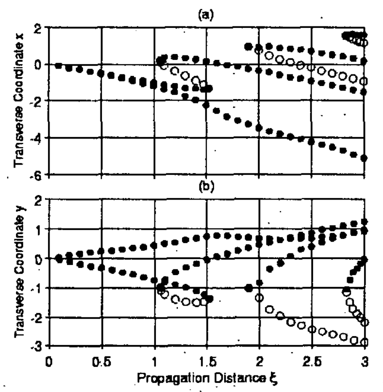

Figure 2: Location of all single-charge vortices present in the SH beam as a function of crystal length. Filled dots: Positive vortices; open dots: negative vortices. Conditions: δ=2, β=0.

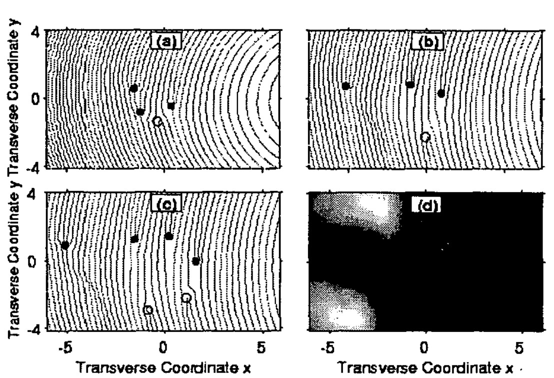

Figure 3: In (a)-(c): Interferograms for the SH beam obtained at selected distances. In (d): amplitude of the SH beam shown in (b). Conditions : δ=2, β=0. Propagation distances: (a) ξ=1.2; (b) ξ=2.4; (c) ξ=3

One finds that as the SH beam propagates and walks off the location of the pump FF beam, multiple vortex twins having a zero net topological charge are continuously nucleated. Such twins explode into the vortices with positive and the negative charges that they contain, which then move away from the birth point. Figure 2 displays the evolution of the transverse location of all the single-charge vortices present in the SH beam as a function of propagation distance as predicted by (1). Figures 3(a)-(c) show the interferograms obtained at selected instances of the beam evolution. The filled dots appearing in the plots stand for vortices with positive charges, defined as those that have the same helicity as the pump FF beam, and the open circles to vortices with negative charge. After the explosion of the nucleated vortex twins, the resulting single-charge vortices move away and interact with each other. Such interaction can include rotation, drift, and vortex-antivortex annihilation when those meet at the same point, as it is visible in Fig.2(b). In any case, one remarkable feature revealed by the calculations is that the vortices that eventually survive arrange themselves in a quasi-aligned geometry, with all the vortices in each line having the same topological charge, either positive or negative. Figure 3(d) shows the amplitude of the SH beam that is observed under such conditions. The location of the self-ordered vortices, one at each of the darkest spots, is clearly visible.

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