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A Study on Scale Free Optics

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ABSTRACT

In this paper we describe the progress in the study of scale-free optical propagation when the cooling rate is above threshold value. In order to grasp the core idea behind scale-free optics, paraxial ray scalar approximation, has been considered. Diffraction-free (zero effective wavelength) solutions of equation(5) are scale free. This effect has been found in the Gaussian exact solution for $8kK = \frac{L^2}{\lambda^2} = 1$.

Keywords: scale-free optics, paraxial ray scalar approximation.

INTRODUCTION

The basic idea underlying scale-free propagation is that when light propagates in a medium in which non-linearity introduces an intensity- independent response that amounts to anti-diffraction[1,5].

Recent experiments report on the demonstration of scale-free propagation in disordered ferroelectric KTN: Li (a newly engineered cu-doped lithium enriched potassium-tantalate-niobate) crystals[6]. In this system a specific role is played by i) ferro-electricity, ii) photo-refraction i) Ferro-electricity is the property of a dielectric to manifest, below a specific Curie temperature, a spontaneous breaking of the crystal symmetry and an associated finite static electric polarization that can be switched through an external bias field. ii) A ferroelectric electro-optic crystal can also be photorefractive. Photo refraction is characterized by a strong optical non-linearity mediated by an indirect optical self-action: light photo induces charges from in-band impurities that redistribute in the crystal through drift and diffusion and give rise to a space-charge field which, through the electro- optic effect, changes the index of refraction and hence the propagation of the light itself. To understand the phenomena of diffraction cancelation, we recall that photo-refraction leads to a diffusive nonlinearity[7,8], which profoundly alters beam propagation, in that diffraction is goverened by an effective refractive index[9,11] n_{eff}

$$n_{eff} = \frac{n_0}{(1-(L/\lambda)^2)}, \tag{1}$$

Where n_0 is the unperturbed refractive index, λ the wavelength and $L = 4\pi n_0^2 \varepsilon_0 \sqrt{g}\chi_{NPR}(K_B T/q)$. Here, g is the effective quadratic electro-optic coefficient, χ_{NPR} is the effective history-dependent low-frequency dielectric susceptibility of the dipolar glass, K_B the Blotzmann constant, T the crystal equilibrium temperature (i.e. the temperature measured at a given instant) and q is the charge of the photoexcited carriers. Eq(1) is valid for $\lambda \geq L$. As $L \rightarrow \lambda$, n_{eff} □ n_0 and diffraction is cancelled, the scale-free regime, independently of beam size and intensity. Scale- free optics opens the way to a number of enticing effects, such as wavelength-intensive propagation[10] and scale-free spatial instability[12].

MODEL

In order to grasp the core idea behind scale-free optics, we consider the propagation of an optical wave in the paraxial scalar approximation[13]. The slowly varying part of the optical field A (i.e. $|A|^2 = I$ is the optical intensity) obeys the paraxial wave equation

$$2ik\partial_Z A + \nabla_\perp^2 A + \frac{2k^2}{n}\Delta n A = 0 \tag{2}$$

Where, $k = (\omega/c)n$ is the wave number, ω is the optical angular frequency, z is the propagation direction of the beam and $\perp \equiv (x, y)$ are the two transverse coordinates and n is the electro optic response of the PNR [14-19]. It is expressed as

$$\Delta n_{PNR} = -\frac{n^3}{2} g\varepsilon_0^2 \chi_{PNR}^2 E \tag{3}$$

and the diffusive photo-induced electric field is

$$E = -\frac{K_B T}{q}\frac{\Delta I}{I} \tag{4}$$

Substituting (3) in (2)

$$\Delta n = \Delta n_{PNR} = -\frac{n^3}{2} g\varepsilon_0^2 \chi_{PNR}^2 \left(\frac{K_B T}{q}\right)^2 \frac{(\partial_x I)^2 + (\partial_y I)^2}{I^2} \tag{5}$$

With $g = g_{11} + g_{12}$ (that depends on the specific PNR- supporting ferroelectric used).

Inserting the non linear response term, Δn in equation (2), the nonlinear propagation equation is

$$i\frac{\partial A}{\partial Z}+\frac{1}{2k}\nabla_{\perp}^{2}A-K\frac{\left(\frac{\partial|A|^{2}}{\partial x}\right)^{2}+\left(\frac{\partial|A|^{2}}{\partial y}\right)^{2}}{|A|^{4}}A=0, \tag{6}$$

Where

$$K=kg\left(\frac{n\varepsilon_{0}\chi_{PNR}K_{B}T}{\sqrt{2}q}\right)^{2}$$

The focusing/defocusing nature of the effect depends on the sign of $g=g_{11}+g_{12}$ .i.e., on the specific lattice structure of the underlying composite crystal.

In the case of KTN:Li, here considered, $g_{11}\rangle 0$ is dominant with respect to $g_{12}\langle 0$, which is an order of magnitude smaller, such that $g_{11}+g_{12}\rangle 0$ (g_{11}=0.16 m ^{4} C^{-2}, g_{12}=-0.02 m ^{4} C^{-2}), and the effect is self focusing[14].

Introducing the anstaz, $A(x,y,z)=A_{0}(x,y,z)e^{-i\Omega(x,y,z)}$ in equ. (6)

$$\left(i\frac{\partial A_0}{\partial Z}+A_0\frac{\partial\Omega}{\partial Z}\right)$$
$$+\frac{1}{2k}\left\{\left(\frac{\partial^2 A_0}{\partial x^2}+\frac{\partial^2 A_0}{\partial y^2}\right)-2i\left(\frac{\partial A_0}{\partial x}\frac{\partial\Omega}{\partial x}+\frac{\partial A_0}{\partial y}\frac{\partial\Omega}{\partial y}\right)-i\left(A_0\frac{\partial^2\Omega}{\partial x^2}+A_0\frac{\partial^2\Omega}{\partial y^2}\right)-\left(A_0\left(\frac{\partial\Omega}{\partial x}\right)^2+A_0\left(\frac{\partial\Omega}{\partial x}\right)^2\right)\right\} \tag{7}$$
$$-K\frac{\left(\frac{\partial|A_0|^2}{\partial x}\right)^2+\left(\frac{\partial|A_0|^2}{\partial y}\right)^2}{|A_0|^4}A_0=0$$

Equating real and imaginary parts separately, we get following two equations:

$$A_0\frac{\partial\Omega}{\partial Z}+\frac{1}{2k}\left\{\left(\frac{\partial^2 A_0}{\partial x^2}+\frac{\partial^2 A_0}{\partial y^2}\right)-\left(A_0\left(\frac{\partial\Omega}{\partial x}\right)^2+A_0\left(\frac{\partial\Omega}{\partial y}\right)^2\right)\right\}-K\frac{\left(\frac{\partial|A_0|^2}{\partial x}\right)^2+\left(\frac{\partial|A_0|^2}{\partial y}\right)^2}{|A_0|^4}A_0=0 \tag{8}$$

and

$$\frac{\partial A_0}{\partial Z}-\frac{1}{k}\left(\frac{\partial A_0}{\partial x}\frac{\partial\Omega}{\partial x}+\frac{\partial A_0}{\partial y}\frac{\partial\Omega}{\partial y}\right)-\frac{1}{2k}\left(A_0\frac{\partial^2\Omega}{\partial x^2}+A_0\frac{\partial^2\Omega}{\partial x^2}\right)=0 \tag{9}$$

We look for a solution of the form

$$A_0(x,y,z) = \frac{A_{00}}{\sqrt{f_1(z)}\sqrt{f_2(z)}} e^{-\frac{x^2}{2r_0^2 f_1^2(z)}} e^{-\frac{y^2}{2r_0^2 f_2^2(z)}} \quad 10(a)$$

and

$$\Omega = \frac{x^2}{2}\beta_1(z) + \frac{y^2}{2}\beta_2(z) \quad 10(b)$$

Where, $\beta_1(z) = -\frac{k}{f_1}\frac{\partial f_1}{\partial Z}$ and $\beta_2(z) = -\frac{k}{f_2}\frac{\partial f_2}{\partial Z}$ and $r_0 f_1$ and $r_0 f_2$ are the beam width parameters in the x and y directions respectively f_1 and f_2 are functions of z. Putting 10(a) and 10(b) in equ.(8) we get

$$\frac{kx^2}{2f_1}\frac{\partial^2 f_1}{\partial Z^2} + \frac{ky^2}{2f_2}\frac{\partial^2 f_2}{\partial Z^2} + K\frac{4x^2}{f_1^4 r_0^4} + K\frac{4y^2}{f_2^4 r_0^4} - \frac{x^2}{2kf_1^4 r_0^4} - \frac{y^2}{2kf_2^4 r_0^4} + \frac{1}{2kf_1^2 r_0^2} + \frac{1}{2kf_2^2 r_0^2} = 0 \quad (11)$$

Collecting the coefficients of x^2andy^2 from eqn. (11), we can easily derive the following pair of coupled nonlinear differential equations.

$$\frac{\partial^2 f_1}{\partial Z^2} = \left(\frac{1}{k^2}\right)\frac{1}{f_1^3 r_0^4} - \left(\frac{8K}{k}\right)\frac{1}{f_1^3 r_0^4} \quad 12(a)$$

$$\frac{\partial^2 f_2}{\partial Z^2} = \left(\frac{1}{k^2}\right)\frac{1}{f_2^3 r_0^4} - \left(\frac{8K}{k}\right)\frac{1}{f_2^3 r_0^4} \quad 12(b)$$

For $f_1 = f_2 = 1$

$$\frac{1}{kr_0^4} - \frac{8K}{kr_0^4} = 0$$

$\frac{1}{k} - 8K = 0$ or $8K = \frac{1}{k}$

Therefore, $8Kk = 1$ (13)

Eq.(13) can be stated in terms of PNR susceptibility: $\chi_{PNR} \geq \chi_{thr} \square 10^5$, which also states that there exist a critical value for the non-linear optical response due the PNR[15-19] for which $L = \lambda$ ($\lambda = 632.8nm$ in our experiments). Notably enough, the density and the size of the PNR, that are directly related to the cooling rate, determine χ_{PNR} : as a result the scale-free regime will exist only above a cooling rate threshold. Diffraction free (zero effective wavelength) solutions of Eq.(6) are scale free. This effect is found in the Gaussian exact solution for $8kK = 1$.

CONCLUSION

We find that the Gaussian scale-free solutions when the condition $8kK = \frac{L^2}{\lambda^2} = 1$ is satisfied and diffraction is fully cancelled. When, $8kK \rhd 1$, a wholly new optics can be predicted.

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