Self-Focusing of an Intense Laser Pulse Propagating in a Magnetized Bulk Medium of Graphite Nanoparticles

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Abstract- In this paper self-focusing of an intense laser pulse propagating through a magnetized bulk medium containing graphite nanoparticles is studied. Using a perturbative method, wave equation describing nonlinear interaction of laser fields with graphite magnetized nanoparticles is derived. Evolution of laser spot size for the circular polarization with Gaussian profile is considered. An especial attention is paid on the role of external magnetic field in the self-focusing.

Keywords: laser, nanoparticles lattice, nonlinear wave equation, self-focusing, spot size
Self-Focusing of an Intense Laser Pulse Propagating in a Magnetized Bulk Medium of Graphite Nanoparticles

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1 Introduction

Nonlinear interaction of laser with one-dimensional periodically nanostructured metals can lead to the localization or focusing of light in a region with characteristic dimensions smaller than the incident wavelength. This phenomenon called nano-focusing. Such a nano-focusing property is observed theoretically and experimentally in the interaction of laser with determinate number or chain of nanoparticles [1,2]. Moreover, localization of intense Electromagnetic Wave (EMW) can occur macroscopically during interaction of laser with a bulk medium consisting nanoparticles via so-called well-known phenomenon Self-Focusing (SF) [3] that appears via the change of the medium refractive index exposed to the intense EM radiation. SF of unmagnetized bulk medium including metallic NPs has been studied theoretically by Sepehri Javan [4]. In this paper we have studied effect of external magnetic field on the SF of laser in the interaction with a bulk medium consisting of spherical graphite nanoparticles.

2 Nonlinear wave equation

We consider the propagation of an intense EMW through a magnetized bulk medium of graphite nanoparticles with average radius $r$, and average separation $d$. We suggest that the external magnetic field is along the $z$ axis $B_z = B_0 \hat{e}_z$. Electric and magnetic fields of the laser beam are as bellow

$$E_L = E^{(i)} = \frac{\hat{E}}{2} (\hat{e}_x + i \hat{e}_y) e^{-i(k_0 z - \omega t)} + c.c.,$$

(1)

$$B_L = B^{(i)} = -\frac{i c k c \hat{E}}{2 \omega} (\hat{e}_x + i \hat{e}_y) e^{-i(k_0 z - \omega t)} + c.c.,$$

(2)

where, $\hat{E}, k, c$ are the slowly varying amplitude, frequency and wave number of the laser, speed of light and $\sigma = +1, -1$, denotes the right- and left-hand circularly polarized waves, respectively. Equation describing the relativistic interaction of laser fields with electronic cloud of each nanoparticle can be written as

$$d(\vec{r})/dt + \Gamma \vec{r} + \omega_j^2 \vec{r} / 3 = -(e/m) \{ \vec{E}(0) + (r.\vec{\nabla})\vec{E}(0) + \vec{v} \times [\vec{B}(0) + \vec{B}_n] + (r.\vec{\nabla})\vec{B}(0) \}/c \}$$

(3)

where $\gamma, \vec{v}, \omega, \omega_j = (4 \pi n_e e^2 / m)^{1/2}$, $\Gamma, e$ and $m$ are the relativistic Lorentz factor, velocity, displacement of the electron cloud from the equilibrium state, electron plasma frequency, damping factor related to electron scattering, magnitude of electron charge and electron rest mass, respectively, $\vec{E}(0)$ and $\vec{B}(0)$ represent the electromagnetic fields in the center of the particle. First order momentum equations is

$$dv^{(i)}/dt + \Gamma v^{(i)} + \dot{\omega}^2 r^{(1)} / 3 = -(e/m) \{ E^{(i)}(0) + (v^{(i)} \times B_n) \}/c \}$$

(4)

where superscripts (1) refer to the first order perturbed parameters. The solution of Equation (4) is

$$v^{(i)} = \frac{-i}{2} \frac{a c \omega^2 e^{-i(k_0 z - \omega t)}}{(\omega^2 + i \Gamma \omega - \omega_j^2 / 3 - \sigma \omega_j)} + c.c.,$$

(5)

where $a = e \hat{E} / mc \omega$ is the normalized laser amplitude. We know that circular EMW cannot cause the second order displacement of electrons. The third-order equation of the electron cloud movement is
\[ d[\mathbf{v}^{(3)} + \mathbf{v}^{(1)}] / dt + \Gamma \mathbf{v}^{(3)} + \omega_0^2 \mathbf{v}^{(3)} / 3 = -e(\mathbf{v}^{(3)} \times \mathbf{B}_0) / mc . \]  

(6)

From Equation (6) we can obtain

\[ \mathbf{v}^{(3)} = i a^3 c \omega e^{-i(\omega_0 z - k z)} \left( \mathbf{\hat{e}}_x + i \mathbf{\hat{e}}_y \right) \]

\[ \times \left[ (\omega^2 + i \Gamma / \omega - \omega_0^2 / 3 - \sigma \omega_0) \right]^{2} + c.c. \]

\[ \times 4[(\omega^2 - \omega_0^2 / 3 - \sigma \omega_0) \right]^{2} + \Gamma^2 \omega^2 \]  

(7)

Graphite consists of atoms regularly located on planes (basal planes) which are equally separated from each other. Quality of EMW propagation is different in the case of parallel or perpendicular orientation of electric field with respect to the graphite basal plane. We will use indices \( \perp \) and \( \parallel \) for the configurations \( E \perp \hat{n} \) and \( E \parallel \hat{n} \), respectively, where \( \hat{n} \) is a unit vector normal to the basal plane. Now we consider a bulk medium including equal amounts of two different sorts of graphite nanoparticles, i.e. \( \perp \) and \( \parallel \) orientations of basal planes. We suppose that statistically both kinds of nanoparticles have same average radius and separation. For such a medium we can write the following wave equation

\[ (\nabla^2 - \frac{\varepsilon_{eff}}{c^2} \frac{\partial^2}{\partial t^2}) \mathbf{E} = \frac{4 \pi \varepsilon_{0}}{c^2} \frac{\partial \mathbf{J}}{\partial t}, \]  

(8)

where \( \mathbf{J} = -\sum_{\text{species}} (4 \pi \varepsilon_{0}) (n_{0,i})(\mathbf{v}^{(i)} + \mathbf{v}^{(3)}) \) is the total macroscopic current density, index \( s \) denotes sort of orientation of basal plane of nanoparticle, \( n_{0,i} \) is the electron density of the electron cloud, \( l_{s} = (r_{s}/d_{s})^{3} \) and \( \varepsilon_{eff} \) is the effective permittivity related to the bound electrons of medium. Using Equation (1) and multiplying both sides of Equation (11) by \( \varepsilon_{0}/mc \omega \) yields

\[ \left[ (\nabla^2 - \frac{\varepsilon_{eff}}{c^2} \frac{\partial^2}{\partial t^2}) \right] \mathbf{E} e^{-i\omega_{0} t - k z} = \left[ \frac{4 \pi \varepsilon_{0}}{3 c^2} \right] [H] \mathbf{E} e^{-i\omega_{0} t - k z} \]  

(9)

where \( \omega_{0} = eB_{0}/mc \) is electron cyclotron frequency.

\[ H = \sum_{s \perp} \left( \omega_{0}^{2} \omega_{s} / (\omega_{0}^{2} + i \Gamma / \omega - \omega_{s}^{2} / 3 - \sigma \omega_{s}) - \omega_{s}^{2} \right) N_{s} \cdot \mathbf{a}^{(s)} \]  

and

\[ \mathbf{N}_{s} = \left( \omega_{0}^{2} \omega_{s} / (\omega_{0}^{2} + i \Gamma / \omega - \omega_{s}^{2} / 3 - \sigma \omega_{s}) \right)^{2} 2[(\omega^{2} - \omega_{0}^{2} / 3 - \sigma \omega_{s})^{2} + \Gamma^{2} \omega^{2}] \]  

In the absence of interaction, when \( a = a_{0} \) is a constant, Equation (9) leads to the following nonlinear dispersion relation

\[ D_{NL} = k^{2} - \omega_{0}^{2} \varepsilon_{eff} / c^{2} + (4 \pi / 3 c^{2}) H = 0. \]  

(10)

3 Envelope evolution

To study the problem of SF we use a method like the well-known source dependent expansion (SDE) method [5]. First, we introduce dimensionless electric field of laser as following

\[ a(r, \theta, z, t) = a(r, \theta, z) e^{i(kz-\omega t)} / 2 + c.c., \]  

(11)

Substituting Equation (11) in Equation (9) results

\[ \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{k^2}{\partial \theta^2} + \frac{2i}{c} \frac{\partial}{\partial \varphi} \right] a(r, \theta, z) = S(r, \theta, z), \]  

(12)

where the source term of the right hand side is

\[ S(r, \theta, z) = \frac{\omega_{0}^{2}}{c^{2}} [1 - n^{2}(r, \theta, z, a)] a(r, \theta, z) \]  

(13)

and nonlinear complex refractive index can be achieved from equation (10)

\[ n^{2} = \varepsilon_{eff} - 4 \pi H / (3 \omega^{2}). \]  

(14)

By expansion of the amplitude \( a(r, \theta, z) \) as a series of associated Laguerre-Gaussian source-dependent modes [5], we obtain Equation (12) as

\[ \frac{d^{2} r_{s}}{d z^2} + 2 C_{2} \frac{d r_{s}}{d z} + C_{3} r_{s} - C_{4} r_{s}^{3} - \frac{C_{5}}{r_{s}^{2}} = 0, \]  

(15)

where

\[ C_{1} = \left( F_{1,0} / a_{0,0} \right) \text{Re}, \quad C_{2} = \left( F_{1,0} / a_{0,0} \right) \text{Im}, \]

\[ C_{3} = (2c / \omega)^{3}, \quad C_{4} = (4c C_{3} / \omega) \]  

and indices Re and Im refer to the real and imaginary parts of any quantity. \( F_{1,0} \) and \( a_{0,0} \) have been introduced in Ref. [5] and for brevity we don’t bring them here.

4 Numerical discussions

A numerical analysis has been carried out in order to solve equation (15) for finding spatial evolutions of laser spot size. It is well-known that effect of external magnetic field on the nonlinear property of circularly polarized left-hand laser beam is inverse [4,6] and increase in the magnetic field leads to decrease in the nonlinearity of medium and consequently to decrease in the self-focusing quality of laser, therefore we consider only the right-hand polarization. Figure (1) shows variations of normalized laser spot size \( r_{s} / r_{0} \) with respect to normalized propagation distance.
We investigated SF of an intense laser pulse in a magnetized bulk medium of graphite nanoparticles. Spot size evolution of right-handed circularly-polarized laser is studied. Effect of external magnetic field on the SF is considered. It is observed that increase in the magnetic field causes improvement of focusing property of medium.

Figure 1: Variation of $r_z/r_0$ with respect to $z/z_R$ for five different values of external magnetic field.

Figure 2: Variation of $r_z/r_0$ with respect to $z/z_R$ for unmagnetized and magnetized cases.

5 Conclusion

We investigated SF of an intense laser pulse in a magnetized bulk medium of graphite nanoparticles. Spot size evolution of right-handed circularly-polarized laser is studied. Effect of external magnetic field on the SF is considered. It is observed that increase in the magnetic field causes improvement of focusing property of medium.

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