Optics Communications 358 (2016) 92–96

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Self-focusing threshold of partially coherent light in large mode area fibers

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ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form
5 September 2015
Accepted 7 September 2015
Available online 18 September 2015

MSC:
00-01
99-00

Keywords:
Incoherence
Self-focusing
Kerr effect
Fiber optics

ABSTRACT

Coherent property of light is taken into consideration by utilizing Wigner transform method in solving self-focusing threshold of partially coherent light in LMA silica fibers. The formula for self-focusing threshold applicable for both coherent and partially coherent light in LMA silica fibers is derived, which only depends on beam quality factor M^2 and bandwidth $\Delta\lambda$. It can be conveniently used to estimate self-focusing threshold in experiment and design partially coherent high power fiber amplifiers.

1. Introduction

With rapid development of high power pulsed fiber lasers and amplifiers, the pulse peak powers are getting increased. Megawatt level peak powers have been reported by many groups [1–5]. With such high peak power, self-focusing effect becomes the most important factor that limits the fiber amplifier output power [6].

Self-focusing effect has been theoretically predicted and experimentally verified for over 50 years [7–9]. Theory of self-focusing effect gives the widely accepted power threshold for self-focusing $P_{cr} = \alpha\lambda^2/(4\pi n_0 n_2)$ [10]. It is worth noting that this threshold formula is under the hypothesis that the propagated light is coherent. In recent years, incoherent light source with large amount of random-phased longitudinal modes becomes popular in the application areas such as imaging Lidar and smooth irradiation for high energy physical experiments [11], as it can suppress the speckle noise, realize smooth irradiation and in the meanwhile retain good beam quality in fiber as common fiber laser does. However, to the best of our knowledge, the self-focusing threshold formula for partially coherent light in LMA fibers has not been given so far. In this paper, the self-focusing threshold of partially coherent light such as SLD or ASE source in LMA silica fibers is numerically investigated. The self-focusing power threshold suitable for both coherent and partially coherent light in LMA fibers is found. Given measured or estimated M^2 and bandwidth $\Delta\lambda$, self-focusing threshold in LMA fibers can be readily calculated, which can be conveniently used in experiment and is instructive for designing partially coherent high power fiber amplifiers.

2. Self-focusing theory for partially coherent light

There are mainly four approaches developed to describe partially coherent light propagating in inertial nonlinear media, namely the propagation equation for the mutual coherence function, the coherent density method, the self-consistent multimode theory and Wigner transform method. In 2003, Lisak et al. demonstrated that those four approaches are in fact equivalent [12,13]. Among them Wigner transform method describes the electric field by combining its spatial (or temporal) intensity distribution and spatial (or temporal) mutual coherence distribution. This kind of description has advantages that it can easily and correctly describe beams spatial (or temporal) partially coherent

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http://dx.doi.org/10.1016/j.optcom.2015.09.024

properties. Therefore, Wigner transform method is used to study the self-focusing of partially incoherent light in this paper. Wave propagation in nonlinear medium for linearly polarized light is based on the nonlinear Schrodinger equation shown in the following equation:

$$i\frac{\partial\psi(x,y,z)}{\partial z}+\frac{\beta}{2}\nabla^2\psi(x,y,z)+\kappa I(x,y,z)\psi(x,y,z)=0 \quad (1)$$

where ψ is the linearly polarized electric field, $\beta = 1/k_0 n_0$ is the diffraction coefficient with k_0 is the vacuum wave number and n_0 the refractive index, $\kappa = n_2\omega_0/c$ is the Kerr coefficient with n_2 being the nonlinear index of refraction, ω_0 the angular frequency of light and c the speed of light in vacuum, $I(x, y, z)$ is the light intensity distribution. When the Kerr effect is strong enough, the light will be confined in the center of the core and barely samples the cladding. In other words, the light will be guided by the instant refractive index distribution induced by the Kerr effect, as it does in a bulk medium [14]. Therefore it is justifiable to neglect the waveguide structure when self-focusing happens in LMA fibers. Note that the effect of group velocity dispersion is neglected in Eq. (1). It can be calculated [15] that the chromatic dispersion length is on the order of meter scale for light with a central wavelength of 1 μm and a bandwidth of about 10 nm, which is much longer than the self-focusing distance on the order of centimeter scale in a typical high power intensity system with a light intensity of 0.1 kW/μm^2 in LMA fibers. On this basis, group velocity dispersion can be neglected when self-focusing in the LMA fibers is studied. On this basis, group velocity dispersion can be neglected when self-focusing in LMA fibers is studied.

Define 2-D Wigner transform function as the following equation:

$$\rho(x,y,p_x,p_y,z) = \left(\frac{1}{2\pi}\right)^2 \times \int_{-\infty}^{+\infty} e^{i(p_x\xi+p_y\eta)}\left\langle \psi^*\left(x+\frac{\xi}{2},y+\frac{\eta}{2},z\right)\psi\left(x-\frac{\xi}{2},y-\frac{\eta}{2},z\right)\right\rangle d\xi\, d\eta \quad (2)$$

where the bracket $\langle\ \rangle$ functions as taking statistical average of the function in the bracket to include the coherence properties of the light, which will be discussed in detail later. It can be seen from Eq. (2) that Wigner transform function $\rho(x, y, p_x, p_y, z)$ and mutual coherence function $\langle\psi^*(x+\xi/2, y+\eta/2)\psi(x-\xi/2, y-\eta/2)\rangle$ form a Fourier pair. Thus the distributions of p_x and p_y describe the coherent properties of the beam in x and y directions, respectively.

Eq. (1) can be converted to Eq. (3) by using Eq. (2) [16]

$$\frac{\partial\rho}{\partial z}+\beta\left(p_x\frac{\partial\rho}{\partial x}+p_y\frac{\partial\rho}{\partial y}\right)+2\kappa I\sin\left(\frac{1}{2}\left(\frac{\overleftarrow{\partial}}{\partial x}\frac{\overrightarrow{\partial}}{\partial p_x}+\frac{\overleftarrow{\partial}}{\partial y}\frac{\overrightarrow{\partial}}{\partial p_y}\right)\right)\rho=0 \quad (3)$$

The sine operator is defined by its series expansion and the arrows indicate that the derivatives act to the left and the right, respectively. From Eq. (3) the modal area evolution equation shown in Eq. (4) can be derived as follows:

$$\frac{d^2\sigma^2}{dz^2}=2\beta(H-\beta \mathrm{P}^2) \quad (4)$$

where $\sigma^2 = \langle\langle \mathbf{r}^2\rangle\rangle - \langle\langle \mathbf{r}\rangle\rangle^2$ is the mode area with $\mathbf{r} = (x, y)$, H is the Hamiltonian and $\mathbf{P}$ is the momentum, defined as $H = \beta\langle\langle \mathbf{p}^2\rangle\rangle - \kappa\langle\langle I\rangle\rangle$ and $\mathbf{P} = \langle\langle \mathbf{p}\rangle\rangle$ with $\mathbf{p} = (p_x, p_y)$. Here $\langle\langle\cdot\rangle\rangle$ is defined as

$$\langle\langle\chi(\mathbf{r},\mathbf{p})\rangle\rangle=\frac{\iint\chi(\mathbf{r},\mathbf{p})\rho(\mathbf{r},\mathbf{p},z)d\mathbf{r}\,d\mathbf{p}}{\iint\rho(\mathbf{r},\mathbf{p},z)d\mathbf{r}\,d\mathbf{p}} \quad (5)$$

A sufficient condition for collapse in the symmetric case is

$$2\beta(H-\beta\mathrm{P}^2)<0 \quad (6)$$

That means mode area is getting smaller with propagation distance getting farther. A numerical simulation method is put forward to solve Eq. (6). Firstly, given the beam intensity profile and transverse mutual coherence distribution, or in other words, given $\langle\psi^*(x+\xi/2, y+\eta/2)\psi(x-\xi/2, y-\eta/2)\rangle$, Wigner transform function $\rho(x, y, p_x, p_y)$ can be obtained by Eq. (2). Using Eq. (5) and the definitions of H and $\mathbf{P}$, the numerical expression of H and $\mathbf{P}$ is obtained. Note that H depends on intensity distribution $I(x, y)$, which can be expressed as $I(x, y) = Pf(x, y)$, where P is the beam power and $f(x, y)$ is the intensity profile normalized by power. Given intensity profile $f(x, y)$, self-focusing critical power P can be solved out from Eq. (6). In order to study the relationship between self-focusing power threshold and beam quality factor for partially coherent light in LMA fibers, beam quality factor defined [17] as $M^2=\overline{r^2}\,\overline{p^2}-(\overline{rp})^2$ is calculated in the simulations, which is found to have strong impact on self-focusing power threshold.

Before entering the detailed simulation results, we would like to show the validity of the theory we adopted and the correctness of the code we implemented by comparing our simulation results with those by other researchers. In paper [18], a 488 nm cw argon laser beam was sent through a rotating diffuser to generate a spatially incoherent light source. The self-focusing threshold of the light in the experiment was 35.4 times that under coherent condition. In our simulations, we assume that the beam had a waist as the same as in the experiment and adjust the mutual coherence level of the light to make M^2=6.18 as in the experiment. This partially coherent light was calculated to have a self-focusing threshold of 38.2 times that under coherent condition, which showed a good agreement with the experimental result (with relative error of less than 7%). In addition, several LP modes in LMA fibers and their corresponding beam quality factors M^2 were calculated and compared with the results given in paper [19]. Good agreement was found, with relative error of less than 3%. Furthermore, the self-focusing thresholds for LP_{11} and LP_{21} modes were calculated respectively, and found matched well with those by using BPM code [20] (with relative error of less than 5%).

3. Self-focusing threshold simulations for partially coherent light in LMA fibers

In order to solve self-focusing threshold for partially coherent light in LMA fibers, transverse mutual coherence distribution of the beam should be given in the simulation. Recently, Efimov measured the mutual coherence distribution of the partially coherent SLD light after propagating through multimode fibers [21]. He also built up a numerical model to simulate the mutual coherence distribution of partially coherent light after propagating in LMA fibers. The simulated results coincided with his experimental results quite well. In his model, the total light wave is considered as a linear incoherent addition of all the LP modes supported by the LMA fiber. Each LP mode is a linear incoherent addition of all the frequencies determined by the optical spectrum, which means each LP mode has a coherent time of τ_c in time domain. With more LP modes in the light wave, modal dispersion induced random phase change of the wavefront will be larger. If the phase of the total light wavefront changes to a substantially new one (ideally, it has zero correlation with the former phase status), we call that the wavefront has experienced one random phase change. Therefore, for light wave with certain bandwidth and propagating in LMA fiber for a certain distance, the more the LP modes there are, the larger number of times the random phase changes are experienced