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Relative contributions of higher-order Kerr effect and plasma in laser filamentation

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ABSTRACT

The respective contributions of the higher-order Kerr effect (HOKE) and plasma on the propagation of filamentation have been investigated by a modified model, which indicates that HOKE can act as a counterpart of plasma. The determining role of the combination of Kerr self-focusing, defocusing due to HOKE and the plasma generation in the formation of a lengthy filament is confirmed visually. It is favorable to support the view that the general standard Kerr-plasma model should be renewed in some cases accordingly.

1. Introduction

A recent experimental investigation in gases reported that the higher-order nonlinear refractive are sign reversal and proportional to the laser intensity [1,2]. Later on, this work arose an active and meaningful controversy in the ultra-fast nonlinear optics community and paved a new way for femtosecond filamentation. The sign changed refractive can be written as $\triangle n_{Kerr} = \sum n_{2j} I^j$ with $j \in N^*$. It indicates that the higher-order Kerr nonlinearity may play a defocusing mechanism, rather than plasma, in the filamentation process [3–7]. It may therefore come as a challenge that it is necessary to reconsider the current general understanding of the underlying physical paradigm of filamentation, which is based on the classical dynamic balance between Kerr self-focusing ($n_2 I$) and plasma defocusing induced by multiphoton ionization (MPI). To be true, several years ago, researchers recognized that higher-order effects can arrest catastrophic optical self-focusing [8,9] and presented nonlinear dispersion-free propagation phenomenon [10]. This launched the early research upsurge of HOKE. Nevertheless, many contrary views point out that the HOKE may not completely replace the plasma defocusing at play [11–16], because the relative contributions of the HOKE and plasma are not clear not only theoretically but also experimentally on the whole filament regime, due to the challenging and crucial of straightforward measurement. However, researchers experimentally confirmed that the higher-order Kerr terms do exist [7] and the associated defocusing effect should be considered in the standard Kerr effect-plasma (SKE-P) filamentation model. To be true, the existence of HOKE cannot prevent the generation of plasma, due to the high clamping intensity in the filaments.

In this paper, we mainly focus on the respective contributions of the HOKE and plasma in laser filamentation, based on a modified higher-order Kerr effect-plasma (HOKE-P) model. Therefore, once the validity of the HOKE providing the dominant defocusing effect, instead of plasma in the filaments under certain special conditions [7] is substantiated, one can extract the extent of HOKE at play. This finding will help to distinguish the relative contributions of the two concomitant mechanisms in the filamentation and help to drive us to further investigate and determine the different filamentation regimes [17].

2. Numerical model

The HOKE-P model is based on a modification of nonlinear Schrodinger equation [3]:

$$\partial_z E = i\nabla_\perp^2 E/2k_0 - ik''\partial_t^2 E/2 + ik_0 \sum_{j\geq 1}\left(n_{2j}|E|^{2j}\right)E$$
$$-\sigma(1+i\omega_0\tau)\rho/2 - W\left(|E|^2\right)U_i(\rho_{at}-\rho)E/2|E|^2 \tag{1}$$

The plasma generation is governed by [18]:

$$\partial_t \rho = W\left(|E|^2\right)(\rho_{at}-\rho) + \sigma|E|^2\rho/U_i - \alpha\rho^2 \tag{2}$$

where z is the longitudinal propagation distance and $\nabla_\perp^2 = r^{-1}\partial/\partial r(r\partial/\partial r)$ is a Laplacian operator. This is a multispecies code and in the case of air, it sorts N_2, O_2 and Ar with the variable index

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coefficients n_{2j} as described in the Refs. [1–3]. In Eqs. (1) and (2), $k_0=\omega_0/c=2\pi n_0/\lambda_0$, and ω_0 are the wave number and the angular frequency of the carrier wave, respectively. The critical power for self-focusing in air is determined by $p_{cr}=3.77{\lambda_0}^2/8\pi n_0 n_2$ and here n_0 is the linear refractive index. The second-order temporal derivation refers to normal group-velocity dispersion (GVD) with coefficient $k''=\partial k/\partial\omega|\omega_0$. The quantity ρ_{at} denotes the neutral gas density and ρ_c is the critical plasma density. U_i, σ, and α are the molecules ionization potential, inverse bremsstrahlung cross-section and electron recombination rate, respectively. Typically the nonlinear photon absorption comes from the different species O_2 and N_2, and the perturbative intensity is expected to hold for not exceeding the clamping intensity 50 TW/cm^2, which corresponds to MPI being the dominant ionization in the filament channel. Thus, Perelomov–Popov–Terent'ev (PPT) ionization rate can be approximately calculated with Ref. [19]. The equations can be solved with the initial pulse envelope $E(r,t,z=0)=(2p_{in}/\pi {w_0}^2)^{1/2}\exp(-r^2/{w_0}^2-t^2/{t_p}^2)$, where the input power $p_{in}=7p_{cr}$, beam waist $w_0=0.05$ cm and the pulse duration $t_p=30$ fs.

3. Results and discussions

Results of the simulation based on the HOKE-P model are shown in Fig. 1, the periodically dynamic pattern corresponds to the case of filamentation propagation scenario. The transmitted beam will firstly undergo self-focusing along the propagating direction until the intensity reaches a sufficient high value to trigger the higher-order nonlinearity to manifest and the molecule ionization to occur. Then the presence of HOKE and plasma generation together arrest the collapse that would have occurred in the absence of any saturating mechanism [20]. As a consequence, the intensity is clamped at the level of 34.17 TW/cm^2 in the filament and the on-axis plasma peak density approaches $\sim 10^{15}\ cm^{-3}$. The dynamic balance between the optical Kerr self-focusing and the combination defocusing induced by HOKE and plasma can maintain the long range propagation of the laser beam. Further investigation shows that considering of HOKE in the physical model allows a good agreement between experimental results and simulations without changing any parameter, even when comparing the model including the HOKE with previously published data [21].

To demonstrate the filamentation scenario substantially stems from the dynamic balance of the HOKE-P model, rather than the SKE-P model, two points should be clarified. First, it needs to confirm that the HOKE indeed induces defocusing in the filament regime. As expected, the $\triangle n_{HOKE}=n_4I^2+n_6I^3+n_8I^4+\ldots$ provides almost negative contributions along the whole filament, in which the intensity is above 10 TW/cm^2[Fig. 2(a)], while the $\triangle n_{Kerr}$ changed up to $\sim$34 TW/cm^2 in air and $\sim$25 TW/cm^2 in O_2 [2] our result is quantitatively coincident with the reports. It also demonstrates that the validity of considering the HOKE at the transient intensity [22] in the model is maintained. Second, it is necessary to distinguish the relative defocusing contributions of the HOKE and plasma in the filament, to illustrate the HOKE can be a counterpart of plasma defocusing. The relative contributions ratio can be defined as $\xi=|\triangle n_{HOKE}|/|\triangle n_{plasma}|$ [4]. Their respective contributions to the nonlinear refractive index are shown in Fig. 2(b). It indicates that the defocusing contribution of HOKE is much higher than that of plasma along the filament regime (z=50–400 cm), in particular, when the pulse duration is shorten to 10 fs, i.e., a few-cycle pulses (not shown here).

As a separated effort, we should further conduct various experiments on the filament characteristics. It is to clear up that at what extent the HOKE can be a counterpart of plasma to determine the different filamentation regimes. For comparison and illustration convenience, we further conduct the following numerical experiments based on the consideration of the pulse duration and the incidence wavelength just as suggested in Refs. [4,5]. As a consequence, the relative contributions ratio $\xi(t_p,\lambda)=|\triangle n_{HOKE}(t_p,\lambda)|/|\triangle n_{plasma}(t_p,\lambda)|$ as a function of pulse duration and wavelength can be obtained. What is less expected and somewhat counterintuitive is the observed gradual shortening of the longitudinal range of the generated plasma channels beyond the linear focus zone, when the laser pulses are temporally chirped as shown in Fig. 2(c). The "long pulse" not only

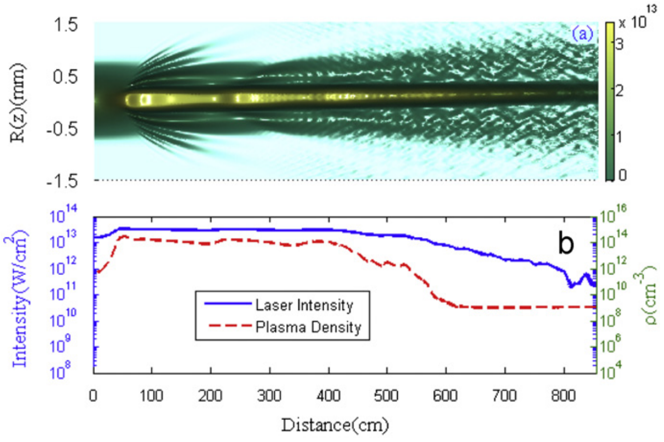

Fig. 1. (a) 2D representation of the intensity profile of the filament governed by HOKE-P model and the figure's chroma represents the intensity amplitude which is inserted in the right hand of the figure, and (b) on-axis intensity (solid curve, left-hand axis) and plasma density (dashed curve, right-hand axis) as a function of the propagation distance.

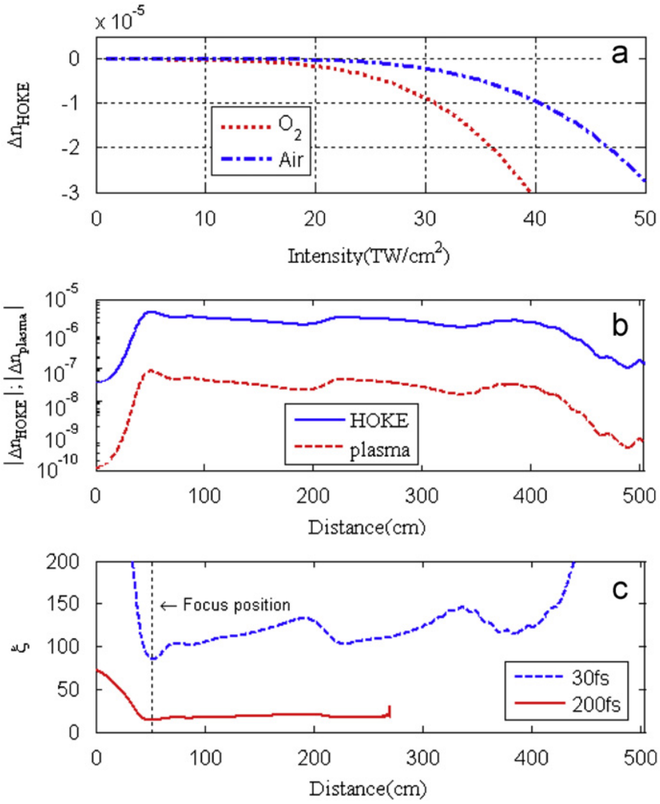

Fig. 2. (a) Higher-order nonlinear refractive index variation versus laser intensities, (b) respective contributions of HOKE and plasma to nonlinear rafractive index, and (c) relative contributions ratio of HOKE and plasma for different durations.

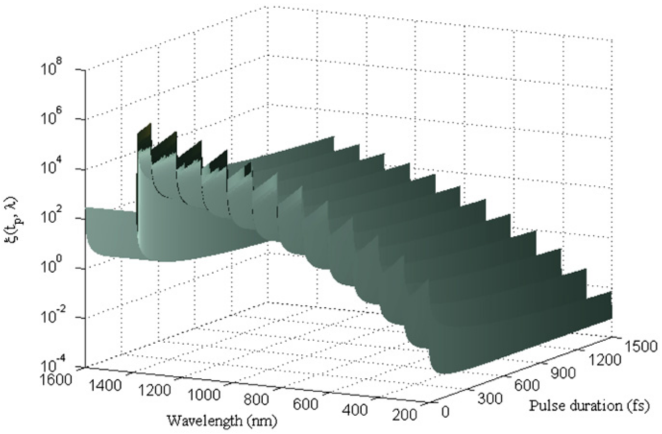

Fig. 3. The pulse duration and wavelength dependence for relative contributions ratio of HOKE and plasma.

makes a weaker function of HOKE, but also reduces the filament length. This due to the “long pulse” can both produce an accumulated plasma sufficiently intense to defocus the optical Kerr self-focusing and lead to a much more energy dissipation of the laser pulse. Comparatively in the case of “short pulse”, over a wide range of pulse durations from 10 to 288 fs ($\xi > 10$) with the same peak intensity [seen in Fig. 3], the refractive index change induced by HOKE increases so drastically that the plasma generation can be decoupled and exhibits neglected effect on the filamentation [3].

In contrast, the dependence on wavelength implies that one can generally consider that the HOKE provides an even more dominant contributions in the IR regime ($\lambda \gg 615$ nm, $\xi \gg 1$) as compared to that of plasma over the whole UV domain. It shows good agreement with the expectation that plasma is dominant in the UV (200–400 nm) regime, where the plasma density is higher than that in the IR regime [18], due to the higher ionization rate for UV pulse. It should be pointed out that plasma density decreases along the UV spectral range, while the contribution of HOKE to nonlinear refractive index increases. However, the integrative effects result in the plasma defocusing as the major mechanism arresting the collapse in the present conditions ($\xi < 1$). These results illustrate that their respective contributions to filamentation are strongly temporal and spectral dependence. The general filemantation process is defocused by plasma for long pulses at short wavelengths and by HOKE for short pulses at long wavelengths. This conclusion is qualitatively coincident with Refs. [5,17]. Quantitatively, according to our results this corresponding transition regimes for pulse duration and wavelength are 288 fs and 615 nm, respectively.

4. Conclusion

In summary, by using the HOKE-P model, which takes HOKE and plasma generation into account in the self-guiding process, the relative contributions of HOKE and plasma have been discussed. It enables us to go one step further and give a rough estimate of the range where each mechanism regime at play dominates. The results demonstrate that the SKE-P model is situation restricted in governing the filamentation phenomenon, especially in the ultra-short regime, i.e., few-femtosecond time scales. It reinforces the believing that HOKE can act as a counterpart of plasma under certain predesigned conditions in filamentation dynamics. Opportunely, a bran-new work claimed that the phenomenon of the ionization channel closure around the intensity, at which the nonlinear refractive index saturates and reverses its sign, occurs for all usual gases [22]. It also illustrates the important role of HOKE in strong-field physics. This work yields insight into laser filamenation and is beneficial to find the “optimum” parameter values favoring filament applications.

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