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## 自陡效应对飞秒脉冲光束自聚焦特性的影响

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**摘要:** 为了研究在非线性正常色散介质中, 自陡效应对高强度飞秒脉冲光束自聚焦特性的影响, 同时考虑色散、时空聚焦和克尔效应。基于 (3+1) 维的修正非线性薛定谔方程, 采用对称分步傅里叶数值计算方法, 分不考虑自陡效应即只有色散、时空聚焦及克尔效应和考虑自陡效应两种情况, 对 90fs 超短脉冲光束的自聚焦特性进行了数值仿真。结果表明, 色散、时空聚焦和克尔效应的共同作用会使脉冲分裂成丝, 能量减少, 脉冲展宽, 时空聚焦和色散的相关性使脉冲产生了另一延迟, 延迟和传输距离及色散成正比; 而自陡效应则可以明显降低脉冲峰值强度, 减弱非线性的影响, 抑制脉冲自聚焦, 使时间波形分裂更小, 对脉冲延迟量影响较小。

**关键词:** 非线性光学; 自聚焦; 自陡效应; 分步傅里叶数值计算; 飞秒脉冲光束; 时空聚焦

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## Influence of self-steepening effect on focusing property of femtosecond pulsed beam

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**Abstract:** The influence of nonlinear shock on the focusing property of femtosecond pulsed beams was studied through numerical simulation by using the modified (3+1)-dimensional nonlinear Schrödinger equation, taking into account of diffraction effects, space-time coupling, normal dispersion, and cubic nonlinearity. The self-focusing properties of the 90fs pulsed beam were analyzed and discussed in the absence and in presence of shock effect respectively. The results show: The space-time coupling, dispersion, and Kerr effect together will cause the pulse filament, amplitude descending and its width broadening. As implied by the functional form, space-time coupling relates to the dispersion will produce a time shift. The shift increases with distance and dispersion, and that the self-steepening effect will result in the peak power decreasing greatly, moreover it will weak the pulse self-focusing effect.

**Key words:** nonlinear optics; self-focusing; self-steepening effect; split Fourier transform method; femtosecond pulsed beam; space-time focusing

### 引 言

高强度的飞秒激光脉冲光束在介质中的传输问题, 特别是在非线性色散介质中的传输问题越来越受到人们的关注<sup>[1-13]</sup>。飞秒激光光束的高强度特性使得它在通过介质时, 对介质的物理特性的改变是不容忽视的, 特别是导致介质的非线性效应, 因为非线性效应反过来会影响脉冲光束的传输行为。且此类脉冲光谱宽度很宽, 脉冲的时间和空间部分在传输过程中会相互耦合、相互影响, 导致所谓的时空耦合现象<sup>[4,8]</sup>。与普通窄带(准单色)的高功率激光传输比较起来, 会带来一系列新的传输效应, 因此称为脉冲光束。对脉宽

小于 1ps 的超短飞秒脉冲光束, 原来窄带脉冲激光的传输方程不得不作进一步改进。要求在其非线性色散介质中的传输理论模型必须包括时空聚焦、高阶色散和高阶非线性效应等效应<sup>[14]</sup>。作者基于 (3+1) 维的非线性传输方程<sup>[1]</sup>, 在包含时空聚焦、色散和克尔效应时, 考察了自陡效应对飞秒脉冲光束自聚焦特性的影响, 主要从轴上时间波形的变化来讨论。

### 1 理论模型

设电场的载波包络的形式为  $E(x, y, z, t) = A(x, y, z, t) \exp(i\beta_0 z - i\omega_0 t)$ , 其中,  $\omega_0$  为载波频率;  $\beta_0 = \text{Re}[k(\omega_0)] = n_0 \omega_0 / c$ ,  $c$  为真空中的光速,  $n_0$  为中心频率处的线性折射率;  $k(\omega) = \sqrt{\epsilon(\omega)} \omega / c$  为复传输常数,  $A(x, y, z, t)$  为复数包络。只要脉冲的宽度不小于 1 个光学周期, 载波包络的表达式总是有效的。根据 BRABEC 的慢演变波近似 (slowly-evolving wave ap-

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proximation, SEWA)理论<sup>[11]</sup>,其复数包络  $A(x, y, z, t)$  可以用以下修正的非线性薛定谔方程来描述:

$$\frac{\partial A}{\partial \xi} = -\frac{\alpha_0}{2}A + \hat{D}A + \frac{i}{2\beta_0} \left( 1 + \frac{i}{\omega_0} \partial T \right)^{-1} \nabla_{\perp}^2 A + i \frac{2\pi\beta_0}{n_0} \left( 1 + \frac{i}{\omega_0} \partial T \right) B \quad (1)$$

这里已经引入了运动坐标  $T = t - \beta_1 z \xi = z_0$  式中,  $\partial_j$  表示对  $j$  求偏导数,  $\nabla_{\perp}^2 = \partial x^2 + \partial y^2$  是横向拉普拉斯算符,色散算符  $\hat{D}$  定义为  $\hat{D} = -\frac{\alpha_1}{2} \partial T + \sum_{m=2}^{\infty} \frac{(i\partial T)^m}{m!} \times \frac{i\alpha_m}{2} + \sum_{m=2}^{\infty} \frac{(i\partial T)^m}{m!} \beta_m$ ,  $\beta_m = \text{Re} \left[ \frac{\partial^m k(\omega)}{\partial \omega^m} \Big|_{\omega=\omega_0} \right]$ ,  $\alpha_m = 2 \text{Im} \left[ \frac{\partial^m k(\omega)}{\partial \omega^m} \Big|_{\omega=\omega_0} \right]$ 。对克尔介质,  $B = n_0 n_2 A^2 A / 2\pi$ ,

(1)式右边各项表示衰减、色散、衍射和非线性自聚焦,  $(1 + i\partial T/\omega_0)$  为自陡峭项 (self-steepening, SS)。

若不考虑介质的损耗和增益,忽略 4 阶及以上高阶色散项。且为方便计算,对 (1) 式进行归一化,引入以下无量纲变量:

$$U = \frac{A}{P_0}, Z = \frac{\xi}{L_d}, \tau = \frac{T}{T_0}, X = \frac{x}{R_0}, Y = \frac{y}{R_0} \quad (2)$$

式中,  $L_d = T_0^2 / \beta_2$  为 2 阶色散长度,  $L_{NL} = 1/\gamma P_0$  为非线性长度。  $T_0, R_0$  分别为脉冲光束初始峰值强度  $1/e^2$  处的脉冲半峰全宽和光束半峰全宽,  $P_0$  为脉冲峰值强度,这样, (1) 式可以简化为无量纲的形式:

$$\frac{\partial U}{\partial Z} = \left[ \frac{i\delta_2}{4} \left( 1 + s_1 \frac{\partial}{\partial \tau} \right)^{-1} \nabla_{\perp}^2 \right] U - \text{sgn}(\beta_2) \frac{i}{2} \frac{\partial^2 U}{\partial \tau^2} + \text{sgn}(\beta_3) \delta_3 \frac{\partial^3 U}{\partial \tau^3} + iN^2 \left[ |U|^2 U + i s_2 \frac{\partial (|U|^2 U)}{\partial \tau} \right] \quad (3)$$

式中,  $N^2 = \frac{L_d}{L_{NL}}$ ,  $s_1 = s_2 = \frac{\gamma}{\omega_0 T_0}$ ,  $\delta_2 = \frac{L_d}{Z_R}$ ,  $\delta_3 = \frac{L_d}{6L_d'}$ ,  $L_d' = \frac{T_0^3}{|\beta_3|}$  为 3 阶色散长度,  $Z_R = kR_0^2/2$  为瑞利距离。

## 2 数值计算及讨论

光束自聚焦等非线性效应一直以来都是人们较为关心的问题,也是在光学设计中需要尽量避免的问题。故在激光器件中,激光光束需要经过整形为填充因子较高,同时还要能较好抑制光束菲涅耳衍射调制及光束自聚焦的超高斯分布光束。因此假设初始场分布为:

$$A = A_0 \exp \left( -\frac{x^2 + y^2}{2R_0^2} - \frac{i}{2T_0} \right) \quad (4)$$

即空间是超高斯分布的光束,时间域是半导体激光器输出的常见的高斯型光脉冲。基于 (3) 式进行讨论,为了提高精度,采用离散的对称分步傅里叶数值计算方法,在正常色散熔石英介质中,计算选取的参量为:

介质的折射率  $n = 1.45$ , 中心波长  $\lambda = 800 \text{nm}$ , 非线性折射率系数  $n_2 = 2.5 \times 10^{-16} \text{cm}^2/\text{W}$ , 群速度色散常数  $\beta_2 = 360 \text{fs}^2/\text{cm}$ , 3 阶色散常数  $\beta_3 = 275 \text{fs}^3/\text{cm}$ , 峰值功率密度  $I_0 = 340 \text{GW}/\text{cm}^2$ , 脉冲半峰全宽的宽度为  $90 \text{fs}$  ( $1/e^2$  半峰全宽  $T_0 = 51.05 \text{fs}$ ), 空间峰值强度上的  $1/e^2$  半峰全宽  $R_0 = 42.04 \mu\text{m}$ , 由上述参量可计算得到非线性长度为  $L_{NL} = c/(\omega_0 n_2 I_0) = 0.15 \text{cm}$ , 2 阶色散长度  $L_d = 8.1 \text{cm}$ , 3 阶色散长度  $L_d' = 574.2 \text{cm}$ , 瑞利长度  $Z_R = 1 \text{cm}$ 。

### 2.1 不含自陡效应的自聚焦特性分析

首先给出了不考虑自陡效应时脉冲光束的自聚焦特性,即先令 (3) 式中的  $s_2 = 0$ , 这样 (3) 式中就只包括衍射、色散和克尔效应。数值计算结果见图 1。分析

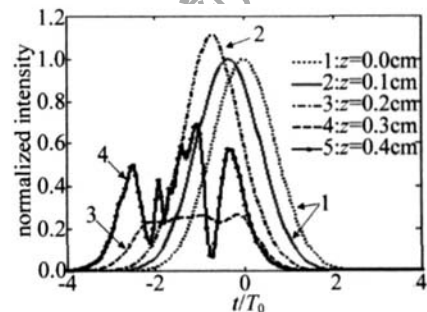


Fig 1 Axial time profile of femtosecond pulse vs propagation length (exclude shock effect)

图 1 可以发现,首先时空耦合与介质色散的相关性,其相互的影响,使得色散引起另一延迟,轴上时间波形向轴外偏移,成为旁轴脉冲,其偏移量  $\Delta t$  与传播距离、色散成正比,随着传播距离的增大,脉冲的傍轴延迟相应增大,色散越大,傍轴延迟越大。其次分析比较图 1 中的曲线 1 和曲线 2 可知,开始阶段克尔效应较强,引发的自聚焦效应使脉冲峰值功率增大。最后由图 1 中的曲线 3 和曲线 4 可知,随着传输距离增加,脉冲受色散的影响增强,加上克尔效应产生的正啁啾,脉冲迅速展宽,光强减弱,另一方面延迟使光强远离光束轴中心,光束中央的轴上光强减少,衍射、色散和克尔效应的相互作用,使得脉冲发生分裂,完全失真变形。在色散和克尔效应的继续作用下,延迟进一步增加,脉冲进一步展宽,光功率会逐渐降到自聚焦的临界功率以下。

### 2.2 包含自陡效应的自聚焦特性分析

令 (3) 式中的  $s_2 \neq 0$  来分析自陡峭效应对超短脉冲光束自聚焦特性的影响,数值计算的结果见图 2。比较分析图 2 和图 1 可知,自陡峭效应明显降低了脉冲光束自聚焦的峰值功率,但对时空聚焦和色散引起的脉冲延迟几乎没有影响。图 2 中的曲线 3 和图 1 中的曲线 3 相比较可以发现,自陡引起脉冲强度下降,非线性的影响减弱,使得脉冲分裂稍晚。比较图 2 中的

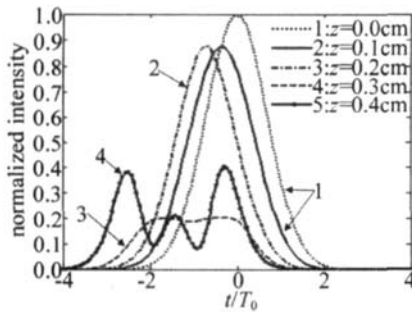


Fig 2 Axial time profile of femtosecond pulse vs propagation length (include shock effect)

曲线 4 和图 1 中的曲线 4 可知,考虑自陡峭后,分裂的子脉冲数减少。由  $s_2$  的数学定义式可知,脉冲越短,自陡影响越大,越能较好地抑制脉冲光束的自聚焦和光束中央的自聚焦崩溃。同样在自陡效应继续作用下  $t=0$  时的光功率会更快地降到自聚焦的临界功率以下。

### 3 结论

从修正的非线性薛定谔方程出发,分别研究了不包含自陡效应和包含自陡效应时,飞秒脉冲光束在非线性色散介质中的自聚焦特性。研究发现,不包含自陡时,空间特性、色散效应和克尔效应的相互作用使得时间域脉冲波形分裂失真,脉冲展宽,能量减少,且时空聚焦和色散的相关性使脉冲产生了另一延迟,延迟与传输距离及色散成正比,随着传输距离的增加,在色散和克尔效应的继续作用下,延迟增加,脉冲进一步展宽,光功率会逐渐降到自聚焦的临界功率以下;考虑自陡效应后,自陡明显且迅速地降低了脉冲聚焦的峰值强度,从而减弱非线性的影响,抑制脉冲自聚焦,使时间波形分裂更晚更小,但脉冲延迟量的相对影响较小。脉冲越短,自陡影响越大,这时需要同时考虑喇曼延迟响应的影响,这将在以后的工作中进行深入探讨。

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差以及该方法的普适性,还有待进一步研究。

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