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群色散光纤中高强度光脉冲传输与压缩的研究

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提 要

考虑非线性四阶折射率,推导了光脉冲在群色散单模光纤中传输的非线性方程,并得到孤子型解析解.同时指出在Sech型光纤脉冲压缩实验中,光强度的阈值.

关键词 四阶折射率, 非线性, 脉冲压缩.

旨在获得飞秒脉冲的光纤脉冲压缩技术受到关注[1~4].由于脉冲的不断压缩,脉冲光的功率变得很强,因而光纤中的四阶非性折射率已不可忽略.本文研究色散光纤中,同时考虑二阶和四阶非线性的光脉冲传输,得到非线性薛定谔方程的解析解.同时指出,为得到压缩的Sech型脉冲,光强度必须低于 10^{11} W/cm^2.

1 方程推导及求解

同时考虑二阶和四阶非线性折射率(n_2 和 n_4)光纤中的折射率可表为

$$n(\omega,|E|^2)=n(\omega)+n_2|E|^2+n_4|E|^4, \tag{1}$$

介质中的电场可设为

$$E(x,t)=\mathrm{Re}\{u(x,t)\exp[i(k_0x-\omega_0t)]\}, \tag{2}$$

式中 $u(x,t)$ 为缓变振幅,$k_0=\omega_0n_0/c$ 为波数,ω_0 为频率,而 $n_0=n(\omega_0)$. 如 $E(x,t)\sim\exp[i(kx-\omega t)]$,则 $u(x,t)\sim\exp\{i[(k-k_0)x-(\omega-\omega_0)t]\}$. 而在色散光纤中

$$k=k_0+\left.\frac{\partial k}{\partial\omega}\right|_{\omega_0}(\omega-\omega_0)+\frac{1}{2}\left.\frac{\partial^2k}{\partial\omega^2}\right|_{\omega_0}(\omega-\omega_0)^2+\frac{\omega_0n_2}{c}|E|^2+\frac{\omega_0n_4}{c}|E|^4, \tag{3}$$

作算符代换: $(k-k_0)\sim i(\partial/\partial X)$, $(\omega-\omega_0)\sim i(\partial/\partial t)$. 并设 $\zeta=x$, $\tau=t-(x/v_g)$, $v_g=(\partial k/\partial\omega)|_{\omega_0}$ 为 $\omega=\omega_0$ 处的群色散. 可得光脉冲在光纤中传播的非线性方程为下列形式:

$$\left.\begin{aligned}&i\frac{\partial u}{\partial\zeta}+\alpha\frac{\partial^2u}{\partial\tau^2}+\beta|u|^2u+\gamma|u|^4u=0,\\&\alpha=-\frac{1}{2}\left.\frac{\partial^2k}{\partial\omega^2}\right|_{\omega_0},\qquad\beta=\frac{\omega_0n_2}{c},\qquad\gamma=\frac{\omega_0n_4}{c}.\end{aligned}\right\} \tag{4}$$

下面求方程(4)的解析解. 设 $u=\rho(\zeta,\tau)\exp[i\phi(\zeta,\tau)]$ 代入方程(4),并令实、虚部分别相等,得

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$$\left.\begin{aligned}\rho\phi_\zeta &= \alpha\rho_{\tau\tau} - \alpha\rho\phi_\tau^2 + \beta\rho^3 + \gamma\rho^5,\\ \rho_\zeta &= -2\alpha\rho_\tau\phi_\tau - \alpha\rho\phi_{\tau\tau}.\end{aligned}\right\} \tag{5}$$

为了得到方程(5)的孤波解,进一步可设[5]

$$\rho = \rho(z), \qquad \phi = \phi(z,\zeta) \tag{6}$$

式中 $z = \tau - M\zeta$,且 $\phi_\zeta = \text{cosnt.} = k, \phi_z'$ 与 ζ 无关. 常数 M 和 K 分别对应孤子速度的倒数和波数漂移. 把(6)式代入(5)式,得

$$\rho(K - M\phi_z') = \alpha\rho'' - \alpha\rho\phi_z'^2 + \beta\rho^3 + \gamma\rho^5, \tag{7}$$

$$M\rho' = 2\alpha\rho'\phi_z' + \alpha\rho\phi_{zz}''. \tag{8}$$

(8)式两边同乘以 ρ,积分一次得

$$(1/2)M\rho^2 - \alpha\rho^2\phi_z' = 常数. \tag{9}$$

考虑到在反常色散($(\partial^2K/\partial\omega^2)_{\omega_0} < 0$)介质中,只存在 $z \to \pm\infty$ 时,$\rho \to 0$ 的孤子解,故积分常数为零. 从而

$$\phi_z' = M/2\alpha. \tag{10}$$

将(10)式代入(7)式,有

$$\rho'' + (\gamma/\alpha)\rho^5 + (\beta/\alpha)\rho^3 - \left(\frac{K}{\alpha} - \frac{M^2}{4\alpha^2}\right)\rho = 0. \tag{11}$$

将(11)式积分一次得

$$\begin{aligned}&(1/2)(\rho')^2 + \pi(\rho) = 0,\\ &\pi(\rho) = (1/6\alpha)\gamma\rho^6 + (\beta/4\alpha)\rho^4 - \frac{1}{2}\left(\frac{K}{\alpha} - \frac{M^2}{4\alpha^2}\right)\rho^2 + c.\end{aligned} \tag{12}$$

积分常数 c,根据条件 $z \to \pm\infty$, $\rho \to 0$, $\rho' \to 0$ 决定,可知 $c = 0$.

不失一般性,可假设脉冲峰值位于 $z = 0$ 处,即 $\rho(0) = \rho_0$, $\rho'(0) = 0$. 通过下式

$$\int_{\rho_0}^{\rho} \frac{d\rho}{[-2\pi(\rho)]^{1/2}} = \pm z. \tag{13}$$

可求得

$$\left.\begin{aligned}&\rho^2 = \frac{\rho_0^2}{2-\nu}\left[\cosh^2(uz) + \frac{\nu-1}{2-\nu}\right]^{-1},\\ &u^2 = (\gamma/3\alpha)\rho_0^4 + (\beta/2\alpha)\rho_0^2, \qquad \nu = (\beta\rho_0^2/2\alpha u^2).\end{aligned}\right\} \tag{14}$$

(10)式和(14)式即是非线性方程(4)的解.

2　分析和讨论

将(10)式变回到时间坐标,可知在光纤脉冲压缩实验中,自相位调制是线性的. 这符合不考虑四阶非线性折射率时光脉冲压缩实验结果[2]. 从推导中知道,四阶非线性折射率不影响相位调制,故在光纤脉冲压缩实验中总可以得到线性相位调制. 但如考虑光脉冲在光纤中长距离传输,则非线性方程中必须加入微分项 $\partial(|u|^2u)/\partial\tau$ 的贡献,得到修正的非线性方程[6,7],这时自相位调制就不再是线性的了,从(14)式知,只要 $\gamma \neq 0$ 则恒有 $\nu \neq 1$. 也就是说,如果考虑四阶非线性折射率的影响,则得不到 sech 型脉冲. 这样,为得到在测量方面应用广泛的 sech 型脉冲,光脉冲强度必须低于一阈值. 下面对强度阈值作一数量级估计. n_2 一般为 10^{-21} (MKS), $n_4 \sim 10^{-41}$ MKS[8],故对光强 $I > 10^{11}\ \text{W/cm}^2$ 的光脉冲,四阶非线性折射率的影响已不可忽略. 可以认为,$I_t = 10^{11}\ \text{W/cm}^2$ 就是 sech 型光脉冲压缩的强度阈值.

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Propagation and compression of high intensity pulse in GVP optical fibers

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Abstract

Taking into account of the fourth-order nonlinear refractive index, we have obtained the soliton solution of the nonlinear equation which governs the propagation of optical pulse in group velocity dispersion (GVP) single-mode fibers. And we point out that there is a intensity threshold for the sech-type pulse compression.

Key words fourth-order refractive index, nonlinear and pulse compressiom, optical fiber.