物理学报 Acta Physica Sinica
Chinese Physical Society
Institute of Physics, CAS

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Study on transmission characteristics of dark solitons in inhomogeneous optical fibers

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引用信息 Citation: Acta Physica Sinica, 64, 090504 (2015) DOI: 10.7498/aps.64.090504
在线阅读 View online: http://dx.doi.org/10.7498/aps.64.090504
当期内容 View table of contents: http://wulixb.iphy.ac.cn/CN/Y2015/V64/I9

物理学报 Acta Phys. Sin. Vol. 64, No. 9 (2015) 090504

非均匀光纤中暗孤子传输特性研究*

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(2014 年 11 月 12 日收到; 2014 年 12 月 15 日收到修改稿)

由于变系数非线性 Schrödinger 方程的增益、色散和非线性项都是变化的, 根据方程这一特点可以研究光脉冲在非均匀光纤中的传输特性. 本文利用 Hirota 方法, 得到非线性 Schrödinger 方程的解析暗孤子解. 然后根据暗孤子解对暗孤子的传输特性进行讨论, 并且分析各个物理参量对暗孤子传输的影响. 经研究发现, 通过调节光纤的损耗、色散和非线性效应都能有效的控制暗孤子的传输, 从而提高非均匀光纤中的光脉冲传输质量. 此外, 本文还得到了所求解方程的解析双暗孤子解, 最后对两个暗孤子相互作用进行了探讨. 本文得到的结论有利于研究非均匀光纤中的孤子控制技术.

关键词: 暗孤子, 非均匀光纤, 孤子控制, 非线性 Schrödinger 方程

PACS: 05.45.Yv, 42.65.Tg, 42.65.Wi, 42.65.Re **DOI:** 10.7498/aps.64.090504

1 引 言

1973 年, Hasegawa 等在理论上首次提出了能够利用光纤非线性平衡光纤色散, 并在光纤中实现了孤子的稳定传输, 从而开辟了光纤孤子通信这一新领域 [1]. 1980 年, Mollenauer 等在实验上验证了光孤子通信的可能性. 光孤子在介质中的传输可以用非线性 Schrödinger(NLS) 方程进行描述, 并在光通信、非线性光学、等离子体物理 [2]、光子晶体 [3,4] 和 Bose-Einstein 凝聚 [5−7] 等研究领域中有广泛应用. 通常情况下, 光纤中的反常色散区存在亮孤子, 正常色散区存在暗孤子. 由于在损耗和背景噪声的影响下, 暗孤子比亮孤子具有更高的稳定性和自我恢复性 [8,9], 同时具有展宽慢、受各种扰动 (如拉曼自频移) 的影响更小的优点 [10,11], 所以暗孤子被认为是更好的光纤通信的传输载体. 暗孤子的这些优点, 使得其在超长距离光纤通信的未来通信中存在很多潜在的应用价值.

孤子在光纤传输过程中, 增益、色散和非线性效应是影响孤子传输的主要因素 [12,13]. 增益、色散和非线性效应会引起孤子的脉冲展宽和啁啾的产生, 从而导致孤子传输不稳定 [14]. 因而有必要讨论损耗、色散和非线性效应对孤子传输的影响, 进而通过调整相关效应达到控制光孤子传输的效果 [15−23]. 通常情况下, 当光脉冲宽度大于 5 ps 时, 可以用 NLS 方程描述光脉冲在光纤中的传输特性. 但是当光脉冲宽度小于 5 ps 时, 一般用高阶 NLS 方程对光脉冲的传输特性进行描述.

本文主要研究皮秒光脉冲在非均匀光纤中的传输特性. 在非均匀光纤的正常色散区中, 该光脉冲的传输特性可以用如下变系数 NLS 方程来描述 [24]:

$$\frac{\partial u}{\partial z} - \mathrm{i}\frac{D(z)}{2}\frac{\partial^2 u}{\partial \tau^2} + \mathrm{i}\rho(z)\left|u\right|^2 u = g(z)u, \tag{1}$$

其中 $u(z,\tau)$ 表示电场的慢变包络, z 表示孤子沿光纤方向的传输距离, τ 表示坐标系中的归一化时间. $D(z)$ 代表群速度色散 (group velocity dispersion, GVD) 参数, $\rho(z)$ 表示 Kerr 非线性参数, $g(z)$ 表示光纤增益系数.

* 国家自然科学基金 (批准号: 61205064) 资助的课题.

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方程(1)能够用来实现光孤子的调控[24−27], 并在文献中提出了光孤子调控的方法. 在本文中, 我们将利用Hirota方法, 得到方程(1)的解析暗孤子解. 通过分析暗孤子的传输特性, 讨论光纤的增益、色散和非线性效应对暗孤子传输的影响. 我们将借鉴色散管理的思想, 得到较为丰富的光孤子传输.

2 方程(1)的双线性形式

通过引入因变量变换[28−32]

$$u(z,\tau)=\frac{h(z,\tau)}{f(z,\tau)}, \tag{2}$$

其中$h(z,\tau)$是复函数, $f(z,\tau)$是实函数, 通过计算, 得到方程(1)的双线性形式如下:

$$D_z h\cdot f-\frac{\mathrm{i}}{2}D(z)D_\tau^2 h\cdot f-g(z)h\cdot f=0, \tag{3}$$

$$D(z)D_\tau^2 f\cdot f+2\rho(z)h\cdot h^*=0, \tag{4}$$

其中, $*$表示复共轭, D_z和D_τ是Hirota的双线性算子, 定义如下:

$$D_z^x D_\tau^y(s\cdot t)=\Big(\frac{\partial}{\partial z}-\frac{\partial}{\partial z'}\Big)^x\Big(\frac{\partial}{\partial \tau}-\frac{\partial}{\partial \tau'}\Big)^y \times s(z,\tau)t(z',\tau')\,|_{z'=z,\tau'=\tau}\,, \tag{5}$$

其中, m和n都是正整数, $s(z,\tau)$是z和τ的函数, $t(z',\tau')$是z'和τ'的函数.

通过把$h(z,\tau)$和$f(z,\tau)$写成如下幂级数展开形式:

$$h(z,\tau)=h_0(z,\tau)(1+\varepsilon h_1(z,\tau)+\varepsilon^2 h_2(z,\tau)+\cdots), \tag{6}$$

$$f(z,\tau)=1+\varepsilon f_1(z,\tau)+\varepsilon^2 f_2(z,\tau)+\cdots, \tag{7}$$

其中, ε是形式扩展参数.

3 方程(1)的解析求解

3.1 单暗孤子解

将表达式(6)和(7)代入方程(3)和(4), 并提取ε相同幂级数的系数为0, 从而得到方程(1)的解析单暗孤子解.

为了得到方程(1)的单暗孤子解, 我们假设

$$h_0=\mu\,\mathrm{e}^{\theta},\ h_1=n\,\mathrm{e}^{\vartheta},\ f_1=m\,\mathrm{e}^{\vartheta}, \tag{8}$$

其中, μ是任意复参数, $\theta=\mathrm{i}a(z)+\mathrm{i}b\tau$, $\vartheta=k(z)+w\tau+\sigma$ ($a(z)$和$k(z)$待求), b, w, σ, m和n是任意实数. 把$h(z,\tau)$和$f(z,\tau)$代入方程(3)和(4), 经过计算, 我们可以得到

$$\begin{aligned}
a(z)&=\int\frac{1}{2}\big\{-b^2D(z)\\
&\quad-2\mathrm{i}\,[g\,(z)+-\mathrm{i}\mu\mu^*\rho(z)]\,\big\}\,\mathrm{d}z,\\
k(z)&=\int -bwD\,(z)\,\mathrm{d}z,\\
\rho(z)&=\frac{w^2D\,(z)}{4\mu\mu^*},\quad n=-m,\\
h_n(z,\tau)&=0,\quad f_n(z,\tau)=0\quad(n=2,3,4,\cdots),
\end{aligned}$$

其中, μ^*是μ的复共轭, 不失一般性, 我们假设$\varepsilon=1$, 从而得到如下形式的单暗孤子解:

$$\begin{aligned}
u(z,\tau)=\Big\{&\mathrm{e}^{\mathrm{i}b\tau+\frac{1}{2}\mathrm{i}\int\{-b^2D(z)-2\mathrm{i}[g(z)-\frac{1}{4}\mathrm{i}w^2D(z)]\}\,\mathrm{d}z}\\
&\times n\Big[1+\mathrm{e}^{\tau w+\sigma-bw\int D(z)\,\mathrm{d}z}m\varepsilon\Big]\Big\}\\
&\times\Big[1-\mathrm{e}^{\tau w+\sigma-bw\int D(z)\,\mathrm{d}z}m\varepsilon\Big]^{-1}.
\end{aligned} \tag{9}$$

对于单暗孤子解(9), 我们可以通过选择不同的损耗、色散和非线性效应来得到不同的暗孤子传输特性. 当色散$D(z)$呈正弦变化, 增益系数$g(z)$呈Gauss变化时, 暗孤子传输情况如图1所示. 当增益系数的振幅增大时, 暗孤子传输的振幅也在传输过程中突然增大, 如图1(b).

当增益系数为Gauss函数不变时, 色散分别为Gauss形式和Bessel函数形式时, 暗孤子稳定传输情形如图2, 可知暗孤子的传输相位发生了改变. 图2(a)是色散为Gauss形式时暗孤子传输的情形, 图2(b)是色散为Bessel函数形式时暗孤子传输的情形, 经分析知通过改变色散的类型, 可以达到改变孤子相位的目的.

当增益系数为Gauss函数不变时, 色散分别为Gauss形式和给Gauss形式加正弦的方式, 暗孤子稳定传输情形如图3. 图3(a)是色散为Gauss形式时暗孤子传输的情形, 图3(b)是色散为给Gauss形式加正弦形式时暗孤子传输的情形, 经分析知通过改变色散的类型, 可以达到改变孤子传输相位振荡的目的.

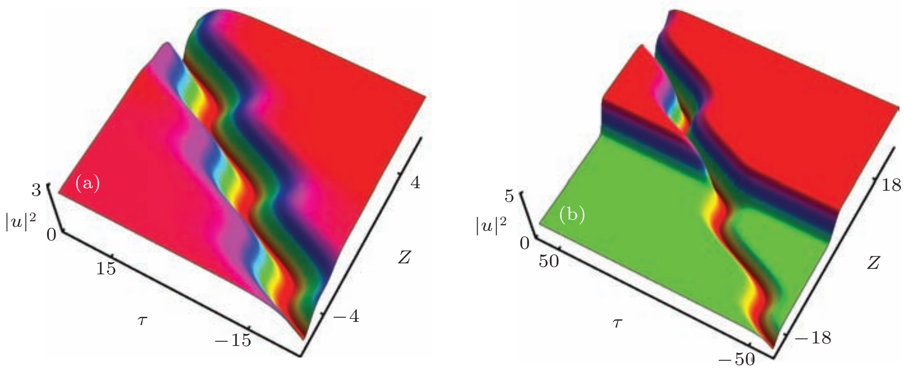

图1 (网刊彩色) 色散呈 Gauss 和 Bessel 函数变化, 增益系数呈 Gauss 变化时, 暗孤子稳定传输情形 (各参数取为 $\varepsilon = 1$, $w = -0.3$, $\sigma = 1.2$, $m = 1.6$, $\mu = 1.6$, $m = 0.5$, $b = 1$) (a) 为 $D(z) = 5\sin(2z) + 5$, $g(z) = 0.01\,\mathrm{e}^{-z^2}$; (b) 为 $D(z) = 3\sin(0.5z) + 3$, $g(z) = 0.3\,\mathrm{e}^{-z^2}$

Fig. 1. (color online) Dispersion is changing with the function of Gauss and Bessel, gain is changing with the function of Gauss, and the propagation of dark solition is stable(each parameters taken as$\varepsilon = 1$, $w = -0.3$, $\sigma = 1.2$, $m = 1.6$, $\mu = 1.6$, $m = 0.5$, $b = 1$). (a) $D(z) = 5\sin(2z) + 5$, $g(z) = 0.01\,\mathrm{e}^{-z^2}$; (b) $D(z) = 3\sin(0.5z) + 3$, $g(z) = 0.3\,\mathrm{e}^{-z^2}$.

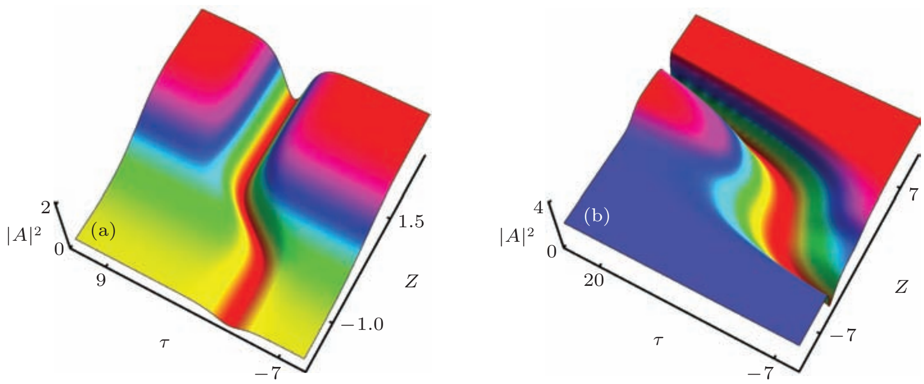

图2 (网刊彩色) 色散呈 Gauss 和 Bessel 函数变化, 增益系数呈 Gauss 变化时, 暗孤子稳定传输情形 (各参数取为 $\varepsilon = 1$, $w = -0.3$, $\sigma = 1.2$, $m = 1.6$, $\mu = 1.6$, $m = 0.5$, $b = 1$) (a) 为 $D(z) = 5\,\mathrm{e}^{-3z^2}$, $g(z) = 0.4\,\mathrm{e}^{-0.8z^2}$; (b) 为 $D(z) = \mathrm{BesselI}(0, z)$, $g(z) = 0.1\,\mathrm{e}^{-z^2}$

Fig. 2. (color online) Dispersion is changing with the function of Gauss and Bessel, gain is changing with the function of Gauss, and the propagation of dark solition is stable(each parameters taken as$\varepsilon = 1$, $w = -0.3$, $\sigma = 1.2$, $m = 1.6$, $\mu = 1.6$, $m = 0.5$, $b = 1$). (a) $D(z) = 5\,\mathrm{e}^{-3z^2}$, $g(z) = 0.4\,\mathrm{e}^{-0.8z^2}$; (b)$D(z) = \mathrm{BesselI}(0, z)$, $g(z) = 0.1\,\mathrm{e}^{-z^2}$.

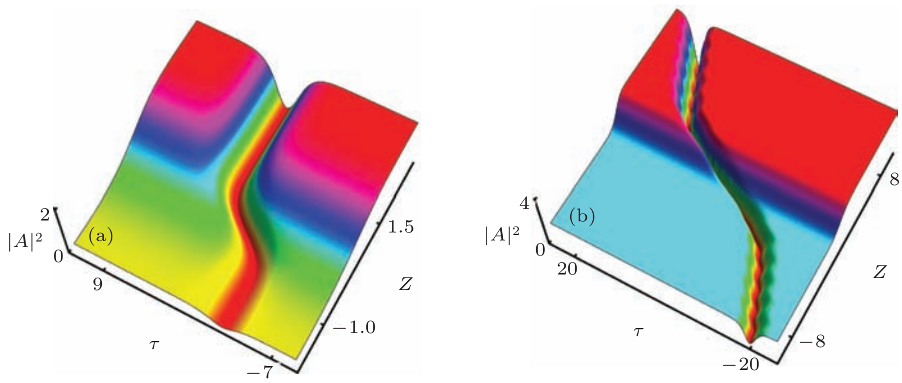

图3 (网刊彩色) 色散呈 Gauss 和对 Gauss 形式加限定项的形式变化, 增益系数呈 Gauss 变化时, 暗孤子稳定传输情形 (各参数取为 $\varepsilon = 1$, $w = -0.3$, $\sigma = 1.2$, $m = 1.6$, $\mu = 1.6$, $m = 0.5$, $b = 1$) (a) 为 $D(z) = 5\,\mathrm{e}^{-3z^2}$, $g(z) = 0.4\,\mathrm{e}^{-0.8z^2}$; (b) 为 $D(z) = 5\,\mathrm{e}^{-0.2z^2} + 2\sin(2z)$, $g(z) = 0.2\,\mathrm{e}^{-z^2}$

Fig. 3. (color online) Dispersion is changing with the function of Gauss and Bessel and the limited form, gain is changing with the function of Gauss, and the propagation of dark solition is stable(each parameters taken as $\varepsilon = 1$, $w = -0.3$, $\sigma = 1.2$, $m = 1.6$, $\mu = 1.6$, $m = 0.5$, $b = 1$). (a) $D(z) = 5\,\mathrm{e}^{-3z^2}$, $g(z) = 0.4\,\mathrm{e}^{-0.8z^2}$; (b) $D(z) = 5\,\mathrm{e}^{-0.2z^2} + 2\sin(2z)$, $g(z) = 0.2\,\mathrm{e}^{-z^2}$.

3.2 双暗孤子解

对于长距离光通信系统中, 通常会有多个脉冲进行传输. 本节主要讨论双暗孤子解的求解过程及暗孤子相互作用.

为了得到方程(1)的双暗孤子解, 我们假设

$$\begin{aligned} h(z,\tau) &= h_0[1+\varepsilon h_{11}(z,\tau)+\varepsilon^2 h_{12}(z,\tau)],\\ f(z,\tau) &= 1+\varepsilon f_{11}(z,\tau)+\varepsilon^2 f_{12}(z,\tau), \end{aligned} \tag{10}$$

其中,

$$\begin{aligned} &h_0=\mu_1\,\mathrm{e}^{\mathrm{i}\theta_1},\quad \theta_1=\mathrm{i}a_1(z)+\mathrm{i}b_1\tau,\\ &h_{11}=m_1\,\mathrm{e}^{\vartheta_1+\mathrm{i}Q_1}+\mathrm{e}^{\vartheta_2+\mathrm{i}Q_2},\\ &h_{12}=\kappa m_1 m_2\,\mathrm{e}^{\vartheta_1+\vartheta_2+\mathrm{i}Q_1+\mathrm{i}Q_2},\\ &f_{11}=m_1\,\mathrm{e}^{\vartheta_1}+m_2\,\mathrm{e}^{\vartheta_2},\quad f_{12}=M\,\mathrm{e}^{\vartheta_1+\vartheta_2},\\ &\vartheta_j=k_j(z)+w_j\tau(j=1,2). \end{aligned}$$

将表达式(10)代入方程(3)和(4), 并提取ε相同幂级数的系数为0, 可以得到

$$a_1(z)=\int\frac{1}{2}[b_1D(z)+2\mu\mu^*\rho(z)\,\mathrm{e}^{\int g(z)\,\mathrm{d}z}]\,\mathrm{d}z,$$

$$w_1=\frac{w_2\,\mathrm{e}^{\mathrm{i}Q_2/2}(-1+\mathrm{e}^{\mathrm{i}Q_1})}{\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}},$$

$$\rho(z)=\frac{w_1^2\,\mathrm{e}^{\mathrm{i}Q_1-\int g(z)\,\mathrm{d}z}D(z)}{\mu\mu^*(1-\mathrm{e}^{\mathrm{i}Q_1})^2},\quad M=\kappa m_1m_2,$$

$$\begin{aligned} k_j(z)=&\int[2b_1w_j(-1+\mathrm{e}^{\mathrm{i}Q_j})\\ &-\mathrm{i}w_j^2(-1+\mathrm{e}^{\mathrm{i}Q_j})]D(z)\\ &\times\big(2(-1+\mathrm{e}^{\mathrm{i}Q_j})\big)^{-1}\mathrm{d}z,\\ \kappa=&\Big(\mathrm{e}^{\mathrm{i}Q_1}+\mathrm{e}^{\mathrm{i}Q_2}-\mathrm{e}^{2\mathrm{i}Q_2}-\mathrm{e}^{\mathrm{i}(Q_1+Q_2)}\\ &+2\,\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}\Big)\\ &\times\Big(1-\mathrm{e}^{\mathrm{i}Q_2}+\mathrm{e}^{\mathrm{i}(Q_1+Q_2)}-\mathrm{e}^{\mathrm{i}(Q_1+2Q_2)}\\ &+2\,\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}\Big)^{-1}, \end{aligned}$$

其中w_2, m_j^s和Q_j^s是任意实数, 不失一般性, 我们假设$\varepsilon=1$, 从而得到如下形式的双暗孤子解:

$$u(z,\tau)=\frac{h_0(z,\tau)[1+h_{11}(z,\tau)+h_{12}(z,\tau)]}{1+f_{11}(z,\tau)+f_{12}(z,\tau)}, \tag{11}$$

其中

$$h_0(z,\tau)=\exp\left(\frac{1}{2}\mathrm{i}\left\{2b\tau+\left[b_1^2-\frac{2\,\mathrm{e}^{\mathrm{i}Q_2w_2^2}}{(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}\right]\int D(z)\,\mathrm{d}z\right\}z_1\right),$$

$$\begin{aligned} h_{11}(z,\tau)=&\exp\left\{\mathrm{i}Q_1+\frac{\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}(-1+\mathrm{e}^{\mathrm{i}Q_1})\tau w_2}{\sqrt{\mathrm{e}^{\mathrm{i}Q_1(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}}+\frac{1}{2}\mathrm{e}^{\mathrm{i}Q_2}(-1+\mathrm{e}^{\mathrm{i}Q_1})w_2\left[\frac{2b_1}{\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}\right.\right.\\ &\left.\left.-\frac{\mathrm{i}\,\mathrm{e}^{-\mathrm{i}Q_1+\frac{\mathrm{i}Q_2}{2}}(i+\mathrm{e}^{\mathrm{i}Q_1})w_2}{(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}\right]\int D(z)\,\mathrm{d}z\right\}m_1\\ &+\exp\left\{\mathrm{i}Q_2+\tau w_2+\frac{w_2[2b_1(-1+\mathrm{e}^{\mathrm{i}Q_2})-\mathrm{i}(-1+\mathrm{e}^{\mathrm{i}Q_2})w_2]\int D(z)\,\mathrm{d}z}{2(-1+\mathrm{e}^{\mathrm{i}Q_2})}\right\}m_2, \end{aligned}$$

$$\begin{aligned} h_{12}(z,\tau)=&\exp\left\{\mathrm{i}Q_1+\mathrm{i}Q_2+\tau w_2+\frac{\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}(-1+\mathrm{e}^{\mathrm{i}Q_1})\tau w_2}{\sqrt{\mathrm{e}^{\mathrm{i}Q_1(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}}+\frac{1}{2}\mathrm{e}^{\mathrm{i}Q_2}(-1+\mathrm{e}^{\mathrm{i}Q_1})w_2\right.\\ &\times\left[\frac{2b_1}{\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}-\frac{\mathrm{i}e^{-\mathrm{i}Q_1+\frac{\mathrm{i}Q_2}{2}}(\mathrm{i}+\mathrm{e}^{\mathrm{i}Q_1})w_2}{(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}\right]\int D(z)\,\mathrm{d}z\\ &\left.+\frac{w_2[2b_1(-1+\mathrm{e}^{\mathrm{i}Q_2})-\mathrm{i}(-1+\mathrm{e}^{\mathrm{i}Q_2})w_2]\int D(z)\,\mathrm{d}z}{2(-1+\mathrm{e}^{\mathrm{i}Q_2})}\right\}\\ &\times\frac{\mathrm{e}^{\mathrm{i}Q_1}+\mathrm{e}^{\mathrm{i}Q_2}-\mathrm{e}^{2\mathrm{i}Q_2}-\mathrm{e}^{i(Q_1+Q_2)}+2\,\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}{1-\mathrm{e}^{\mathrm{i}Q_2}+\mathrm{e}^{\mathrm{i}(Q_1+Q_2)}-\mathrm{e}^{\mathrm{i}(Q_1+2Q_2)}+2\,\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}m_1m_2, \end{aligned}$$

$$f_{11}(z,\tau)=\exp\left\{\frac{1}{2[\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2]^{\frac{3}{2}}}\left\{\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}(-1+\mathrm{e}^{\mathrm{i}Q_1})w_2\{2\,\mathrm{e}^{\mathrm{i}Q_1(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}\tau\right.\right.$$

$$+ [2b_1\,\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2 - \mathrm{i}\,\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}(-1+\mathrm{e}^{\mathrm{i}Q_2})\sqrt{\mathrm{e}^{\mathrm{i}Q_1(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}w_2]\int D(z)\mathrm{d}z\}\Big\}m_1$$

$$+\exp\Big\{\tau w_2 + \frac{w_2[2b_1(-1+\mathrm{e}^{\mathrm{i}Q_2}) - \mathrm{i}(-1+\mathrm{e}^{\mathrm{i}Q_2})w_2]\int D(z)\mathrm{d}z}{2(-1+\mathrm{e}^{\mathrm{i}Q_2})}\Big\}m_2,$$

$$f_{12}(z,\tau) = \exp\Big\{\frac{1}{2}w_2\Big\{2\tau + \frac{2\,\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}(-1+\mathrm{e}^{\mathrm{i}Q_1})\tau}{\sqrt{\mathrm{e}^{\mathrm{i}Q_1(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}} + \mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}(-1+\mathrm{e}^{\mathrm{i}Q_1})$$

$$\times\Big[\frac{2b_1}{\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}} - \frac{\mathrm{i}\,\mathrm{e}^{-\mathrm{i}Q_1+\frac{\mathrm{i}Q_2}{2}}(\mathrm{i}+\mathrm{e}^{\mathrm{i}Q_1})w_2}{(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}\Big]\int D(z)\mathrm{d}z$$

$$+\frac{[2b_1(-1+\mathrm{e}^{\mathrm{i}Q_2}) - \mathrm{i}(-1+\mathrm{e}^{\mathrm{i}Q_2})w_2]\int D(z)\mathrm{d}z}{-1+\mathrm{e}^{\mathrm{i}Q_2}}\Big\}\Big\}$$

$$\times\frac{\mathrm{e}^{\mathrm{i}Q_1}+\mathrm{e}^{\mathrm{i}Q_2}-\mathrm{e}^{2\mathrm{i}Q_2}-\mathrm{e}^{\mathrm{i}(Q_1+Q_2)}+2\,\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}{1-\mathrm{e}^{\mathrm{i}Q_2}+\mathrm{e}^{\mathrm{i}(Q_1+Q_2)}-\mathrm{e}^{\mathrm{i}(Q_1+2Q_2)}+2\,\mathrm{e}^{\frac{\mathrm{i}Q_2}{2}}\sqrt{\mathrm{e}^{\mathrm{i}Q_1}(-1+\mathrm{e}^{\mathrm{i}Q_2})^2}}m_1m_2.$$

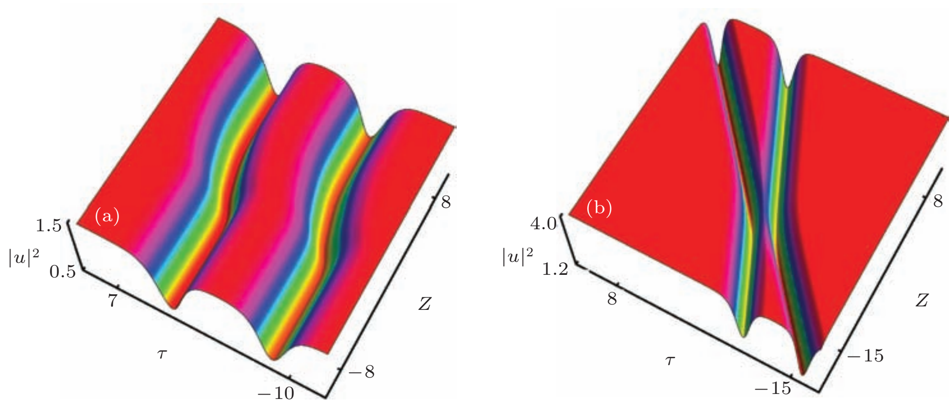

图4 (网刊彩色) 色散呈叠加的Gauss函数和常数变化, 增益系数为常数时, 暗孤子传输情形 (a) 中各参数取为 $\varepsilon=1$, $\mu_1=1.2$, $b_1=0.2$, $w_2=1.3$, $m_1=1.6$, $m_2=0.01$, $Q_1=-4.5$, $Q_2=4.5$, $D(z)=\mathrm{e}^{-0.1(z-1)^2}+\mathrm{e}^{-(z-1)^2}$, $g(z)=-0.42$; (b) 中各参数为 $\varepsilon=1$, $\mu_1=1.2$, $b_1=1$, $w_2=1.8$, $m_1=1.6$, $m_2=0.8$, $Q_1=-1.9$, $Q_2=1.6$, $D(z)=-3.1$, $g(z)=-5.6$

Fig. 4. (color online) Dispersion is changing with the function of Gauss and constant, gain is constant, and the propagation of dark solition is stable. (a) each parameters taken as $\varepsilon=1$, $\mu_1=1.2$, $b_1=0.2$, $w_2=1.3$, $m_1=1.6$, $m_2=0.01$, $Q_1=-4.5$, $Q_2=4.5$, $D(z)=\mathrm{e}^{-0.1(z-1)^2}+\mathrm{e}^{-(z-1)^2}$, $g(z)=-0.42$; (b)each parameters taken as $\varepsilon=1$, $\mu_1=1.2$, $b_1=1$, $w_2=1.8$, $m_1=1.6$, $m_2=0.8$, $Q_1=-1.9$, $Q_2=1.6$, $D(z)=-3.1$, $g(z)=-5.6$.

对于双暗孤子解(11), 我们也可以通过选择不同的损耗、色散和非线性效应来控制两个孤子的相互作用. 当色散 $D(z)$ 呈叠加的Gauss函数变化, 增益系数 $g(z)$ 为常数时, 暗孤子传输情况如图4(a)所示. 两个暗孤子在传输过程中彼此会有一个恒定的分离并且互不影响, 按照原有路径进行传输, 这可能为提高通信系统的容量提供一定的理论依据. 当色散 $D(z)$ 和增益系数 $g(z)$ 均为常数时, 暗孤子传输情况如图4(b)所示. 两个暗孤子并没有发生碰撞, 只是相互吸引, 并且能够一直保持稳定的传输.

4 结 论

本文主要研究了通过调节光纤的损耗、色散和非线性效应来实现对暗孤子传输的控制. 利用Hirota方法, 得到了非线性Schrödinger方程(1)的双线性形(3)—(4)式. 基于该双线性形式, 解析研究了方程(1)的暗孤子解(9). 在非均匀光纤的正常色散区, 我们考虑了方程(1)具有不同增益系数、色散和非线性系数的情形, 并讨论了光纤的增益系数、色散和非线性效应对暗孤子传输特性的影响.

另外, 我们还讨论了暗双孤子的相互作用. 通过调节增益系数、色散和非线性效应, 能够实现暗孤子稳定传输的目的, 并且能控制暗孤子的传输特性. 本文的结论期望能为光纤中暗孤子控制技术提供一定的理论依据.

感谢中国科学院物理研究所魏志义研究员、韩海年副研究员的讨论.

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Study on transmission characteristics of dark solitons in inhomogeneous optical fibers*

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(Received 12 November 2014; revised manuscript received 15 December 2014)

Abstract

The terms of gain(or absorption), dispersion, and nonlinearity in the nonlinear Schrödinger equation are usually variables, which can be used to study the propagation of optical pulses in inhomogeneous optical fibers. In this paper, with the aid of the Hirota method, the bilinear forms of the Schrödinger equation are derived. Based on the bilinear form, the analytic dark soliton solutions to the nonlinear Schrödinger equation are obtained. The properties of dark solitons are discussed. Stable dark solitons are observed in the normal dispersion regime. In addition, corresponding parameters for controlling the propagation of dark solitons are analyzed. Results of our research show that the propagation route of solitons can be effectively controlled by the gain(or absorption), dispersion, and nonlinearity, which can improve the quality of signal transmission in optical communications. When the amplitude of the loss coefficient increases, the amplitude of the dark soliton increases suddenly during the transmission process.By means of changing the type of dispersion, the purpose of controlling the dark soliton phase and phase oscillation is achieved. The possibly applicable soliton control techniques, which are used to design dispersion and nonlinearity-managed systems, are proposed. The proposed techniques may find applications in soliton management communication links, like soliton control.In addition, two-soliton solution is obtained. With the dark two-soliton solution, the interaction between two solitons is discussed in the paper. The result may be of potential application in the ultralarge capacity transmission systems.

Keywords: dark soliton, inhomogeneous optical fiber, soliton control, nonlinear Schrödinger equation

PACS: 05.45.Yv, 42.65.Tg, 42.65.Wi, 42.65.Re **DOI:** 10.7498/aps.64.090504

* Project supported by the National Natural Science Foundation of China (Grant No. 61205064).

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