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High-order solitons transmission in hollow-core photonic crystal fibers

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Abstract – Hollow-core photonic crystal fibers (HC-PCFs) can be used for the supercontinuum generation. Because the design of HC-PCFs is flexible, the dispersion and nonlinear effects is variable, and the pulses in HC-PCFs can show different transmission characteristics. In this paper, the transmission of high-order solitons in HC-PCFs is studied. Through adjusting the group-velocity dispersion and nonlinear effects of HC-PCFs, we present the different transmission of high-order solitons, and analyze their characteristics. Results are conducive to the applications of HC-PCFs in nonlinear optics and ultrafast optics.

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Introduction. – Soliton transmission in optical fibers with different properties and structures has been widely studied in nonlinear optics recently [1,2]. In the transmission media for solitons, photonic crystal fibers (PCFs) have attracted much attention due to the wavelength of the order periodic or quasi-periodic distribution of air holes in the cladding region [3–5]. They have exhibited characteristics such as dispersion tunability and high nonlinearity. Thus, researches on PCFs have become one of the hot research problems in nonlinear optics, ultrafast optics, optoelectronics and optical communications [6–11].

Among the PCFs, hollow-core PCFs (HC-PCFs) have the advantages of the broadband dispersion profile and highly nonlinear, and show excellent performance in ultrafast optics [12–17]. In recent years, HC-PCFs have been extensively investigated [18–23]. Stimulated Raman scattering has been reported in HC-PCFs filled with hydrogen gas [18]. Based on HC-PCFs, the gas-laser devices with high performance have been reported [19]. When the HC-PCFs, which act as the gas absorption chamber, have been used in the laser cavity, the fiber sensor has been demonstrated [20]. In HC-PCFs, when the pulse has been propagated in it, ref. [21] has presented that the noise has been increased, and the polarization noise has been observed. Besides, the interaction between the Raman and nonlinear photoionization effects in HC-PCFs has been investigated [22]. Using HC-PCFs, the generation of transient and persistent optical depths of alkali vapors has been studied [23].

The transmission of optical solitons in HC-PCFs can be modeled by the nonlinear Schrödinger (NLS) equation [24–26]:

$$i\,\partial_\xi\psi - \frac{1}{2}\,\beta_2\,\partial_\tau^2\psi - \frac{i}{6}\,\beta_3\,\partial_\tau^3\psi + |\psi|^2\,\psi - \tau_R\,\psi\,\partial_\tau|\psi|^2$$
$$-\eta\,\psi\int_{-\infty}^{\tau}|\psi|^2\mathrm{d}\tau' = 0. \quad (1)$$

For eq. (1), the instructions on $\psi(\xi,\tau)$, ξ, τ, β_2, β_3, τ_R and η can be seen in ref. [26]. The analytic solutions for eq. (1) have been derived with the Hirota bilinear method. The breathers have been observed in the HC-PCFs. Moreover, the dynamics behavior of breathers has been shown.

However, the analytic investigation of the high-order soliton transmission in HC-PCFs has not been reported before. This investigation will be useful for the generation of a supercontinuum spectrum. In this paper, we will study the transmission of high-order solitons in HC-PCFs analytically. Besides, we will adjust the group-velocity dispersion (GVD) and nonlinear effects of HC-PCFs to control the high-order soliton transmission. Furthermore, the design of HC-PCFs to generate the supercontinuum spectrum will be proposed.

The structure of this paper will be as follows. In the next section, the analytic solutions for eq. (1) will be presented, and the transmission of high-order solitons will be analyzed. Finally, our conclusions will be given in the third section.

Analysis and discussions for eq. (1). – According to ref. [26], the analytic soliton solutions for eq. (1) can be written as

$$\psi(\xi,\tau)=\frac{g_1(\xi,\tau)+g_3(\xi,\tau)}{1+f_2(\xi,\tau)+f_4(\xi,\tau)}, \qquad (2)$$

where $g_1(\xi,\tau)$, $f_2(\xi,\tau)$, $g_3(\xi,\tau)$, and $f_4(\xi,\tau)$ are defined in the following:

$$\begin{aligned}
g_1(\xi,\tau) &= e^{\theta_1}+e^{\theta_2},\\
f_2(\xi,\tau) &= A_1e^{\theta_1+\theta_1^*}+A_2e^{\theta_2+\theta_2^*}+A_3e^{\theta_1+\theta_2^*}+A_4e^{\theta_2+\theta_1^*},\\
g_3(\xi,\tau) &= E_1e^{2\theta_1+\theta_1^*}+E_2e^{2\theta_1+\theta_2^*}+E_3e^{\theta_1+\theta_2+\theta_1^*}\\
&\quad +E_4e^{\theta_1+\theta_2+\theta_2^*}+E_5e^{2\theta_2+\theta_1^*}+E_6e^{2\theta_2+\theta_2^*},\\
f_4(\xi,\tau) &= M_1e^{2\theta_2+2\theta_2^*}+M_2e^{\theta_1+\theta_2+2\theta_2^*}+M_3e^{2\theta_1+2\theta_2^*}\\
&\quad +M_4e^{2\theta_2+\theta_1^*+\theta_2^*}+M_5e^{\theta_1+\theta_2+\theta_1^*+\theta_2^*}\\
&\quad +M_6e^{2\theta_1+\theta_1^*+\theta_2^*}+M_7e^{2\theta_2+2\theta_1^*}\\
&\quad +M_8e^{\theta_1+\theta_2+2\theta_1^*}+M_9e^{2\theta_1+2\theta_1^*}
\end{aligned}$$

with

$$\begin{aligned}
\theta_j &= a_j\,\xi+b_j\,\tau+k_j\\
&= (a_{j1}+i\,a_{j2})\,\xi+(b_{j1}+i\,b_{j2})\,\tau+k_{j1}+i\,k_{j2},\\
a_{j1} &= \frac{1}{3}\beta_2\tau_Rb_{j1}^3-b_{j2}\beta_2b_{j1}-b_{j2}^2\beta_2\tau_Rb_{j1},\\
a_{j2} &= -\frac{1}{3}\beta_2\tau_Rb_{j2}^3-\frac{1}{2}\beta_2b_{j2}^2+b_{j1}^2\beta_2\tau_Rb_{j2}+\frac{1}{2}b_{j1}^2\beta_2,\\
A_1 &= \frac{1}{4b_{11}^2\beta_2}, \qquad A_2=\frac{1}{4b_{21}^2\beta_2},\\
A_3 &= \frac{1}{(b_1+b_2^*)^2\beta_2}, \qquad A_4=A_3^*,\\
E_1 &= \frac{4ib_{11}b_{12}\tau_R-\eta}{8b_{11}^3\beta_2\,(2b_1\tau_R+i)},\\
E_2 &= \frac{(b_1^2-b_2^{*2})\tau_R-\eta}{(b_1+b_2^*)^3\beta_2\,(2b_1\tau_R+i)},\\
E_3 &= \frac{i\,(b_1-b_2)^2+\eta\,(b_1-b_2)-4\eta b_{11}+D_1}{4b_{11}^2\,(b_1^*+b_2)^2\beta_2\,(b_1\tau_R+b_2\tau_R+i)},\\
D_1 &= \left(b_2^3-b_1^3\right)\tau_R+2ib_{12}\tau_R+D_1\left(7b_{11}^2-b_{12}^2\right)\\
&\quad +b_2b_1^*\,(b_2-b_1^*)\,\tau_R,\\
E_4 &= \frac{i\,(b_2-b_1)^2+\eta\,(b_2-b_1)-4\eta b_{21}+D_2}{4b_{21}^2\,(b_1+b_2^*)^2\beta_2\,(b_1\tau_R+b_2\tau_R+i)},\\
D_2 &= \left(b_1^3-b_2^3\right)\tau_R+2ib_{22}\tau_R\left(7b_{21}^2-b_{22}^2\right)\\
&\quad +b_1b_2^*\,(b_1-b_2^*)\,\tau_R
\end{aligned}$$

$$\begin{aligned}
E_5 &= \frac{(b_2^2-b_1^{*2})\tau_R-\eta}{(b_1^*+b_2)^3\beta_2\,(2b_2\tau_R+i)},\\
E_6 &= \frac{4ib_{21}b_{22}\tau_R-\eta}{8b_{21}^3\beta_2\,(2b_2\tau_R+i)},\\
M_1 &= \frac{E_6+E_6^*}{16b_{21}^2\beta_2}, \quad M_3=\frac{E_2+E_5^*}{4\,(b_1+b_2^*)^2\beta_2},\\
M_2 &= \frac{E_4+E_5^*+E_6^*-A_2A_3\beta_2\,(b_1-b_2)^2}{(b_1+b_2^*+2b_{21})^2\beta_2},\\
M_4 &= \frac{E_4^*+E_5+E_6-A_2A_4\beta_2\,(b_1^*-b_2^*)^2}{(b_1^*+b_2+2b_{21})^2\beta_2},\\
M_5 &= \frac{E_3+E_4+E_3^*+E_4^*+D_3}{4\,(b_{11}+b_{21})^2\beta_2},\\
D_3 &= 4A_3A_4\beta_2\,(b_{12}-b_{22})^2-4A_1A_2\beta_2\,(b_{11}-b_{21})^2,\\
M_6 &= \frac{E_1+E_2+E_3^*-A_1A_3\beta_2\,(b_1^*-b_2^*)^2}{(b_1+b_2^*+2b_{11})^2\beta_2},\\
M_7 &= \frac{E_2^*+E_5}{4\,(b_1^*+b_2)^2\beta_2}, \quad M_9=\frac{E_1+E_1^*}{16b_{11}^2\beta_2},\\
M_8 &= \frac{E_1^*+E_2^*+E_3-A_1A_4\beta_2\,(b_1-b_2)^2}{(b_1^*+b_2+2b_{11})^2},
\end{aligned}$$

and b_{j1}'s, b_{j2}'s, k_{j1}'s and k_{j2}'s ($j=1,2$) are real constants.

Choosing $b_{11}=0.15$, $b_{12}=0.5$, $b_{21}=0.15$, $b_{22}=-1$, $k_{11}=-2$, $k_{12}=1.5$, $k_{21}=-1$ and $k_{22}=0.5$ in the analytic solutions (2), we can obtain the different transmission of high-order solitons through adjusting the GVD and nonlinear effects of HC-PCFs. In fig. 1, optical solitons are transmitted in HC-PCFS with different forms. They show the gradual attenuation in figs. 1(a) and (b). Moreover, due to the GVD effect, we can find that optical solitons have a blue shift with the increase of the GVD, and the pulse intensity is gradually reduced with the increase of transmission distances. For figs. 1(c) and (d), the peak power of the optical solitons is gradually increased, and has a red shift with the increase of the nonlinearity. In the transmission process, the optical solitons are compressed.

For fig. 2, because of the strong nonlinearity, the phenomena of the splitting of optical solitons appear. At the beginning, the original shape of the optical solitons can be maintained in the short transmission distance in fig. 2(b). But after transmitting a certain distance, optical solitons are split resulting in the cumulative effect of the nonlinearity, and they transmitted in oscillation modes. For fig. 2(c), the nonlinear effects are weakened, and the oscillation is reduced compared to fig. 2(a). But the nonlinearity is still relatively strong, and the split phenomenon will still appear after a distance of transmission. For fig. 2(d), the optical solitons can be split in a short distance when the nonlinear effects are enhanced, and the optical solitons are broadened. Thus, high nonlinearity is more likely to generate the supercontinuum spectrum.

In fig. 3, the optical solitons can transmit stably in a short distance because of the weak nonlinearity. However, when the nonlinearity accumulates to a certain extent, the

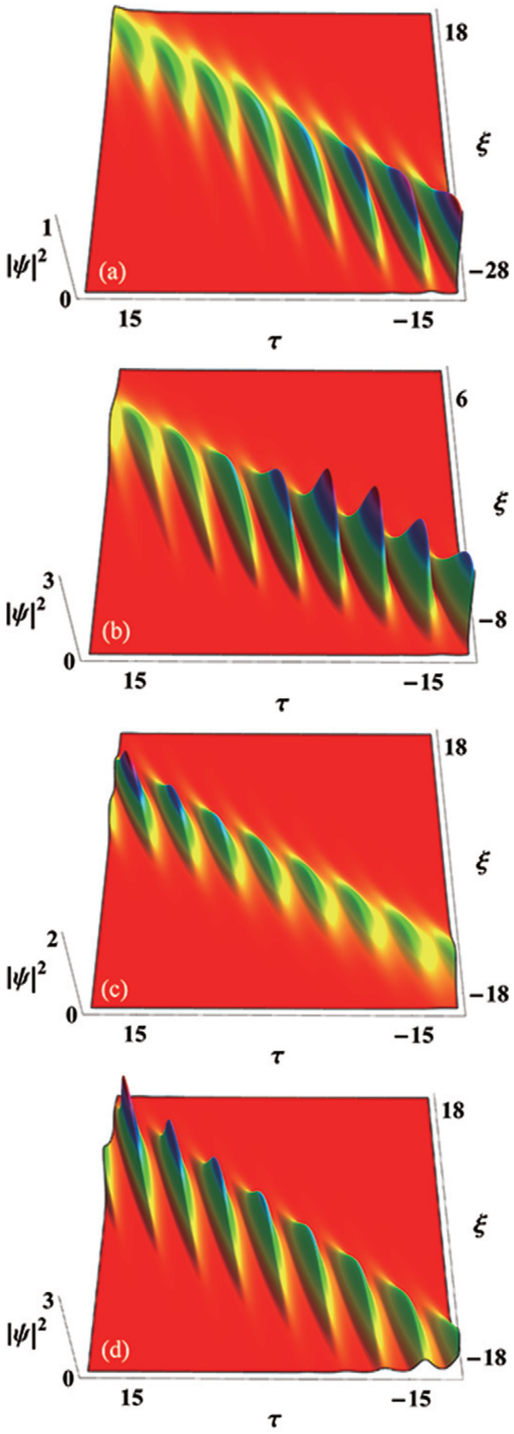

Fig. 1: (Colour online) Transmission of high-order solitons in the HC-PCF. The corresponding parameters for the analytic solutions (2) are chosen as follows: (a) $\beta_2 = 1.47$, $\tau_R = 1.7$, $\eta = 0.59$; (b) $\beta_2 = 5.5$, $\tau_R = 1.6$, $\eta = 0.7$; (c) $\beta_2 = 1.1$, $\tau_R = 2.5$, $\eta = 2.3$; (d) $\beta_2 = 1.1$, $\tau_R = 2.9$, $\eta = 2.8$.

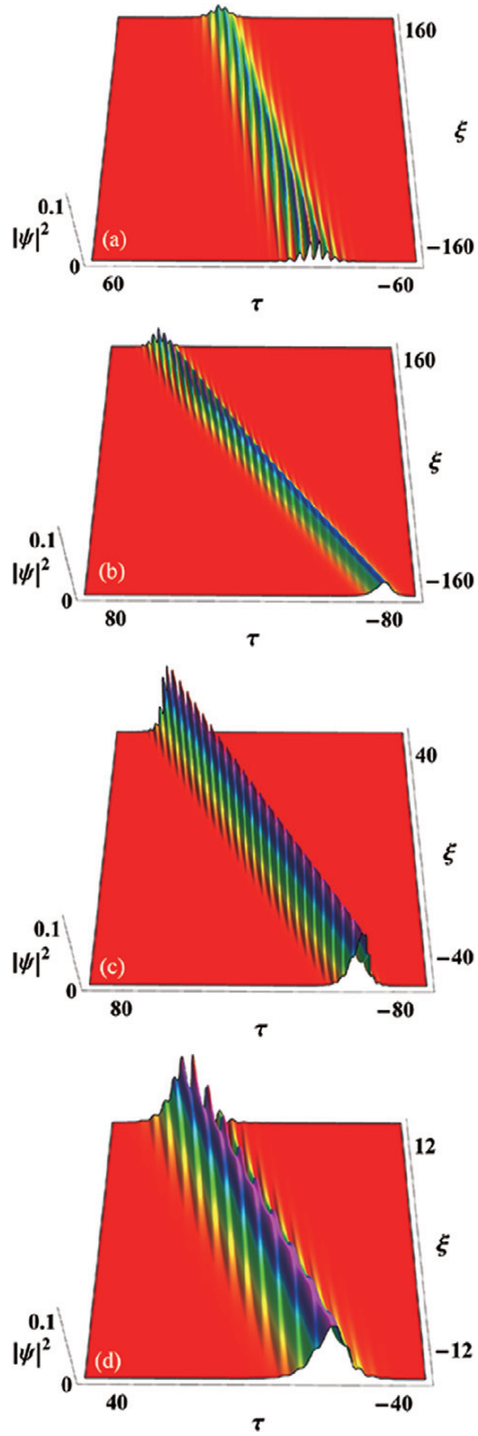

Fig. 2: (Colour online) Transmission of high-order solitons in the HC-PCF. The corresponding parameters are chosen as follows: (a) $\beta_2 = 0.16$, $\tau_R = 1.8$, $\eta = 0.55$; (b) $\beta_2 = 0.31$, $\tau_R = 2.4$, $\eta = 0.35$; (c) $\beta_2 = 1.1$, $\tau_R = 2.1$, $\eta = 0.55$; (d) $\beta_2 = 1.1$, $\tau_R = 2.4$, $\eta = 0.25$.

oscillation is aggravated, the optical solitons are split, and the pulse duration of the optical solitons becomes large. After the oscillating transmission, the pulse duration can withstand the pulse energy, and optical solitons achieve the stable transmission once again. Increasing the GVD and decreasing the nonlinearity can result in the relatively short transmission distance from the stable transmission to the oscillation transmission in fig. 3(b). Moreover, due to the large GVD, optical solitons are broadened more greatly after the oscillating transmission, compared with

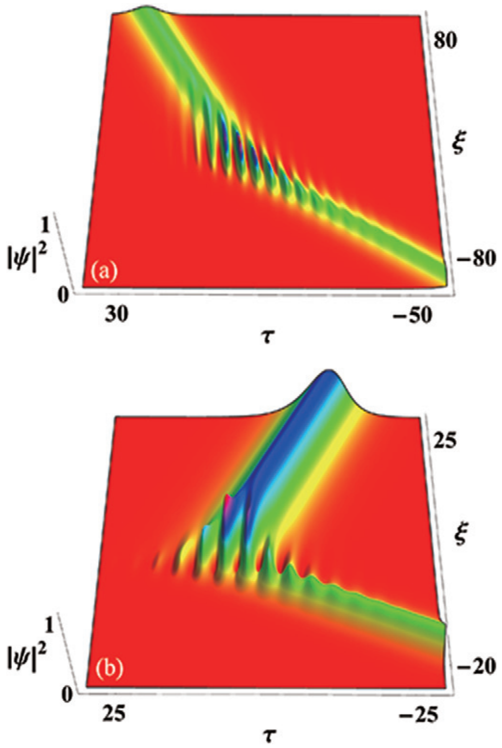

Fig. 3: (Colour online) Transmission of high-order solitons in the HC-PCF. The corresponding parameters are chosen as follows: (a) $\beta_2 = 0.94$, $\tau_R = 1.3$, $\eta = 0.55$; (b) $\beta_2 = 3.9$, $\tau_R = 0.86$, $\eta = 0.3$.

fig. 3(a). Hence, when we reduce the GVD and increase the nonlinearity, the optical spectrum of the optical solitons can be wider, and the pulse transmission in the HC-PCF will be more stable.

Conclusions. – The transmission of high-order solitons in HC-PCFs have been investigated analytically in this paper. The analytic solutions of eq. (1) have been obtained. The different transmissions of high-order solitons have been presented through adjusting the GVD and the nonlinear effects of HC-PCFs. With the increase of the nonlinearity, the optical solitons have been compressed in the transmission process. Because of the high nonlinearity, the phenomena of the splitting of the optical solitons have appeared, and the high nonlinearity has been more likely to generate the supercontinuum spectrum. Besides, when we have reduced the GVD and increased the nonlinearity, the optical spectrum of the optical solitons has been wider, and the pulse transmission in the HC-PCF has been more stable. The results can provide a valuable reference for the supercontinuum generation in ultrafast optics.

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