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TWO COLOR BRIGHT-BRIGHT VECTOR SOLITONS IN THREE LEVEL CASCADE ATOMIC SYSTEMS

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Abstract

We have investigated two-component spatial optical solitons in cascaded three level atomic systems. We have identified the existence curve in the parameter space of power and spatial widths which reveal the existence of a plethora of stationary coupled solitons. These solitons can exist with two different frequencies and also with two different widths. Our analytical results have been verified by direct numerical simulation of the coupled nonlinear Schrödinger equations. Stability analysis confirms that these solitons are stable.

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Optical solitons in various nonlinear media are extremely attractive subjects for fundamental research and offer potential applications in photonics [1-13]. They are self-trapped and self-guided solitary waves, which retain their shape during propagation [6-8]. Depending on their localization in space, time or both in space and time, they are identified as spatial, temporal or spatiotemporal solitons. Spatial solitons are optical beams that propagate in nonlinear media without diffraction, i.e., the beam width remains invariant during propagation. Though solitons are ubiquitous in various branches of physics, self-trapped optical spatial solitons possess some very attractive features, which make them potentially useful for various applications, such as all optical switching and routing, interconnects, parallel computing, optical storage, etc. [9-12]. Among the known mechanisms, an important physical mechanism, which supports the existence of spatial solitons, is beam self phase modulation (SPM) self focusing. In this case due to nonlinearity in the medium, the optical beam modifies the refractive index and induces an effective waveguide which then self guides the beam. When the optical beam is also a mode of the waveguide that it has induced, the beam propagates as a stationary entity, i.e., a spatial soliton [9]. A wide variety of solitons in different media such as in Kerr media [1,5,6], liquid crystals [7], photorefractive [6] and photovoltaic crystals [8], quantum dots and quantum wells [13,14] and atomic systems [15], have been studied and experimentally detected.

In the present paper we confine our attention to the propagation of two intense optical beams of different frequencies in a three-level atomic system in the cascade configuration. The three-level cascade atomic system has been studied in detail by many groups in quantum optics, non-linear optics and laser physics. In quantum-optics, a number of interesting phenomena such as, phase-sensitive [16] and super radiant amplifications [17], violation of classical effects [18], dipole amplitude square squeezing [19], and phase-dependent fluorescence line width narrowing [20], have all been analyzed. In the area of nonlinear optics, the electromagnetically induced transparency for a probe field in the presence of a strong field [21,22] and field entropy [23] have been considered. This paper deals with a Kerr-like medium composed of uniformly distributed three-level atomic systems in the cascade configuration for which the atoms are initially in the ground level. Two intense optical fields of different frequencies induce the top to intermediate and intermediate to ground atomic level dipole allowed transitions. The transitions from the top to the ground levels are dipole forbidden transitions. We also consider a closed atomic system where the top level decays to the intermediate level and the intermediate level to the ground level with different decaying rates. The steady-state expressions for the third-order susceptibilities experienced by the two fields while propagating through the medium were derived earlier, which were subsequently used to derive the couple nonlinear Schrödinger equations for two propagating waves of different frequencies [24]. We begin our investigation with these coupled equations and reveal several important features of coupled solitons in cascaded atomic systems [24]. Therefore, to reveal several important properties of two component spatial solitons three in level cascade atomic systems we begin with the following equations [24]:

$$i\alpha_1 \frac{\partial \psi_1}{\partial z} + \frac{\partial^2 \psi_1}{\partial x^2} + \sigma_1 M_1 |\psi_2|^2 \psi_1 = 0, \tag{1}$$

and

$$i\alpha_2 \frac{\partial \psi_1}{\partial z} + \frac{\partial^2 \psi_1}{\partial x^2} + \sigma_2 (M_2 |\psi_1|^2 + |\psi_2|^2)\psi_2 = 0\ , \tag{2}$$

where $\alpha_j = 2n_j k_j \eta,\quad \sigma_j = \pm 1\ ,\qquad M_1 = \frac{|\chi_1^3(E_2)|k_1^2}{|\chi_2^3(E_2)|k_2^2}$ and $M_2 = \frac{|\chi_2^3(E_2)|k_2^2}{|\chi_1^3(E_2)|k_1^2}$.

Introducing the following normalization $z' = {}^{z}/_{\alpha_1},\quad \phi_1 = \sqrt{M_2}\,\psi_1\ ,\quad \phi_2 = \sqrt{M_1}\,\psi_2,$ $\frac{1}{M_1} = M$ in equations (1) and (2), the normalized coupled Schrödinger equations turns out to be

$$i\frac{\partial \phi_1}{\partial z} + \frac{\partial^2 \phi_1}{\partial x^2} + \sigma_1 |\phi_2|^2 \phi_1 = 0\quad , \tag{3}$$

and

$$i\alpha\ \ \frac{\partial \phi_2}{\partial z} + \frac{\partial^2 \phi_2}{\partial x^2} + \ \sigma_2 (\ |\phi_1|^2\ +\ M\ \ |\phi_2|^2)\phi_2 = 0\ , \tag{4}$$

where the prime from z has been omitted for brevity and $\alpha = \frac{\alpha_2}{\alpha_1}$. The main task which we are undertaking in the subsequent discussion is not to find out the analytical expression of the coupled solitons, but to identify the solitons existence curve and reveal certain important features of these solitons which may be helpful if one actually wish to detect them experimentally. In order to identify these features of spatial solitons, we substitute in equations (3) and (4) solutions of the form $\phi_1 = U(x,z)exp[-i\Omega_1(\mathrm{x},\mathrm{z})]$ and $\phi_2 = V(x,z)exp[-i\Omega_2(\mathrm{x},\mathrm{z})]$, and obtain

$$\frac{\partial U}{\partial z} - 2\frac{\partial \Omega_1}{\partial x}\frac{\partial U}{\partial x} - U\frac{\partial^2 \Omega_1}{\partial x^2} = 0. \tag{5}$$

$$U\frac{\partial \Omega_1}{\partial z} + \frac{\partial^2 U}{\partial x^2} - U(\frac{\partial \Omega_1}{\partial x})^2 + \sigma_1 V^2 U = 0. \tag{6}$$

$$\alpha\frac{\partial V}{\partial z} - 2\frac{\partial \Omega_2}{\partial x}\frac{\partial V}{\partial x} - V\frac{\partial^2 \Omega_2}{\partial x^2} = 0\ . \tag{7}$$

$$\alpha V\frac{\partial \Omega_2}{\partial z} + \frac{\partial^2 V}{\partial x^2} - V(\frac{\partial \Omega_2}{\partial x})^2 + \sigma_2(\ U^2 + MV^2) = 0. \tag{8}$$

We confine our investigation only to the lowest order localized bright solitons for which light is confined in the central region of the solitons. Therefore $U(x,0) = U_{max} = U_0$ and $V(x,0) = V_{max} = V_0$ as $x \to \infty$. Equations (3) and (4) are modified coupled nonlinear Schrödinger equations and analytical methods, which are indeed approximate, can be adopted to extract useful information and guidelines for subsequent numerical simulations. Since sech profile resembles very close to the solitonic profile in many cases, this profile has been seldom used in appropriate analytic methods and in numerical simulation. However, most widely used approximate solutions for nonintegrable systems are of Gaussian type [25-27] instead of sech. The justification of using the Gaussian ansatz is manifold. Firstly, use of the Gaussian profile makes the calculations remarkably easier. Secondly, numerically computed exact profiles are not widely different from the Gaussian one in most cases. Furthermore, the Gaussian profile is qualitatively very close to the sech profile having nearly the same half width and the integral contents under the two profiles are comparable (differ only by a factor of 0.054) [25]. Also, in most cases the same analytical simplification is not expected by using the sech ansatz [28]. Therefore, use of the Gaussian profile provides much simplicity in calculation without major loss of information. In a trend setting paper [25], Anderson argued in favor of using the Gaussian profile in variational methods that has subsequently been adopted by many researchers in nonlinear optics. In addition to the variational approach, the Gaussian shaped ansatz has been successfully used in the collective variable approach [26], as well as the moment method [27]. Though the Gaussian solution is an approximate solution, it can give useful guidelines for full numerical simulations. Thus, in this paper we introduce the Gaussian ansatz which has been extensively adopted by the soliton community [25–27] in similar situations. However, we wish to point out that this is only an approximate solution whose prediction should be validated by full numerical simulation which will be undertaken in the later part of the paper. Hence, the solutions of the above equations are taken to be Gaussian with amplitude and phase of the following form

$$U = \sqrt{\frac{U_0}{a(z)}}\ exp[-(\frac{x^2}{2r_1^2 a^2})] \tag{9}$$

$$V = \sqrt{\frac{V_0}{b(z)}}\ exp[-(\frac{x^2}{2r_2^2 b^2})] \tag{10}$$

$$\Omega_1 = \frac{\beta_1 x^2}{2}, \qquad \Omega_2 = \frac{\beta_2 x^2}{2}, \qquad \beta_1 = -\frac{d}{dz}(\tfrac{1}{2}\ln a) \qquad \text{and} \qquad \beta_2 = -\frac{d}{dz}(\tfrac{\alpha}{2}\ln a)\ , \tag{11}$$

where U_0 and V_0 are, respectively, peak power of these solitons, r_1 and r_2 are two positive constants, a(z) and b(z) are variable beam width parameters. Note that r_1 a and r_2 b are, respectively, the spatial widths of two solitons. For a pair of nondiverging solitons at z = 0, we should have $a(0) = b(0) = 1$ and $\frac{da}{dz} = \frac{db}{dz} = 0$. This implies r_1 and r_2 are, respectively, the spatial widths of two solitons at $z=0$. Inserting the expressions of U, V, Ω_1 and Ω_2 in equations (6) and (8), expanding the exponential terms by Taylor's expansion around $\frac{x}{r_1 a} \ll 0$ and $\frac{x}{r_2 b} \ll 0$, we obtain the following equations:

$$\frac{x^2}{2}\frac{d\beta_1}{dz} + \left(\frac{x^2}{r_1^4 a^4} - \frac{1}{r_1^2 a^2}\right) - x^2\beta_1^2 + \frac{\sigma_1}{b} V_0 [1 - \frac{x^2}{r_2^2 b^2} + O\left(\frac{x}{r_2\ b}\right)^4 + \cdots\cdots\cdots] = 0, \tag{12}$$

and

$$x^2\left[\beta_2^2 - \frac{\alpha^2}{4b}\frac{d^2 b}{dz^2}\right] + \frac{x^2}{2}\frac{d\beta_1}{dz} + \left(\frac{x^2}{r_2^4 b^4} - \frac{1}{r_2^2 b^2}\right) - x^2\beta_2^2 + \sigma_2\left\{\frac{U_0}{a}\left[1 - \frac{x^2}{r_1^2 a^2} + \cdots\cdots\cdots \cdot\right] + \frac{MV_0}{b}[1 - \frac{x^2}{r_2^2 b^2} + O\left(\frac{x}{r_2\ b}\right)^4 + \cdots\cdots\cdots]\right\} . \tag{13}$$

Equating coefficients of x^2 from both sides of above equations, we immediately get

$$\frac{d^2 a}{dz^2} - \frac{4}{r_1^4 a^3} + \frac{4\sigma_1 a V_0}{r_2^2 b^3} = 0 \quad . \tag{14}$$

$$\frac{d^2 b}{dz^2} - \frac{4}{\alpha^2 r_2^4 b^3} + \frac{4\sigma_2 b}{\alpha^2}\left(\frac{U_0}{r_1^2 a^3} + \frac{V_0 M}{r_2^2 b^3}\right) = 0. \tag{15}$$

Since we are interested in coupled bright-bright solitons, therefore, we look for equilibrium points of the above equations which may be obtained easily from the following relationship:

$$\frac{1}{r_1^4} = \frac{\sigma_1}{r_2^2} V_0. \tag{16}$$

$$\frac{1}{r_2^4} = \sigma_2\left(\frac{U_0}{r_1^2} + M\frac{V_0}{r_2^2}\right). \tag{17}$$

Note that for bright-bright solitons, σ_1 should be positive and σ_2 should be positive as well since $M > 0$. We divide eq.(17) by (16) to yield

$$\left(\frac{r_1}{r_2}\right)^4 = \frac{\sigma_2}{\sigma_1}\frac{r_2^2}{V_0}\left(\frac{U_0}{r_1^2} + M\frac{V_0}{r_2^2}\right). \tag{18}$$

Since for a bright-bright soliton pair $\frac{\sigma_2}{\sigma_1} = 1$, the solitons existence equation may be re casted as

$$r^6 - Mr^2 - \frac{U_0}{V_0} = 0, \tag{19}$$

where r= $\frac{r_1}{r_2}$. Eq.(19) is the existence equation of coupled solitons. The above equation has a lone positive root for r which is found to be

$$r = \frac{[V_0 + \mathrm{M}]^{1/2}}{\sqrt[6]{18}\left(\Lambda V_0^2\right)^{1/3}}, \qquad (20)$$

where $\Lambda = 9U_0 + \sqrt{81U_0^2 - 12M^3V_0^2}$.

The condition for solitons of equal width turns out to be

$$\frac{U_0}{V_0} + M = 1. \qquad (21)$$

Figure (1) illustrates the variation of U_0 and V_0 for different r and this figure is the existence curve of coupled solitons. Each point on any curve of this figure represents a stationary coupled soliton with definite width and peak power, the value of r determines the value of spatial widths r_1 and r_2 . Figure 1 also predicts the existence of coupled solitons in which the peak power of one component could be only a fraction of the other component. This has an important consequence, for example, a very weak optical beam of appropriate width could be self trapped and made to propagate as a stationary spatial soliton with the aid of another co propagating strong beam solely due to the cross phase modulation. Soon this prediction will be verified by full numerical simulation of the coupled NLSE. Overall, figure 1 is unique in the sense that it captures the existence criteria of a large family of single hump bright stationary coupled solitons of different width and peak power. To demonstrate the behavior of these propagating composite solitons, we first choose a value of r and select a point arbitrarily on the curve leveled with this value in figure 1. For this point, we first calculate values of U_0 and $V_0$and then these values are plugged in equation (16) to estimate the value of r_1 and since r is known this will immediately yield the value of r_2. Values of U_0, V_0, r_1 and r_2, thus obtained, are then employed in equations (14) and (15) to solve for a and b with initial conditions $a(0) = b(0) = 1$ and $\frac{da}{dz} = \frac{db}{dz} = 0$ at $z = 0$. As an illustration, we arbitrarily choose $U_0 = 9 \cdot 5$ and $V_0 = 4 \cdot 4$, $r_1 = 9.4352$ and $r_2 = 8 \cdot 4352$ from figure 1. The behavior of a and b for these values has been obtained from equations (14) and (15) and as predicted we find that a and b remain invariant with propagation distance. Thus, the spatial soliton pair is stationary. This stationary property has been verified for several other randomly chosen points on different curves of figure 1.

To this end, It is now appropriate to examine the stability of the identified equilibrium states since only stable solutions are solitons. In order to establish a stability criterion using the Lyapunov's exponent [29–30] we recast eqs.(14) and (15) in the following form:

$$\dot{a} = \sigma = P(a, \ b, \ \sigma, \ \rho) \quad (22)$$
$$\dot{b} = \rho = Q(a, \ b, \ \sigma, \ \rho) \quad (23)$$
$$\dot{\sigma} = \frac{4}{r_1^4 a^3} - \frac{4\sigma_1 a V_0}{r_2^2 b^3} = R(a, \ b, \ \sigma, \ \rho) \quad (24)$$
$$\dot{\rho} = \frac{4}{\alpha^2 r_2^4 b^3} - \frac{4\sigma_2 b}{\alpha^2}\left(\frac{U_0}{r_1^2 a^3} + \frac{V_0 M}{r_2^2 b^3}\right) = S(a, \ b, \ \sigma, \ \rho) \quad (25)$$

where the dot signifies derivative w.r.t z. We expand all the variables around their steady state values $(a_s, b_s, \ \sigma_s, \ \rho_s \ )$ and a small perturbation around the steady state as follows: $a = a_s + \hat{a}$, $b = b_s + \hat{b}$, $\sigma = \sigma_s + \hat{\sigma}$ and $\rho = \rho_s + \hat{\rho}$. Linearizing eqs.(22) – (25) we obtain

$$\dot{\Theta} = \mathcal{J}\Theta, \quad \text{where} \quad \Theta = \begin{pmatrix}\hat{a} & \hat{b} & \hat{\rho} & \hat{\sigma}\end{pmatrix}^T \quad \text{and} \quad \mathcal{J} = \begin{pmatrix} P_a & P_b & P_\sigma & P_\rho \\ Q_a & Q_b & Q_\sigma & Q_\rho \\ R_a & R_b & R_\sigma & R_\rho \\ S_a & S_b & S_\sigma & S_\rho \end{pmatrix}, \quad (26)$$

where the subscript denote partial derivatives with respect to that variable. We construct a Jacobean determinant and for nontrivial solution set its value to zero, hence,

$$\det(\mathcal{J} - \lambda I) \begin{vmatrix} P_a - \lambda & P_b & P_\sigma & P_\rho \\ Q_a & Q_b - \lambda & Q_\sigma & Q_\rho \\ R_a & R_b & R_\sigma - \lambda & R_\rho \\ S_a & S_b & S_\sigma & S_\rho - \lambda \end{vmatrix} = 0. \quad (27)$$

The eigenvalue equation reduces to

$$\lambda^4 - \lambda^2 \Sigma + \Pi = 0 \, , \quad (28)$$

where $\Sigma = (R_a - S_b)_{a_s, b_s}$ and $\Pi = (R_a S_b - S_a R_b)_{a_s, b_s}$. The four eigen values of the above equation are given by $\lambda = \pm \frac{1}{\sqrt{2}}\left[\Sigma \pm \sqrt{\Sigma^2 - 4\Pi}\right]^{1/2}$. Since all the four roots are found to be imaginary, the equilibrium solutions as identifies by the existence curve are all stationary solitons.

In order to verify the prediction of analytic results as elucidated earlier which is based on approximation method, we undertake full numerical simulation of equations (3) and (4) using the Split Step Fourier method [31]. For illustration, we choose three different points from figure 1. In the first case we demonstrate the behavior of coupled solitons in which the amplitude and widths of both solitons are approximately equal. In the second the amplitude of one solitons is approximately twice that of the other. Lastly, in the third case, the amplitude of one soliton is approximately six times larger than the other. To be more specific, as a first example, we choose a point in figure 1 for which $U_0 = 4.0$ and $V_0 = 3 \cdot 5$. The calculated values of other parameters are $r_1 = 8.4352$ and $r_2 = 7 \cdot 4352$. Figure (2) demonstrates the behavior of coupled solitons characterized by these parameters, in this particular example two solitons are of approximately equal power. It is interesting to note that solitons are stable and maintain their shape as they propagate in the atomic system. In the second example, the identified parameters, obviously selected from figure (1), are $U_0 = 9 \cdot 5$ and $V_0 = 4 \cdot 4$, $r_1 = 9.4352$ and $r_2 = 8 \cdot 4352$. The behavior of coupled solitons has been demonstrated in figure(3). In the last example values of solitons parameters are $U_0 = 9 \cdot 5$ and $V_0 = 1 \cdot 5$, $r_1 = 10.4352$, $r_2 = 9 \cdot 4352$ and in this particular case one soliton is fairly weak in comparison to the stronger entity. Figure (4) illustrates the behavior of couple solitons with above parameters. All the three sets of coupled solitons propagate as stationary entities. Therefore, full numerical simulation results confirm that the coupled solitons, which have been identified in figure 1, are stationary. Hence, the U_0, V_0 diagram in figure 1 is unique and identifies a wide parameter space for the existence of stationary composite solitons with different spatial widths. Thus, our analytical results have been verified by direct numerical simulations of coupled NLSEs.

In conclusion, we have identified the existence curve in the parameter space of power and spatial widths which reveal the existence of a plethora of stationary coupled solitons in cascaded three level atomic systems. We have shown that a very weak soliton can be cross trapped and guided by stronger one. Employing direct numerical simulation we have shown that these solitons are stable.

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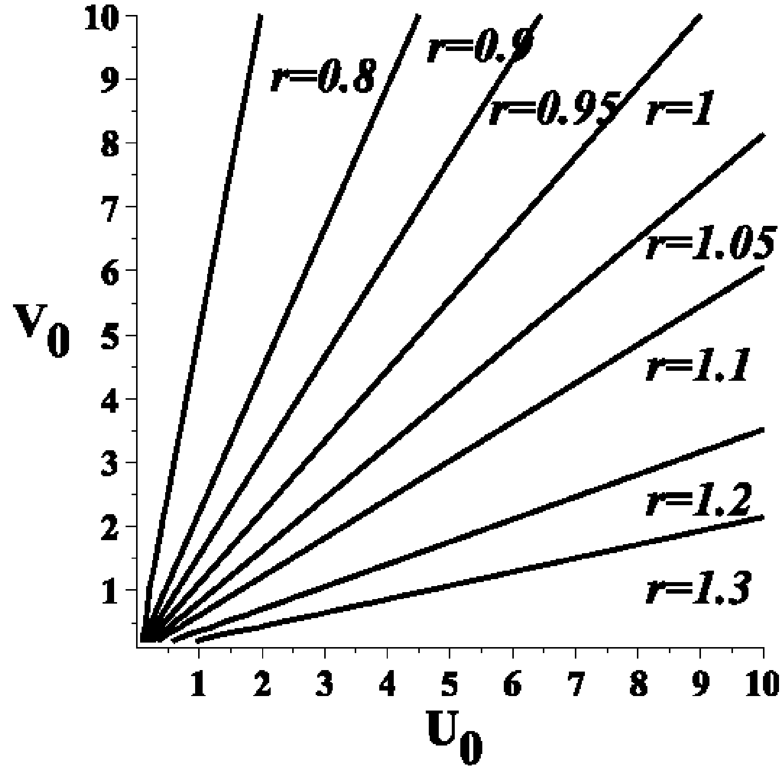

Fig.1. Variation of U_0 with V_0 for different values of r. Value of $M = 0 \cdot 1$. Any point on any of the curves signifies the existence of a coupled solitons.

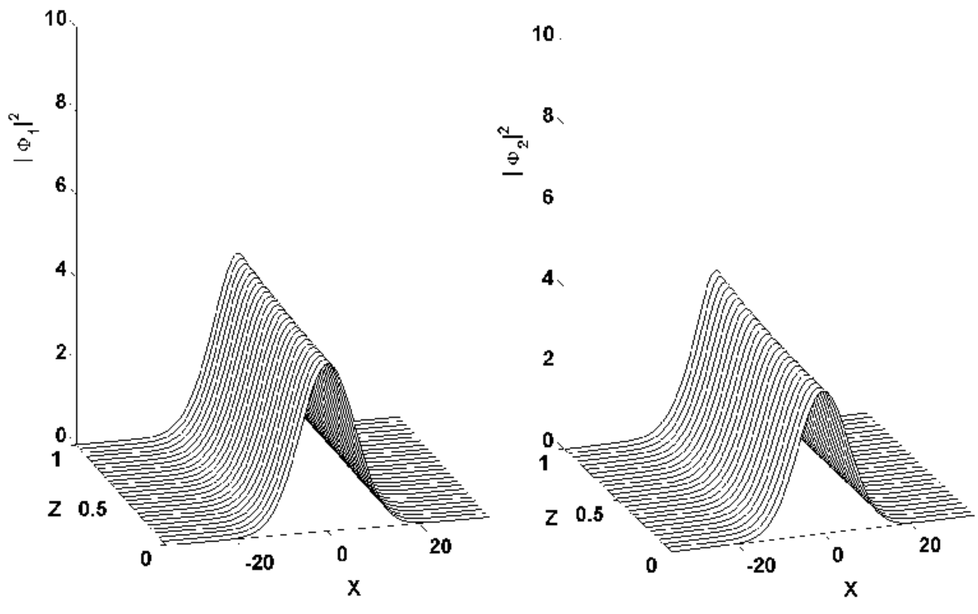

Fig.2. Propagation of coupled solitons as obtained by direct numerical simulation. Two solitons are approximately of same power. Soliton parameters U_0, V_0 r_1 and r_2 were identified from figure 1. The value of these parameters are $U_0 = 4 \cdot 0$, $V_0 = 3 \cdot 5$, $r_1 = 8.4352$ and $r_2 = 7 \cdot 4353$.

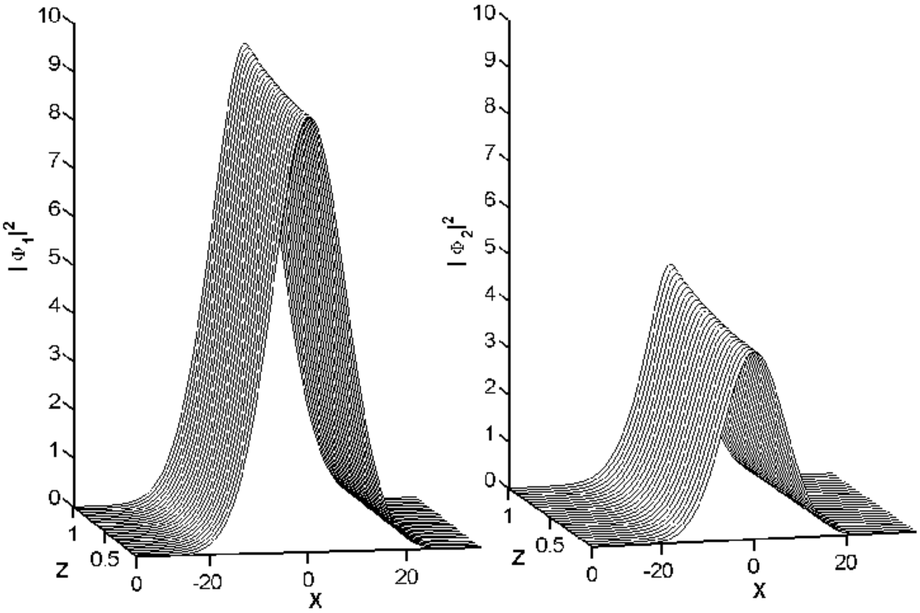

Fig.3. Propagation of coupled solitons as obtained by direct numerical simulation. Power of one solitons is approximately twice than that of the other. Soliton parameters U_0, V_0 r_1 and r_2 were identified from figure 1. The value of different solitons parameters are $U_0 = 9 \cdot 5$, $V_0 = 4.4$ $r_1 = 9.4352$ and $r_2 = 8 \cdot 4352$.

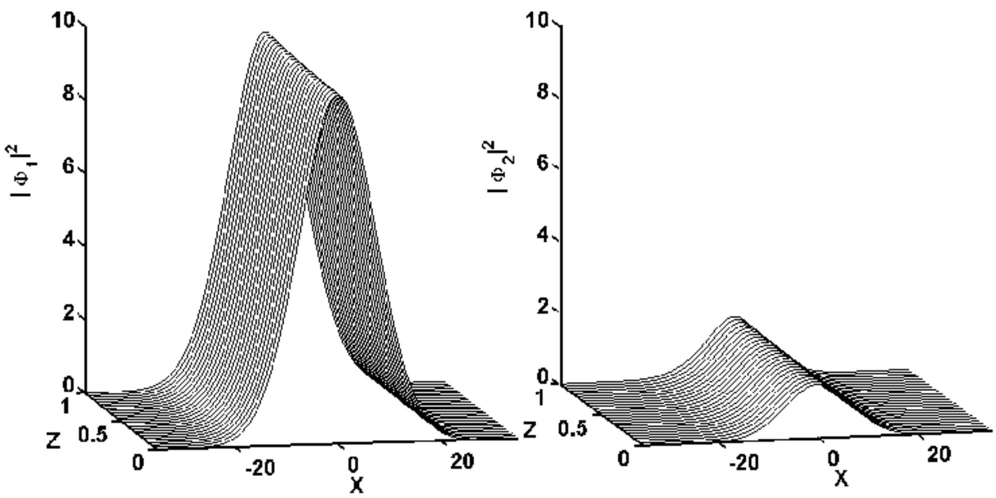

Fig.4. Propagation of coupled solitons as obtained by direct numerical simulation. Power of one solitons is approximately six times larger than the other. Soliton parameters U_0, V_0 r_1 and r_2 were identified from figure 1. The value of parameters are $U_0 = 9 \cdot 5$, $V_0 = 1 \cdot 5$, $r_1 = 10.4352$ and $r_2 = 9 \cdot 4352$.