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China University of Petroleum

Photorefractive Surface Solitons Due to Quadratic Electro-optic Effect

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September 10, 2014

Contents

1 About solitons

Solitary waves---commonly referred to as solitons - have been the subject of intense theoretical and experimental studies in many different fields, including hydrodynamics, nonlinear optics, plasma physics, biology, and Bose-Einstein-Condensates.

The soliton phenomenon was first described in 1834 by John Scott Russell (1808–1882) who observed that a heap of water in a canal propagated undistorted over several kilometers.

(a) Heriot-Watt University , July 12,1995
(b) University of Twente , September 10, 2010
Re-creation of J. S. Russel's soliton.

In 1895,D.J.Korteweg and G. deVries put forward the foumous KdV equation， to explain the above phenomenon, , and realized that for this phenomenon to occur the “solitary wave“ must have an unusually large amplitude.

In 1965，Zabusky and Kruskal investigated the laser self-trapped pulses, realized that these pulses can maintain their identities even when they undergo collisions with each other, and that each one of them conserves its power and initial velocity. They concluded that these pulses behave like particles do, and named them “solitons".

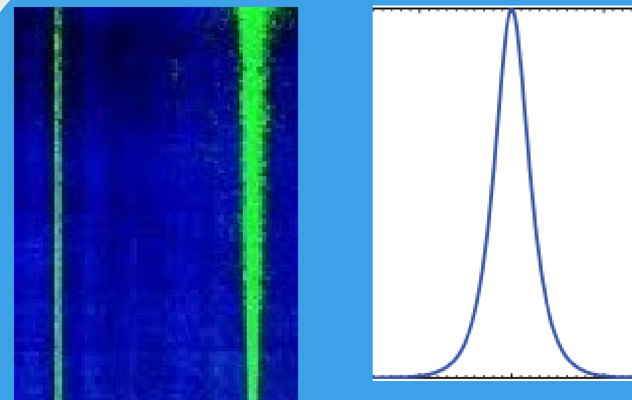
Opical Solitons

Opical Solitons

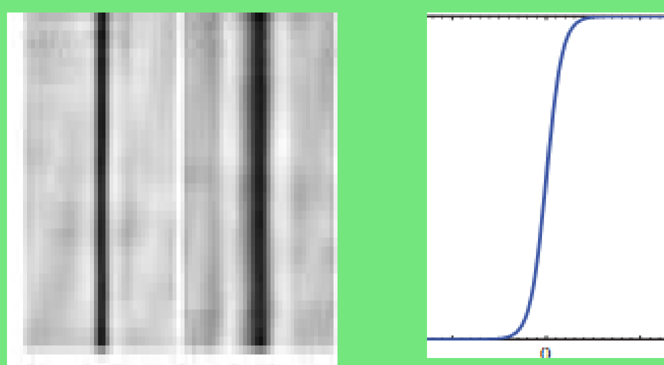
temporal solitons: optical pulses that maintain their shape

spatial Soliton: self-guided beams that remain confined in the transverse directions

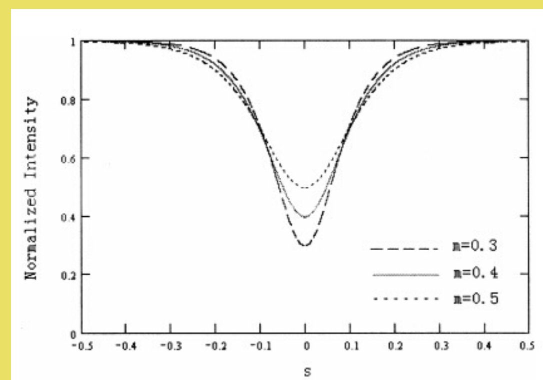
Spatial optical solitons



Bright soliton



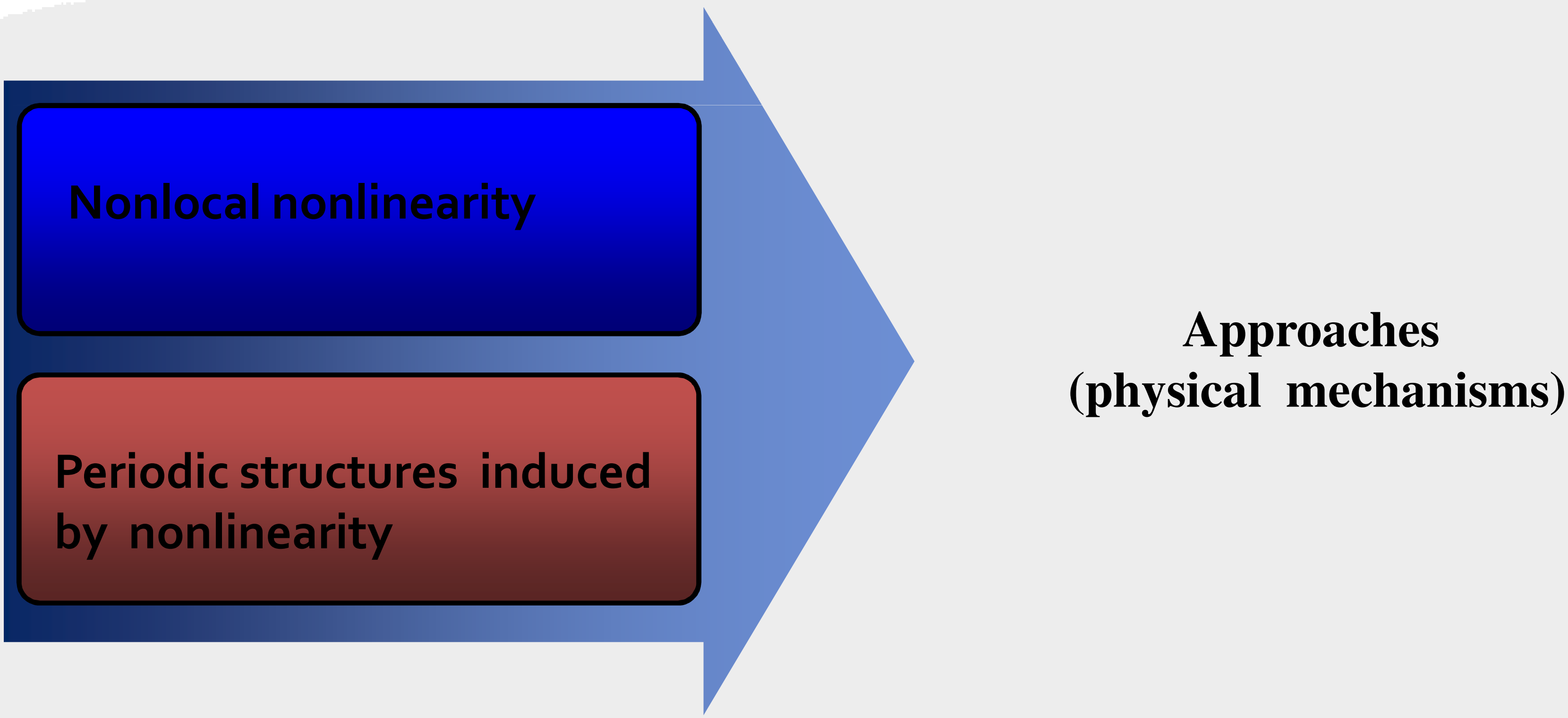
Dark soliton



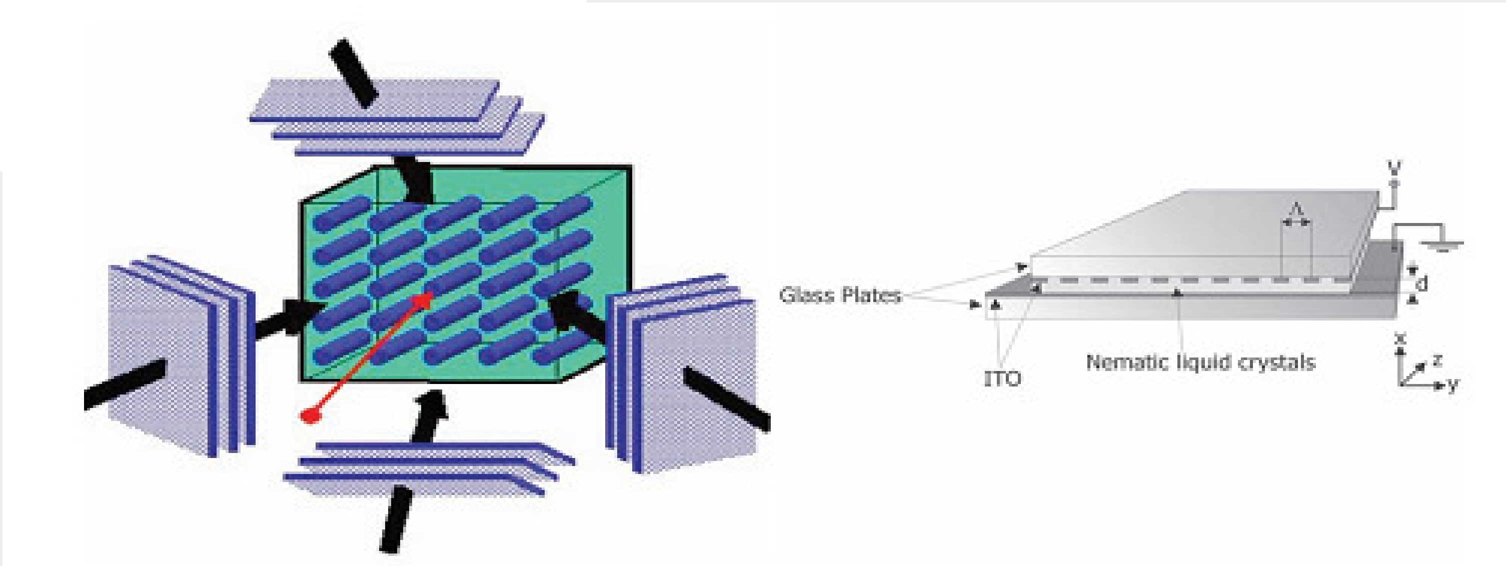
Grey soliton

2 Approaches to achieve surface solitons

Surface solitons are well known localized wave states traveling near the interfaces between two media exhibiting different optical properties. Surface solitons sparked a flurry of activity focused on important concepts due to their unique features.



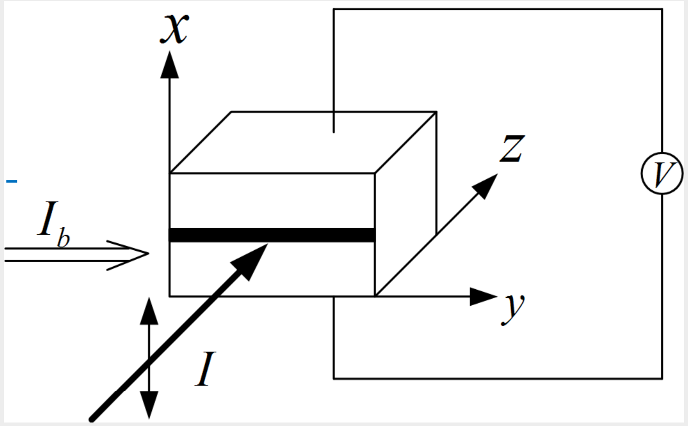
Periodic structures induced by nonlinearity (Optical lattices)



Methods on forming an optical lattice structure

3 Photorefractive effect and solitons

Theoretical model:



$$\frac{\partial \rho}{\partial t} = \frac{\partial N_D^+}{\partial t} + \frac{1}{q}\nabla \bullet J$$

$$\frac{\partial N_D^+}{\partial t} = \left(N_D - N_D^+\right)\left(sI_a + \beta\right) - \gamma_R N_D^+ \rho$$

$$\mathrm{J} = qD\nabla\rho + q\mu\rho(\mathrm{E}_0 + \mathrm{E}_{sc}) + \mathrm{J}_{ph}$$

$$\nabla \bullet \varepsilon(E_0 + E_{sc}) = q\left(N_D^+ - N_A - \rho\right)$$

$$n^2 = n_o^2\left(1 - n_o^2 \gamma_{eff} E_{sc}\right)$$

$$E_{sc} = E_0 \frac{I_\infty + I_b + I_d}{I + I_b + I_d} + E_p \frac{I_\infty - I}{I + I_b + I_d} - \frac{k_B T}{e} \frac{\partial I/\partial x}{I + I_b + I_d}$$

Potassium-lithium-tantalate-niobate (KLTN) doped with different iron crystals

$$\left[i\frac{\partial}{\partial z} + \frac{1}{2k}\frac{\partial^2}{\partial x^2} - \frac{k n_0^2 g_{eff} \varepsilon_0^2 \left(\varepsilon_r - 1\right)^2 E_{sc}^2}{2} \right] A\left(x,z\right) = 0$$

$$E_{sc} = E_0 \frac{I_\infty + I_d}{I + I_d} - \frac{k_B T}{e}\frac{\partial}{\partial x}\left(I + I_d\right)$$

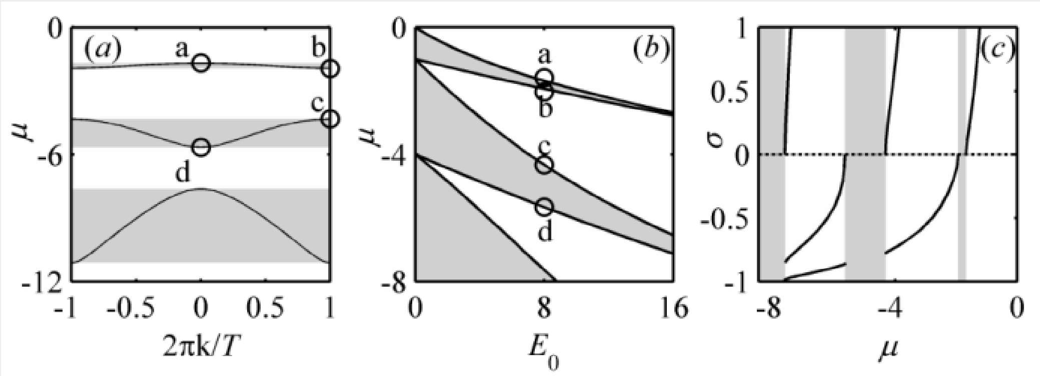
4 Surface solitons due to quadratic electro-optic effect

(1). Bandgap structure of optical lattices

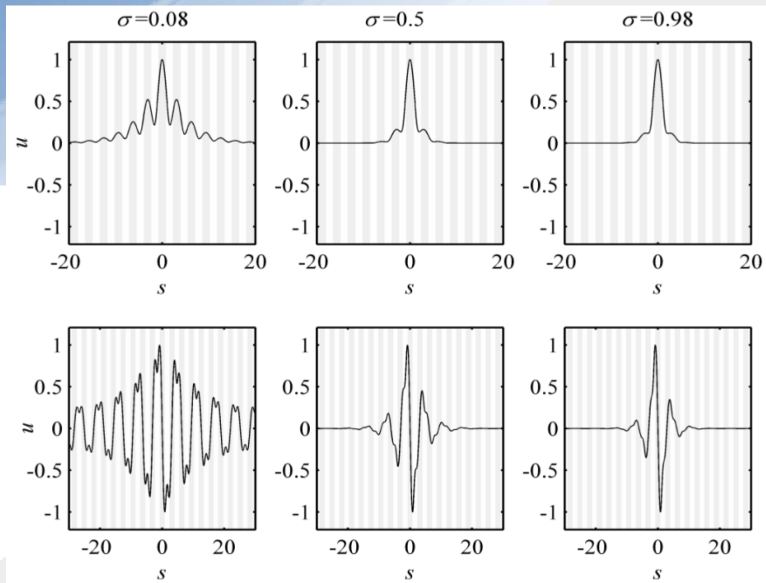
Soliton beam propagation described by the dimensionless nonlinear Schrödinger equation for the light field q

$$i\frac{\partial q}{\partial \xi}+\frac{\partial^2 q}{\partial s^2}-\frac{E_0 q}{\left[1+I_L(s)+|q|^2\right]^2}=0$$

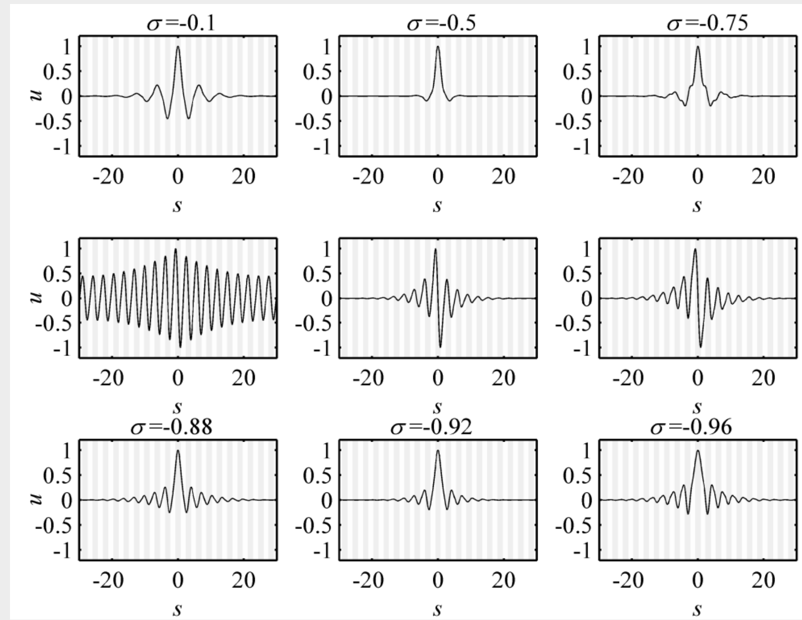
$$I_L = I_0\cos^2(s)[1+\sigma\exp(-s^8/128)] \qquad x\geq -\pi/2$$
$$I_L = 0 \qquad x< -\pi/2$$



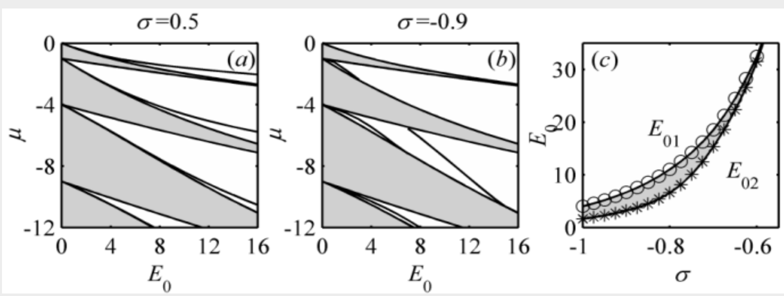
(a) Bandgap structure of a uniform lattice at I_0=3 and E_0=8; (b) Bandgap structure for E_0; (c) Bifurcations of defect modes



Defect modes of three positive defected optcial lattices in semi-infinite bandgap (upper row) and first finite bandgap (lower row).



Defect modes of positive defected optcial lattices. Upper row: three defect mode in first finite bandgap; middle row: defect mode win second finite bandgap; lower row: defect mode in second finite bandgap.



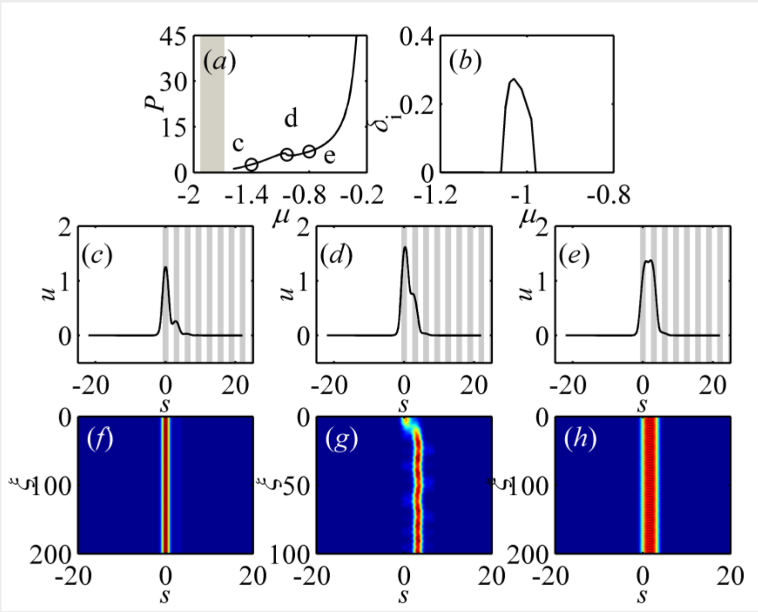
bifurcations of defect modes versus applied field

(2). Surface gap Soliton states Due to Quadratic Electro-optic Effect

$$i\frac{\partial q}{\partial \xi}+\frac{\partial^2 q}{\partial s^2}-\frac{E_0 q}{\left[1+I_L(s)+|q|^2\right]^2}=0$$

$$I_L = I_0\cos^2(s) \qquad x \ge -\pi/2$$

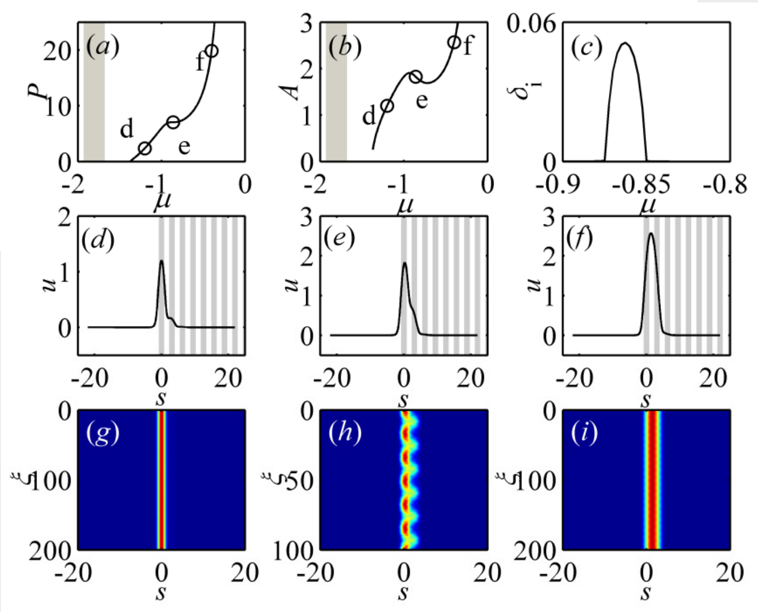
$$I_L = 0 \qquad x < -\pi/2$$



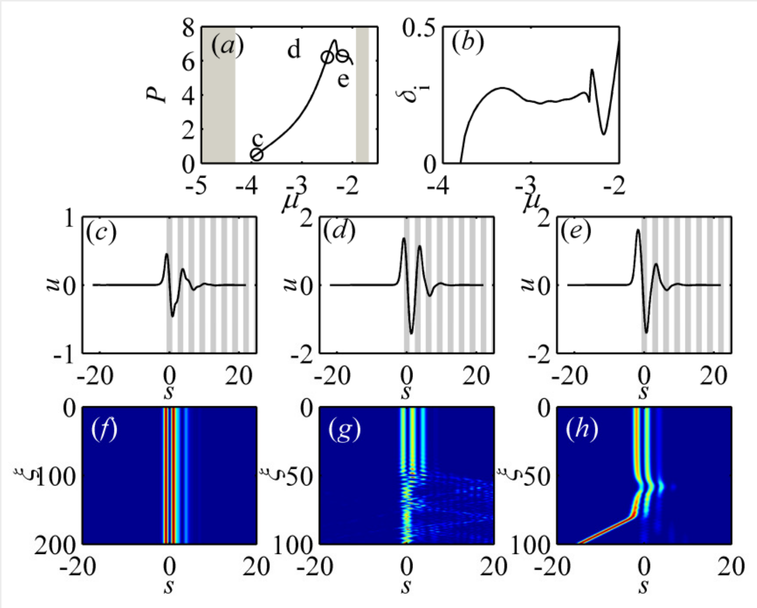
Surface soliton supported by a uniform lattice in the semi-infinite gap.

(3)Surface defect Soliton states Due to Quadratic Electro-optic Effect

Positive defect surface solitons:

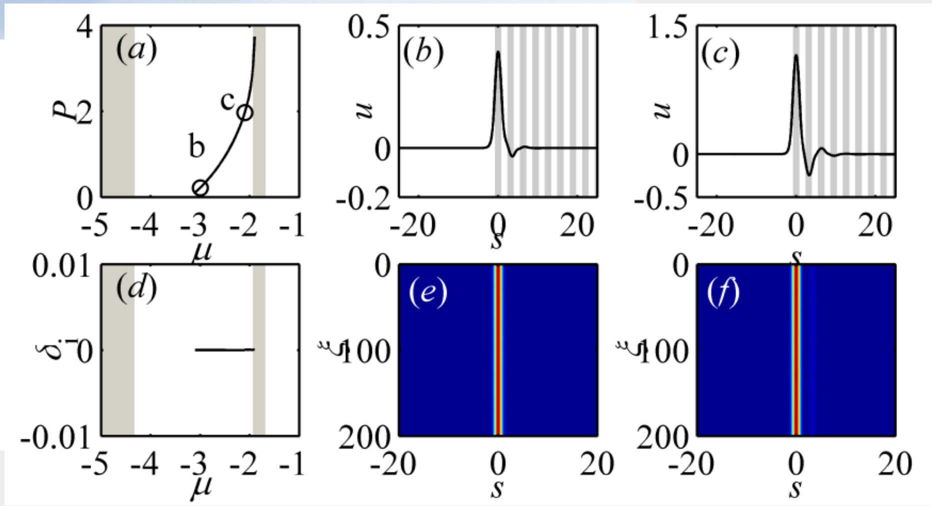


Surface solitons in the semi-infinite bandgap for the positive defect at σ=0.6

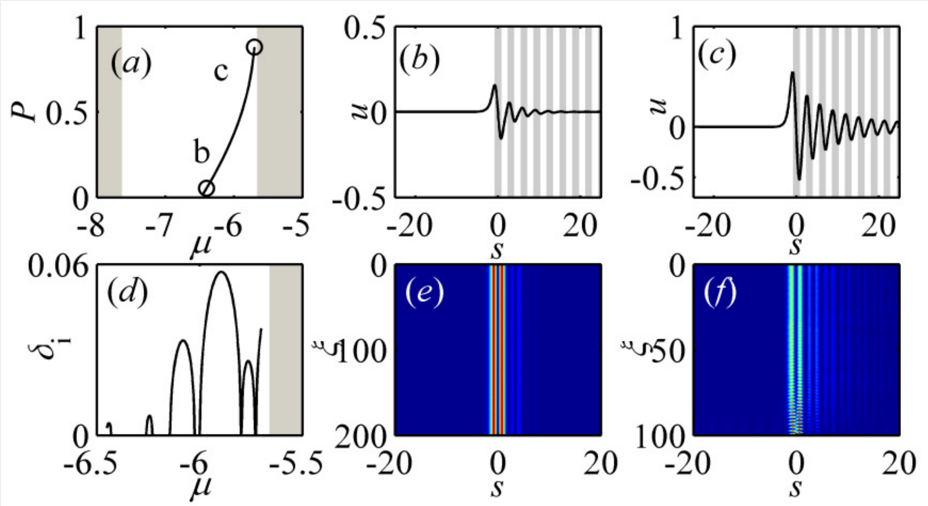


Surface soliton in the first bandgap at σ=0.6

Negative defect surface solitons:



Surface soliton in the first bandgap for the negative defect at σ=-0.6.

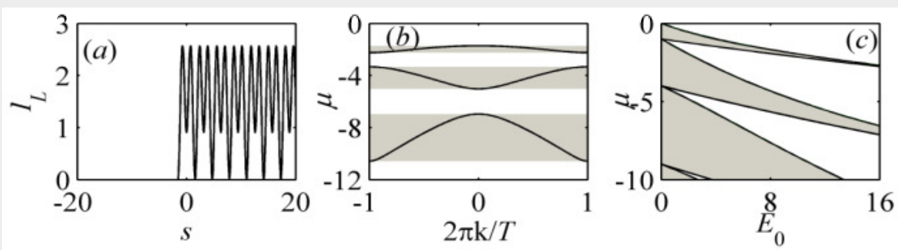


Surface soliton in the second bandgap for the negative defect at σ=-0.6

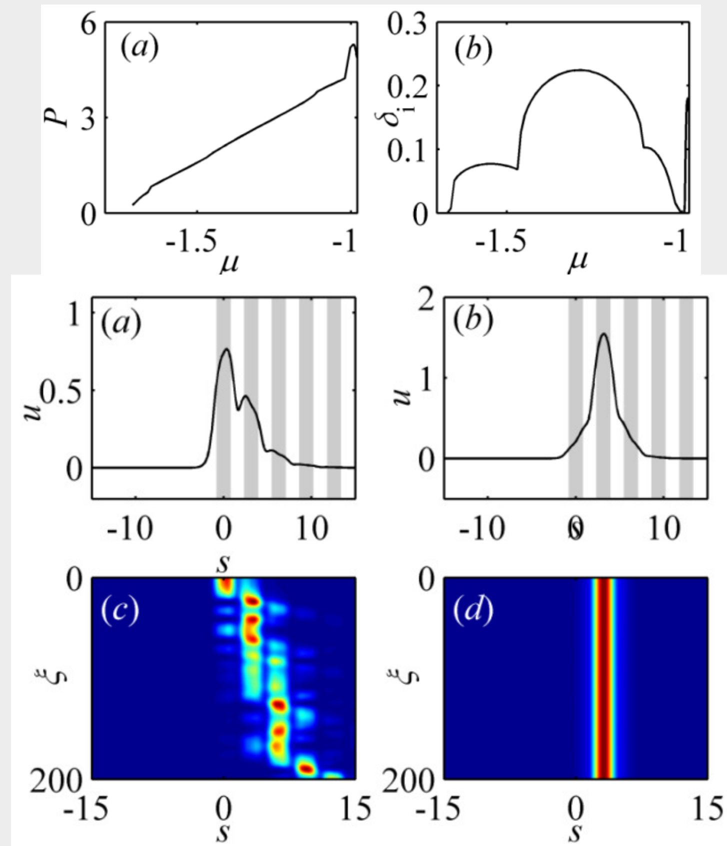
(4)Superlattice Surface Soliton states Due to Quadratic Electro-optic Effect

$$I_L = I_0\left\{\sigma \sin^2\left[\pi(x+\pi/2)/d_1\right] + (1-\sigma)\sin^2\left[\pi(x+\pi/2)/d_2\right]\right\} \quad x \geq -\pi/2$$

$$I_L = 0 \quad x < -\pi/2$$



Bandgap structure of a uniform superlattice



Surface solitons in the semi-infinite gap

(5)Surface solitons with diffusive nonlinearity due to quadratic electro-optic effect

$$i\frac{\partial q}{\partial \xi}+\frac{1}{2}\frac{\partial^2 q}{\partial s^2}+pR(s)q-\beta\frac{q}{\left(1+S|q|^2\right)^2}\left(\frac{\partial |q|^2}{\partial s}\right)^2=0$$

$$R(s)=\cos^2(s) \quad x\geq -\pi/2$$

$$R(s)=0 \qquad x<-\pi/2$$

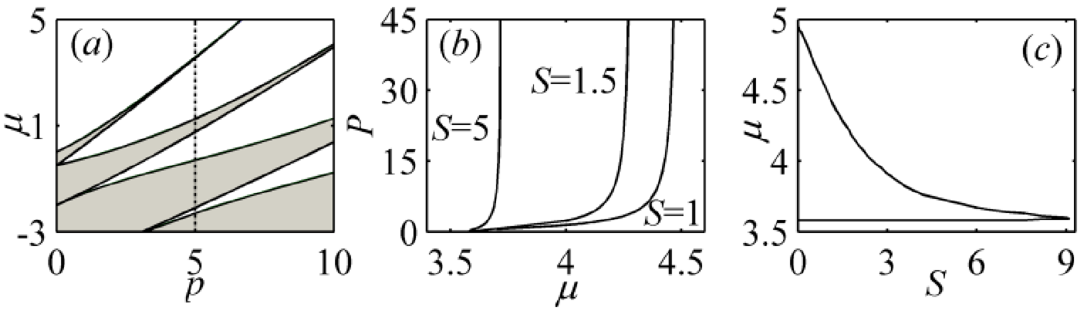
Stability of surface solitons:

$$q(s,\xi)=\left\{u(s)+\left[v_1(\xi)-v_2(\xi)\right]e^{i\delta\xi}+\left[v_1^*(\xi)+v_2^*(\xi)\right]e^{-i\delta^*\xi}\right\}e^{i\mu\xi}$$

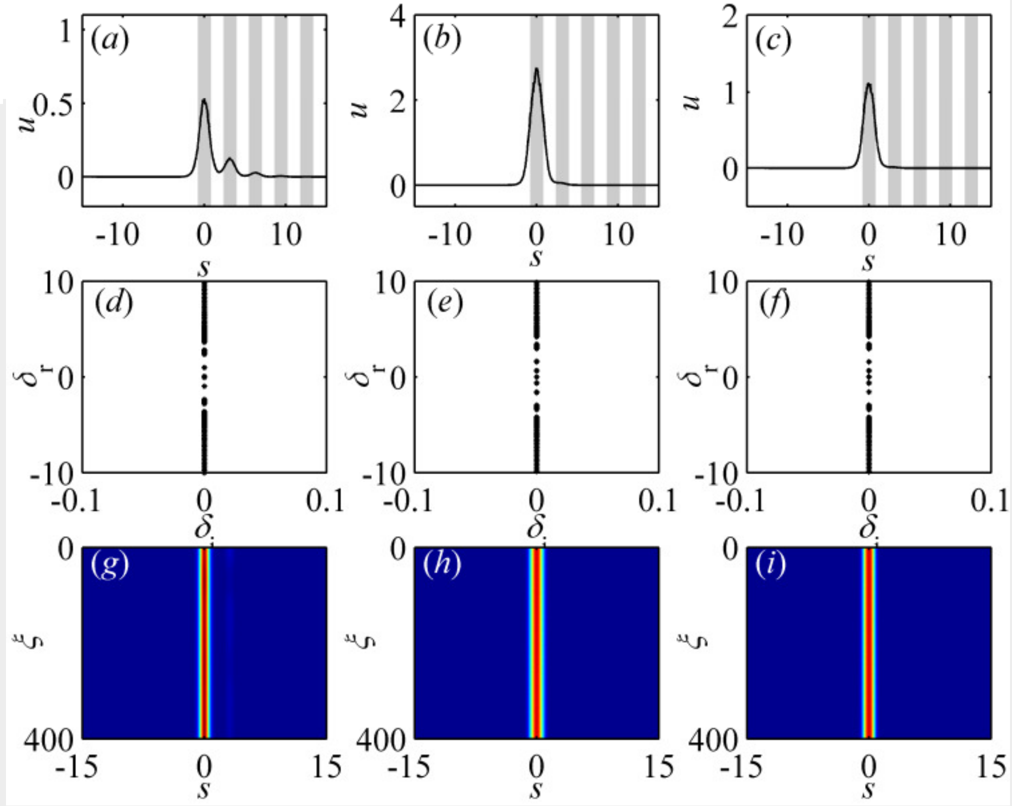
$$\delta v_1=-\frac{1}{2}\frac{d^2 v_2}{ds^2}+\left[\frac{4\beta u^2}{\left(1+Su^2\right)^2}\left(\frac{du}{ds}\right)^2+\mu-pR\right]v_2$$

$$\delta v_2=-\frac{1}{2}\frac{d^2 v_1}{ds^2}+\left[\frac{4\beta u^2\left(3-Su^2\right)}{\left(1+Su^2\right)^3}\left(\frac{du}{ds}\right)^2+\mu-pR\right]v_1+\frac{8\beta Su^3}{\left(1+Su^2\right)^2}\frac{du}{ds}\frac{dv_1}{ds}$$

Surface lattice solitons supported by optical lattices with a self-focusing nonlinearity

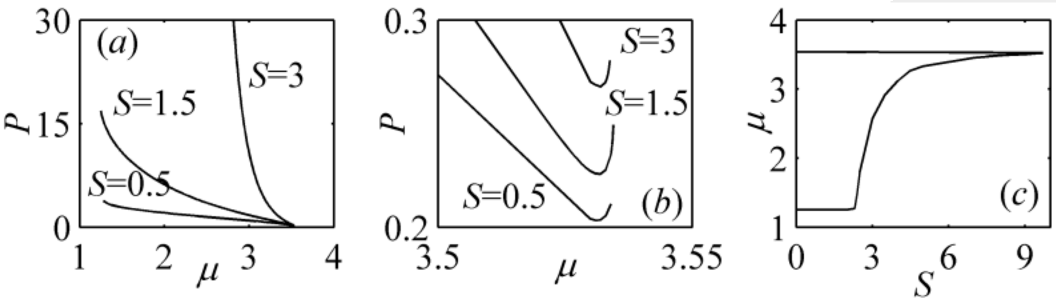


(a) Gap structure of a uniform lattice for different lattice depth *p*. (b) Energy flow versus propagation constant. (c) Existence domain of surface solitons versus *S*.

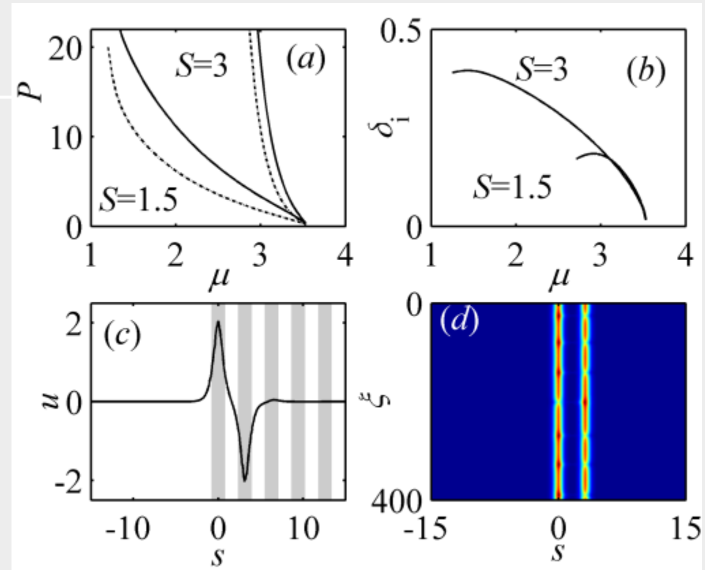


Examples of surface soliton profiles at (a) S=1.5, μ=3.6; (b) S=1.5, μ=4.2; (c) S=0.5, μ=4.2. (d)– (e) are complex planes of the respective stability eigenvalues. (g)– (i) are the stable evolutions of surface solitons under 10% random initial perturbation.

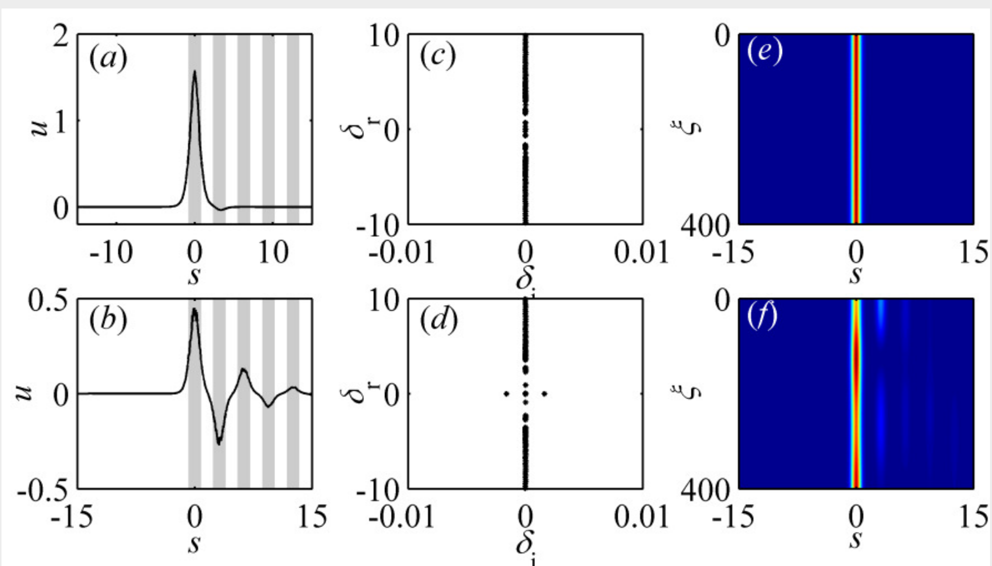
Surface lattice solitons supported by optical lattices with a self-defocusing nonlinearity



(a) Energy flow versus propagation constant. (b) Energy flow curves in low power domain. (c) Existence domain of surface solitons versus *S*.



(a) Energy flow of twisted (solid line) and surface gap (dashed line) solitons. (b) perturbation growth rate. (c) Profile of twisted surface soliton at μ= 2.5. (d) Evolution of surface soliton.



Examples of surface soliton profiles. (c)– (d) are complex planes of the respective stability eigenvalues. (e)– (f) are the evolution of surface solitons.

5 Vector surface solitons in diffusive nonlinear media driven by the quadratic electro-optic effect

$$i\frac{\partial q_1}{\partial \xi}+\frac{1}{2}\frac{\partial^2 q_1}{\partial s^2}+pR(s)q_1-\beta\frac{q_1}{\left(1+|q_1|^2+|q_2|^2\right)}\frac{\partial}{\partial s}\left(|q_1|^2+|q_2|^2\right)=0$$

$$\delta u_1=-\frac{1}{2}v_1''+(b_1-pR)v_1+\beta\frac{\left(w_1^2+w_2^2\right)'}{1+w_1^2+w_2^2}v_1$$

$$\delta v_1=\frac{1}{2}u_1''+(pR-b_1)u_1-\frac{\beta}{\left(1+w_1^2+w_2^2\right)}\left[2w_1^2u_1'+\left(2w_1^2+w_2^2\right)'u_1+2w_1\left(w_2u_2\right)'\right]+\frac{2\beta w_1\left(w_1^2+w_2^2\right)'}{\left(1+w_1^2+w_2^2\right)^2}\left(w_1u_1+w_2u_2\right)$$

$$\delta u_2=-\frac{1}{2}v_2''+(b_2-pR)v_2+\beta\frac{\left(w_1^2+w_2^2\right)'}{1+w_1^2+w_2^2}v_2$$

$$\delta v_2=\frac{1}{2}u_2''+(pR-b_2)u_2-\frac{\beta}{\left(1+w_1^2+w_2^2\right)}\left[2w_2^2u_2'+\left(w_1^2+2w_2^2\right)'u_2+2w_2\left(w_1u_1\right)'\right]+\frac{2\beta w_2\left(w_1^2+w_2^2\right)'}{\left(1+w_1^2+w_2^2\right)^2}\left(w_1u_1+w_2u_2\right)$$

6 Conclusions

1. Adeep understanding on the band structure of several types of optical lattices in centrosymmetric photorefractive crystals has been gotten.

2. several types of surface solitons, i.e., gap solitons, defect solitons, superlattice solitons and surface solitons driven by diffusive effect in centrosymmetric photorefractive crystals have been predicted theoretically.
3. Vector surface solitons in diffusive nonlinear media driven by the quadratic electro-optic effect are studied.

4. The factors affected these surface solitons were systematically studied, four physical factors, i.e., the external bias electric field, lattice depth, saturation parameter and diffusion process, were considered.

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