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Dynamical effect of laser bumped electron-hole semiconductor

By

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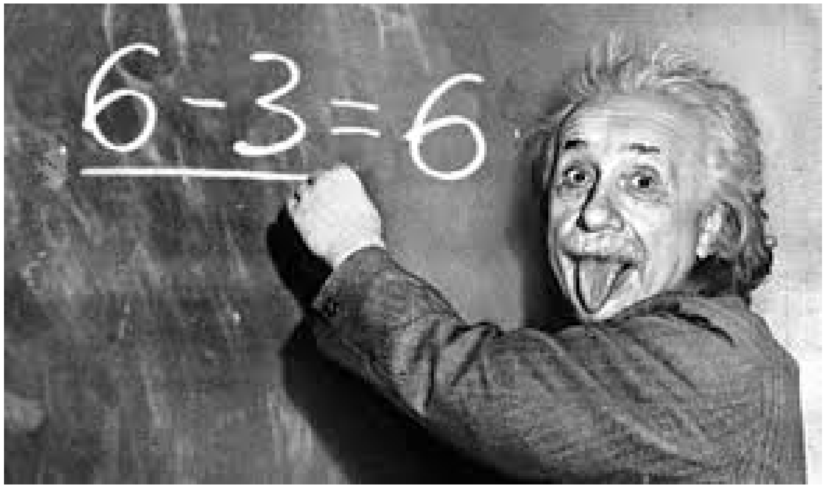
I' m Mathematician not Physicist



Outline

- Introduction
- Electromagnetic wave effect
- Objective of the Paper
- The wave Equation
- Dispersion Relation
- Sagdeev Potential
- Modified NLSE
- Appendix

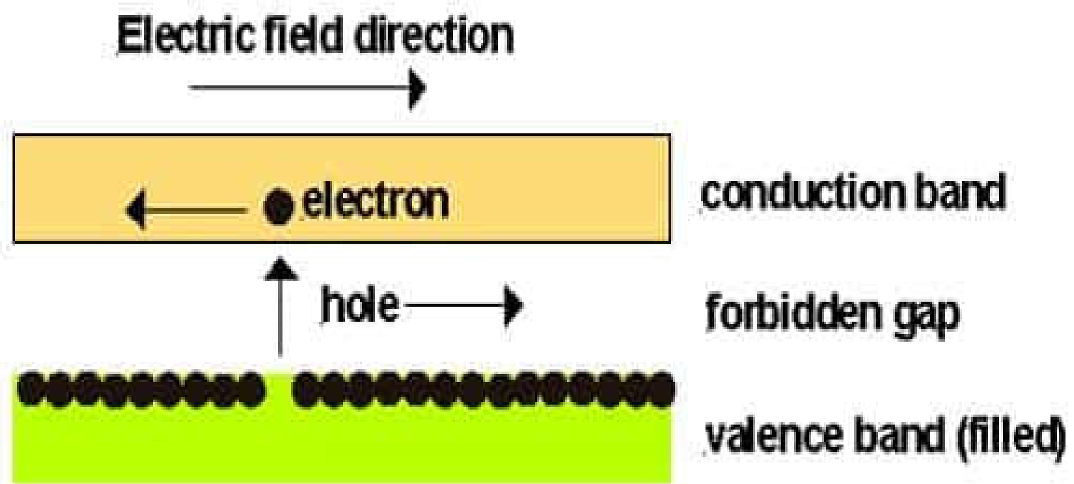
Introduction

An Electron

is defined as a negative charge or negative atomic particle.

A Hole

as a vacancy left in the valence band because of the lifting of an electron from the valence band to a conduction band.



Introduction

- **Hole** is a positive-charge, positive-mass **quasiparticle**.
- **Holes** can move from atom to atom in semiconducting materials as electrons leave their positions.
- **The mobility** of electrons is higher than that of the holes, because the effective mass of electron is less than a hole.

An electron-hole pair

For every electron raised to the conduction band by external energy, there is one hole left in the valence band, creating what is called **an electron-hole pair**.

Introduction

Recombination

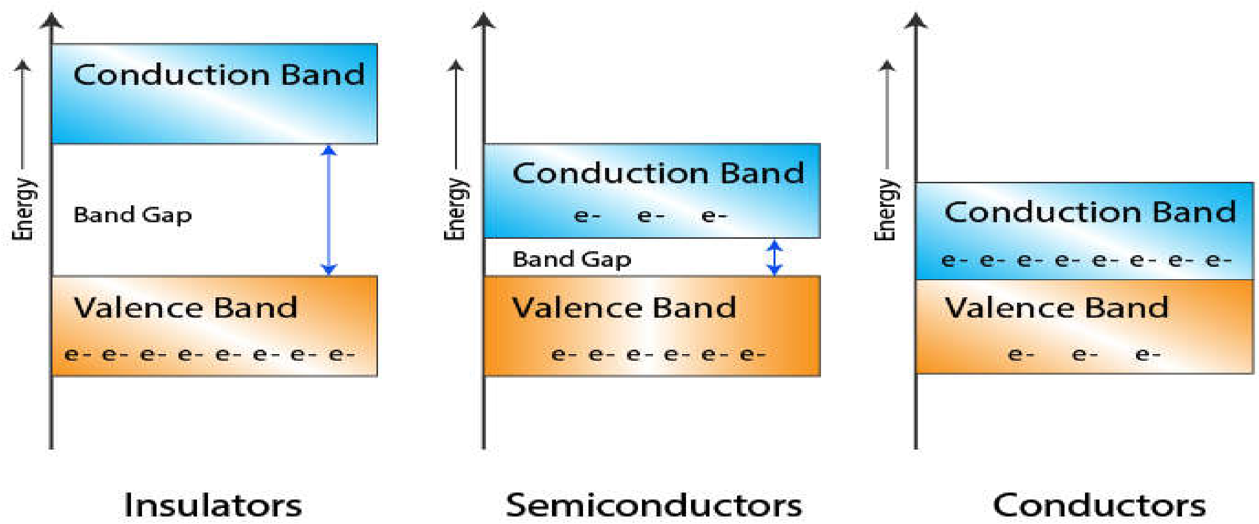
Occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

- Recombination rate is controlled by the minority carrier lifetime.
- Recombination mechanisms for materials is highly important for the optimization of semiconductor devices such as solar cells and light emitting diodes.

Introduction

❑ Semiconductors

are the materials which have a conductivity between conductors (generally metals) and non-conductors or insulators (such ceramics).

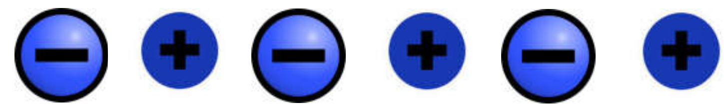


Introduction

❑ Types of Semiconductors

- Intrinsic Semiconductor

  (holes = electrons)

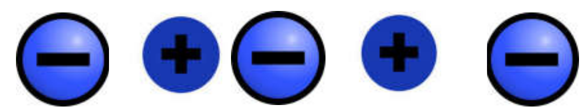


- Extrinsic Semiconductor

  (excess or shortage of electrons)

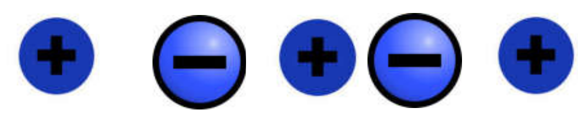
  - ❖ N-Type Semiconductor

    (Mainly due to electrons)



  - ❖ P-Type Semiconductor

    (Mainly due to holes)



Semi-conductor materials

Material	Symbol	Usage
Germanium	Ge	radar detection diodes - first transistors
Silicon	S	integrated circuits -insulation layers
Gallium arsenide	GaAs	high performance RF devices
Silicon carbide	SiC	yellow and blue LEDs.

Semi-conductor materials

Material	Symbol	Usage
Gallium Nitride	GeN	microwave transistors -microwave ICs-blue LEDs
Gallium phosphide	GaP	produce a green light-(+N) yellow-green- (+ZnO) red.
Cadmium sulphide	CdS	photoresistors - solar cells

EMW effect on Semi-Conductor E-H particles

- Recombination Process
- Increase in current flow
- Diffusion of charges
- Decrease the energy gap
- Decrease the mobility of carriers
- Increase the collision rate
- Increase the conductivity (Intrinsic)
- Decrease the conductivity (Extrinsic)

Objectives

- This study introduce the mathematical model of the interaction between electromagnetic field and electron hole particles.
- Using Maxwell's equations along with e-h fluid equations that contain laser field effect, we derive an evolution wave equation describing the system, which called a modified nonlinear Schrödinger equation (mNLSE).
- The mNLSE is reduced to an energy equation containing the Sagdeev potential describing the localized propagating pulses in semiconductor.

The wave equation for homogeneous plasma

- From Maxwell's Eqs. , we can extract the wave equation , which describe the propagation of laser field in the plasma.

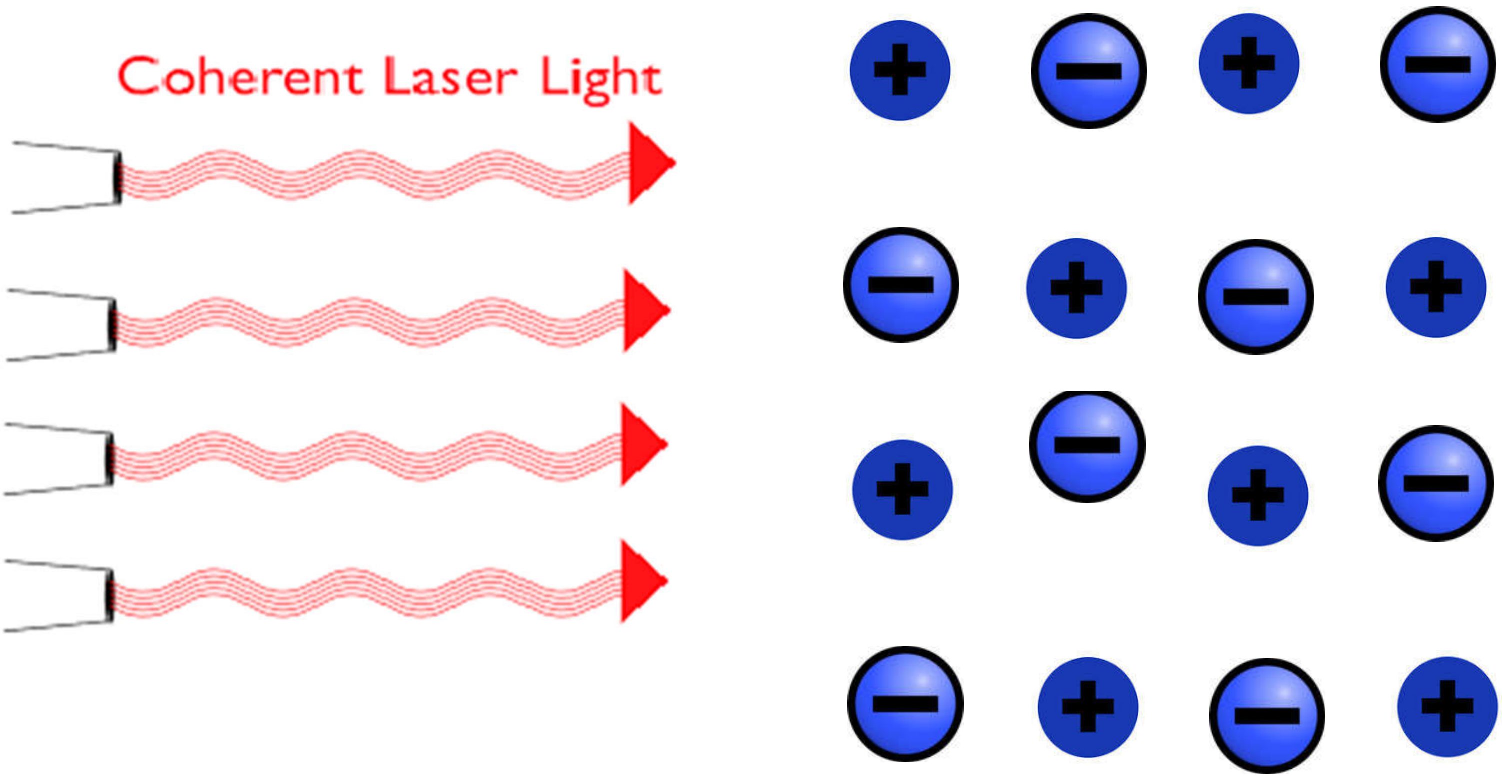
$$\nabla \times \nabla \times A + \frac{1}{c^2}\frac{\partial^2 A}{\partial t^2} = \frac{4\pi J}{c} \qquad (1)$$

$$\nabla^2 \Phi = -4\pi \rho_e \qquad (2)$$

when

$$J = -e n_e v_e + \sum_k q_k n_k v_k \quad , and \quad \rho_e = -e n_e + \sum_k q_k n_k \qquad (3)$$

Laser - Electron – Hole Interaction



Laser - Electron – Hole Interaction

- We can extract the wave equation , which describe the propagation of laser field in the electron-hole plasma.

$$\frac{1}{c^2}\frac{\partial^2 A}{\partial t^2} - \nabla^2 A = -\frac{4\pi e}{c}(n_h v_h - n_e v_e) \qquad (4)$$

- And the Poisson eq.

$$\nabla^2 \phi = -4\pi e(n_e - n_h) \qquad (5)$$

- Where the velocity with relativistic effect

$$v_e = \frac{eA}{m_e c \gamma_e}, \quad v_h = -\frac{eA}{m_h c \gamma_h} \qquad (6)$$

Laser - Electron – Hole Interaction

- Also from the relativistic fluid equation

$$\partial_t p + (v_e.\nabla)\, p = e\left(E + \frac{V \times B}{c} \right) - \frac{1}{n_e} \nabla P \qquad (7)$$

at

$$p = -e\, A / c \quad (momentum)\,, \qquad P = n_e k\, T_e \quad (pressure) \qquad (8)$$

,we derive the densities

(a) for electron ⟶ $$n_e = n_{e0} \exp\left(-\frac{m_e c^2}{T_e}(\gamma_e - 1) + \frac{q_e}{T_e}\phi \right) \qquad (9)$$

(b) for hole ⟶ $$n_h = n_{h0} \exp\left(-\frac{m_h c^2}{T_h}(\gamma_h - 1) + \frac{q_h}{T_h}\phi \right) \qquad (10)$$

Laser - Electron – Hole Interaction

- The vector potential of the light takes the form

$$\mathbf{A} = \frac{1}{2}\chi(\mathbf{r},\mathbf{t})\,(\mathbf{x} + \mathbf{i}\,\mathbf{y})\exp\left(\mathbf{i}\,\mathbf{k}.\mathbf{r} - \mathbf{i}\,\omega\,\mathbf{t}\right) \qquad (11)$$

- The differential equation after substituting in eq. (4) takes the form

$$\mathbf{i}\frac{\partial \chi}{\partial t} + \frac{c^2}{2\omega}\nabla^2\chi + \mathbf{i}\frac{k c^2}{\omega}\nabla\chi + \frac{\omega_{pe}^2}{2\omega}\left(\mathbf{1} - \frac{\mathbf{N_e}}{\sqrt{\mathbf{1} + |\mathbf{a}|^2}} + \mathbf{M}\left[\mathbf{1} - \frac{\mathbf{N_h}}{\sqrt{\mathbf{1} + \mathbf{M}^2|\mathbf{a}|^2}}\right]\right)\chi = \mathbf{0} \qquad (12)$$

Laser - Electron – Hole Interaction

- The resulting form from the wave equation after the scaling, the nondimensional form can be reduced to a modified NLSE

$$\mathbf{i}\frac{\partial \mathbf{a}}{\partial \tau} + \frac{1}{2}\nabla^2 \mathbf{a} + \frac{1}{2}\left(1 - \frac{N_e}{\sqrt{1 + |\mathbf{a}|^2}} + M\left[1 - \frac{N_h}{\sqrt{1 + M^2 |\mathbf{a}|^2}}\right]\right)\mathbf{a} = 0 \quad (13)$$

- Where

$$\chi = \frac{m_0 c^2 \mathrm{a}}{e} \quad , t = \left(\tau\, \omega_0 / \omega_{pe}^2\right) \; , \quad (14)$$

$$r = \left\{c\left(\xi - u_g \tau\right) / \omega_{pe}\right\}, \; u_g = c\, k / \omega_{pe}$$

Modified NLSE

- NL dispersion relation
- The modulat-ional instability growth rate

- The Sagdeev potential.
- The light amplitude.

- Instability of system
- Solution of NLSE by **HPM**

The nonlinear dispersion relation - Growth rate

- At the potential takes the form

$$\mathbf{a} = (a_0 + a_1)\exp(i\delta\tau) \quad , where \ a_0 \gg |a_1| \qquad (15)$$

Substituting in the differential eq.,

$$i\frac{\partial a}{\partial \tau} + \frac{1}{2}\nabla^2 a + \frac{1}{2}\left(1 - \frac{N_e}{\sqrt{1+|a|^2}} + M\left[1 - \frac{N_h}{\sqrt{1+M^2|a|^2}}\right]\right)a = 0 \qquad (16)$$

- The nonlinear frequency shift take the form

$$\delta = \frac{1}{2}\left(1 - \frac{N_e(a_0)}{\sqrt{1+|a_0|^2}} + M\left[1 - \frac{N_h(a_0)}{\sqrt{1+M^2|a_0|^2}}\right]\right) \qquad (17)$$

The nonlinear dispersion relation - Growth rate

- We linearize the differential eq. (16) At $a_1 = (X + iY)\exp(\mathrm{i}k.\xi - i\Omega\tau)$ with respect to a_1 where $\Omega(k)$ is the frequancy of the low frequancy modulations, and X, Y are real constants.

- After Tayler series , and linearization

$$\frac{N_e(a)}{\sqrt{1+|a|^2}} = \alpha + \beta\ (a_1 + a_1^*)\ ,\ \frac{N_h(a)}{\sqrt{1+M^2|a|^2}} = \alpha^* + \beta^*\ (a_1 + a_1^*) \quad (18)$$

The nonlinear dispersion relation - Growth rate

- After substituting in Eq. (16) with respect to a_1 , the differential eq. takes the form

$$i\frac{\partial a_1}{\partial \tau} + \frac{1}{2}\nabla^2 a_1 - \frac{a_0}{2}\left(\beta + \beta^* M\right)(a_1 + a_1^*) = 0 \qquad (19)$$

- Let

$$a_1 = U + iV \quad \Rightarrow \quad a_1^* = U - iV$$

- Assume the plane wave

$$U = u_0 e^{ik.\xi - i\Omega\tau} \quad , and \quad V = v_0 e^{ik.\xi - i\Omega\tau} \qquad (20)$$

The nonlinear dispersion relation - Growth rate

- The nonlinear dispersion relation is

$$\Omega^2 = \frac{k^2}{2}\left(\frac{k^2}{2} + a_0\,(\beta + \beta^* M)\right) \qquad (21)$$

- The modulational instability growth rate

$$\Gamma = -i\,\Omega = \frac{k}{\sqrt{2}}\sqrt{\left(\frac{k^2}{2} + a_0\,(\beta + \beta^* M)\right)} \qquad (22)$$

The Sagdeev potential

- The nonlinear system at

$$\mathbf{a}(z,\tau) = w(z)\exp(-i\Omega\tau) \tag{23}$$

Substituting in the differential eq.,

$$\mathbf{i}\frac{\partial \mathbf{a}}{\partial \tau} + \frac{1}{2}\nabla^2\mathbf{a} + \frac{1}{2}\left(1 - \frac{N_e}{\sqrt{1+|\mathbf{a}|^2}} + M\left[1 - \frac{N_h}{\sqrt{1+M^2|\mathbf{a}|^2}}\right]\right)\mathbf{a} = 0$$

- The integration of a modified NLSE gives this form

$$\frac{1}{2}\left(w'(z)\right)^2 + \psi(w) = 0 \tag{24}$$

The Sagdeev potential

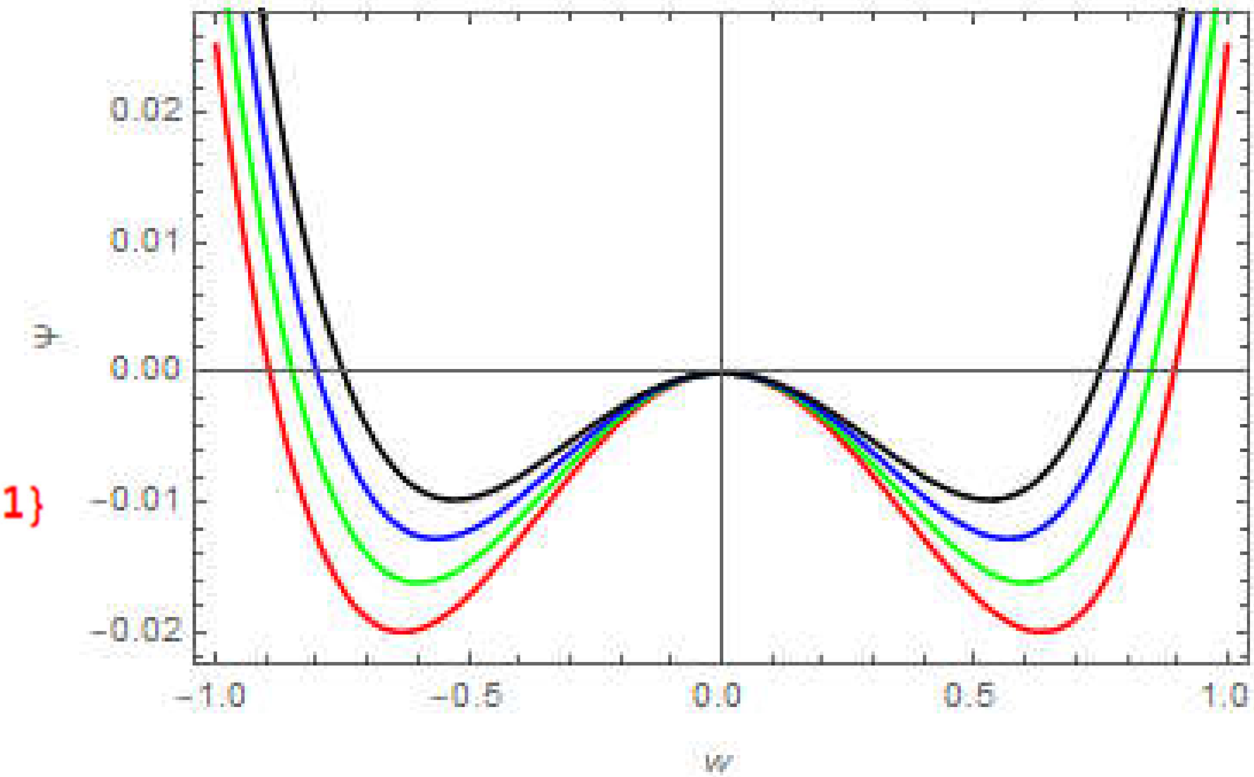
- Where $\psi(w)$ is the Sagdeev potential

$$\psi(w) = \Omega w^2 + \frac{1}{8}\left(1 + M^3 - (1 + E + H M^2)\beta_e\right) w^4 - \frac{1}{8}\left((E M + H M^3 + M^3)\beta_h\right) w^4 + O(w^6) \tag{25}$$

Fig. (1)

$\psi(w)$ is a function of light amplitude w. It have the figure of Sagdeev potential in the (+ve) and (-ve) values of amplitude. At the values ;

$\Omega = \{-0.07, -0.08, -0.09, -0.1\}$



The wave amplitude (EMW)

- Then eq. (24) takes the form

$$\frac{1}{2}\left(w'(z)\right)^2 + \Omega w^2 + \frac{1}{8}\left(1 + M^3 - (1 + E + H M^2)\beta_e\right)w^4 - \frac{1}{8}\left((E M + H M^3 + M^3)\beta_h\right)w^4 + O(w^6) = 0 \qquad (25)$$

- The light amplitude w is

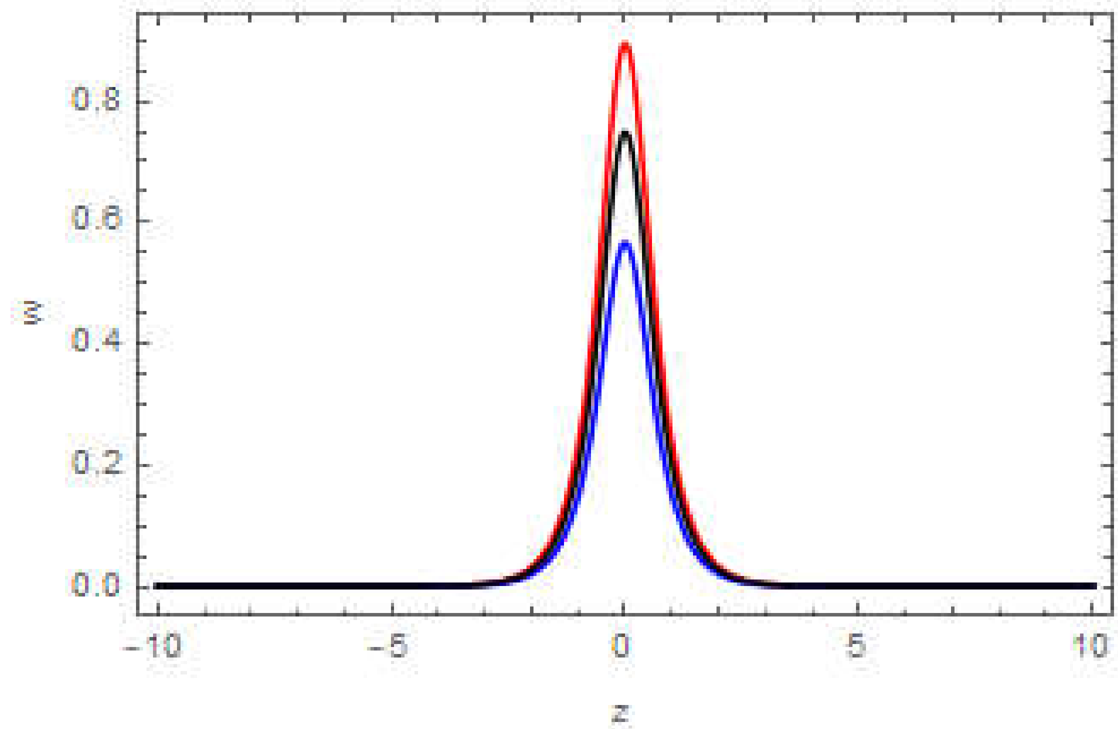
$$\int \frac{dw}{w\sqrt{1 - \frac{A}{8\Omega} w^2}} = \sqrt{-2\Omega} \int dz \qquad (26)$$

$$at \quad A = \left(1 + M^3 - (1 + E + H M^2)\beta_e - (E M + H M^3 + M^3)\beta_h\right)$$

Fig. (2)

The light amplitude $w(z)$ is a function of the distance z , which gives a soliton wave at all values of the distance . At the values ;

$\Omega = \{-0.07 ,\ -0.08 ,\ -0.1\}$



Modified NLSE

- The last differential eq. takes the form

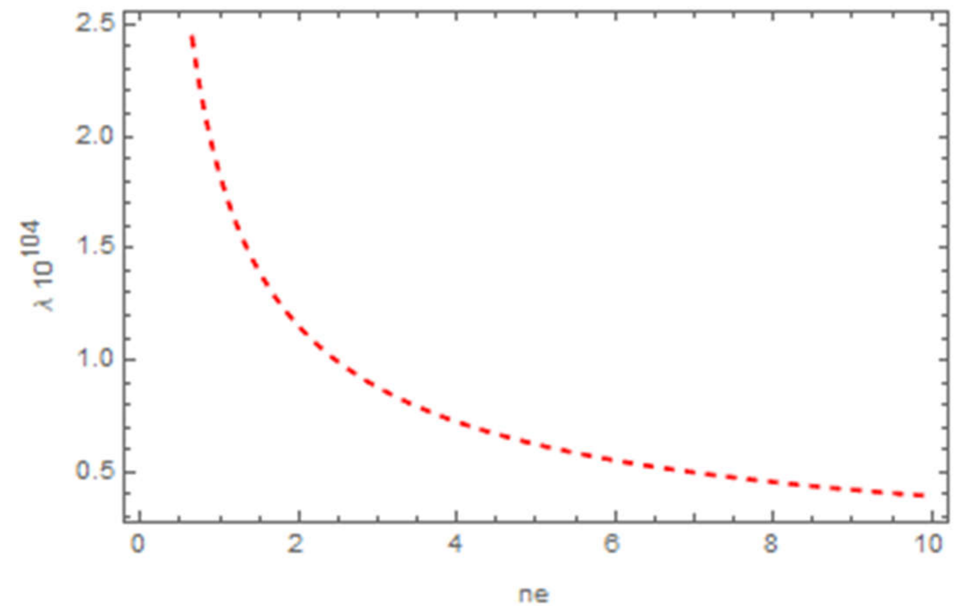
$$i\frac{\partial a}{\partial \tau}+\frac{1}{2}\nabla^2 a+\frac{1}{2}\left(1-\frac{N_e}{\sqrt{1+|a|^2}}+M\left[1-\frac{N_h}{\sqrt{1+M^2|a|^2}}\right]\right)a=0 \qquad (27)$$

- After Tayler series, the differential eq. takes the form

$$i\frac{\partial a}{\partial \tau}+\frac{1}{2}\nabla^2 a+\lambda|a|^2 a=0 \qquad (28)$$

Fig. (3)

This case, with λ positive, gives unstable envelope soliton, which has Bright soliton solutions.



HPM for solving mNLSE

- The last differential eq. takes the form

$$i\frac{\partial a}{\partial \tau}+\frac{1}{2}\nabla^2 a+\frac{1}{2}\left(1-\frac{N_e}{\sqrt{1+|a|^2}}+M\left[1-\frac{N_h}{\sqrt{1+M^2|a|^2}}\right]\right)a=0 \qquad (27)$$

- After Tayler series takes the form

$$i\frac{\partial a}{\partial \tau}+\frac{1}{2}\nabla^2 a+\lambda|a|^2 a=0 \qquad (28)$$

- Using HPM

$$i\frac{\partial a}{\partial \tau}+p\left(\frac{1}{2}\nabla^2 a+\lambda|a|^2 a\right)=0 \qquad (29)$$

HPM for solving mNLSE

- The solution take the formula

$$\mathbf{a} = a_0 + p\, a_1 + p^2 a_2 + p^3 a_3 + \dots \qquad (30)$$

,where p is embedding parameter $0 \le p \le 1$

➢ Substituting from the formula (30) in the eq. (29) ,and compare the coefficients p , we find

HPM for solving mNLSE

$$p^0 : i D_\tau a_0 = 0 \qquad \Rightarrow \quad a_0 = a(z,0) = e^{iz}$$

$$p^1 : i D_\tau a_1 = -\frac{1}{2}\nabla^2 a_0 - \lambda(\bar{a}_0 a_0^2)$$

$$p^2 : i D_\tau a_2 = -\frac{1}{2}\nabla^2 a_1 - \lambda(\bar{a}_0 a_0 a_1 + \bar{a}_0 a_1 a_0 + \bar{a}_1 a_0 a_0)$$

$$p^3 : i D_\tau a_3 = -\frac{1}{2}\nabla^2 a_2 -$$

$$\lambda(\bar{a}_2 a_0 a_0 + \bar{a}_0 a_2 a_0 + \bar{a}_0 a_0 a_2 +$$

$$\bar{a}_0 a_1 a_1 + \bar{a}_1 a_1 a_0 + \bar{a}_1 a_0 a_1)$$

HPM for solving mNLSE

then,

$$a_j = i\tau\left\{\frac{1}{2}\nabla^2 a_{j-1} + \sum_{i=0}^{j-1}\sum_{k=0}^{j-i-1} a_i a_k \overline{a}_{j-i-k-1}\right\} \qquad (31)$$

Then the series takes the four terms

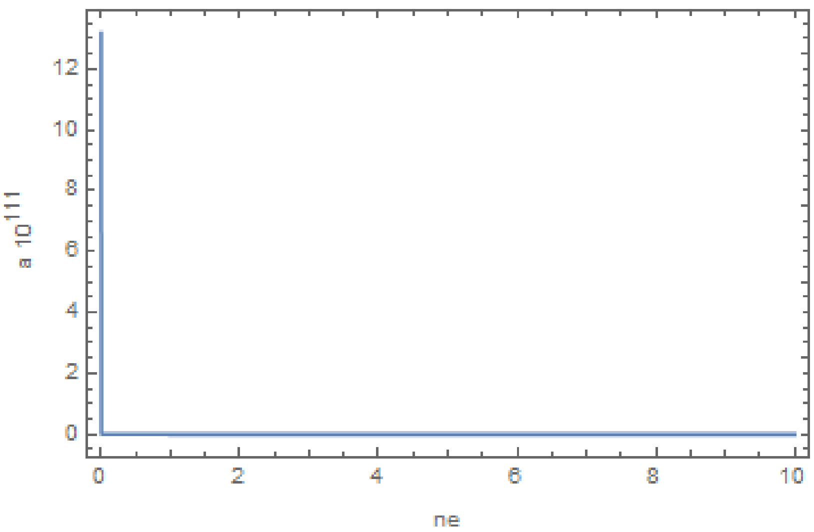
$$a_0 = e^{iz} \quad , \quad a_1 = i\tau\left(\lambda - \frac{1}{2}\right)e^{iz}, \; a_2 = \left(\lambda - \frac{1}{2}\right)\left(\frac{3}{2}(i\tau)^2 - i\tau\right)e^{iz},$$

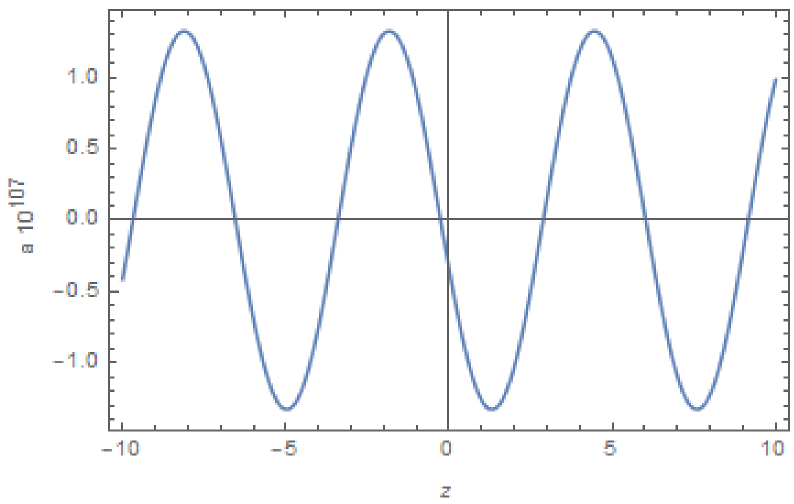
$$a_3 = \left(\lambda - \frac{1}{2}\right)\left(-\frac{3}{4}(i\tau)^3 + \frac{1}{2}i\tau\right)e^{iz}$$

HPM for solving mNLSE

The potential by HPM is

$$\lim_{p \to 1} \mathbf{a} = a_0 + a_1 + a_2 + a_3 + \ldots \qquad (32)$$





Appendix

$$M = \frac{m_e}{m_h} \quad , \quad \omega_{pe}^2 = \frac{4\pi e^2 n_{eo}}{m_e} \quad , \quad \omega_{ph}^2 = \frac{4\pi e^2 n_{ho}}{m_h}$$

$$E = \frac{\beta_e}{\beta_e + M\beta_h} \quad , \quad H = \frac{\beta_h}{\beta_e + M\beta_h}$$

$$N_e = \exp[\beta_e(1 - \sqrt{1 + |a|^2} + \Phi)]$$

$$N_h = \exp[\beta_h(1 - \sqrt{1 + M^2|a|^2} - M\Phi)]$$

$$\Phi = \frac{\beta_e}{\beta_e + M\beta_h}\left(1 - \sqrt{1 + |a|^2}\right) - \frac{\beta_h}{\beta_e + M\beta_h}\left(1 - \sqrt{1 + M^2|a|^2}\right)$$

$$\lambda = \frac{1}{4}\left(1 + \beta_e(1 - E + H M^2) + M^3 + M\beta_h(1 + ME - HM^3)\right)$$

Appendix

$$\alpha = \left\{ \frac{(1+\beta_e(1-E+H)}{2(1+a_0{}^2)^{1/2}} - \beta_e\left(1+E-H\,\frac{(1+M^2a_0{}^2)^{1/2}}{(1+a_0{}^2)^{1/2}}\right)\right\}$$

$$\alpha^* = \left\{ \frac{(1+\beta_h(1+ME-MH)}{2(1+M^2a_0{}^2)^{1/2}} - \beta_h\left(1-MH+ME\,\frac{(1+a_0{}^2)^{1/2}}{(1+M^2a_0{}^2)^{1/2}}\right)\right\}$$

$$\beta = \left\{ \frac{-a_0(1+\beta_e(1-E+H)}{2(1+a_0{}^2)^{3/2}} + \frac{\beta_e H\, a_0(1+M^2a_0{}^2)^{1/2}}{2(1+a_0{}^2)^{3/2}} - \left(\frac{\beta_e H\, a_0{}^2M^2}{2(1+M^2a_0{}^2)^{1/2}(1+a_0{}^2)^{1/2}}\right)\right\}$$

$$\beta^* = \left\{ \frac{-a_0M^2(1+\beta_h(1+ME-MH)}{2(1+M^2a_0{}^2)^{3/2}} + \frac{\beta_h E\, a_0M^3(1a_0{}^2)^{1/2}}{2(1+M^2a_0{}^2)^{3/2}} - \left(\frac{\beta_h E\, a_0M}{2(1+M^2a_0{}^2)^{1/2}(1+a_0{}^2)^{1/2}}\right)\right\}$$

THANK U FOR LISTENING

ANY QUESTION