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# Nonlinear Schrödinger equation for optical media with quintic nonlinearity

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**Abstract.** A nonlinear quintic Schrödinger equation (NLQSE) is developed and studied in detail. It is found that the NLQSE has soliton solutions, the stability of which is analysed using variational method. It is also found that the soliton pulse width in the materials supporting NLQSE is small compared to soliton pulse width of the commonly studied nonlinear cubic Schrödinger equation (NLCSE).

**Keywords.** Nonlinear quintic Schrödinger equation; optical solitons; nonlinear fibre optics; variational method; pulse width; stability; critical energy.

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## 1. Introduction

The possibility of effecting optical communication through fibres, in the form of solitons was theoretically predicted by Hasegawa and Tappert [1, 2] in early 1970s, but it took about a decade for the experimentalists to observe solitons in fibres [3]. Since then this field has been in constant focus of both experimental and theoretical activities. Solitons are supported in an optical fibre by the mutually compensating presence of dispersion and nonlinearity in the medium. Such solitons are generally called envelope solitons which form a class of solutions to nonlinear Schrödinger equation [2]. In most of the earlier experimental and theoretical considerations a Kerr-type nonlinearity and anomalous dispersion was matched. In Kerr type media third order polarization term $\chi^{(3)}$ is responsible for the nonlinearity and the resulting nonlinear equation is usually called nonlinear cubic Schrödinger equation (NLCSE). Because of their unique property of propagation without distortion, optical solitons have attracted intense experimental and theoretical studies.

Recently, thrust has been put on developing materials with non-Kerr like nonlinearity [4]. Success has been achieved in developing materials like semiconductor doped glass, organic polymers, etc. that higher order nonlinearities come into play at not too high intensity of light, which is a necessary requirement for preventing dielectric breakdown. Kaplan [5–7] considered a more generalized nonlinear equation and showed that for a certain class of nonlinearity bistable or more generally multistable soliton solutions can exist. Pushkarov *et al* [8] and Cowan *et al* [9] modified the NLCSE by including a quintic term and obtained a solitary wave solution to NLCQSE. Cowan *et al* [9] used numerical methods to study the stability of the soliton solution to NLCQSE.

Ajit Kumar *et al* [10] have approached the problem of the stability of the solitary wave solutions of NLCQSE using analytical methods and they have observed that inclusion of fifth order nonlinearity in the usual NLCSE considerably modifies the pulse propagation. Recently Angelis [11] has also studied the stability of the solution of NLCQSE using variational approach of Anderson [12].

In this paper we develop a nonlinear Schrödinger equation by considering the effect of quintic non-linearity alone. This situation can be achieved in a fibre by doping it with proper materials [13]. In § 2 the nonlinear quintic Schrödinger equation [NLQSE] is derived. The solution to NLQSE is obtained in § 3 and it possesses soliton behaviour. In § 4 the stability of the solution is studied using the variational method [12] and the present investigation reveals the existence of a critical energy for the soliton solution to exist.

## 2. Nonlinear quintic Schrödinger equation

The basic wave equation for a wave propagating parallel to the $z$ direction (one dimensional wave propagation) is given by [14]

$$\frac{\partial^2 E}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 D}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 P^{(\mathrm{NL})}_{(z,t)}}{\partial t^2} \tag{2.1}$$

where $P^{(\mathrm{NL})}$ is the nonlinear polarization, $E(z,t)$ is the macroscopic electric field. Expanding $P^{(\mathrm{NL})}$ as a series in powers of the macroscopic field $E(z,t)$ associated with the incident laser radiation, we find

$$\begin{aligned} P^{(\mathrm{NL})}_{(z,t)} &= \tilde{\chi}^{(2)}[E_\omega(z,t)\mathrm{e}^{i(kz-\omega t)} + E^*_\omega(z,t)\mathrm{e}^{-i(kz-\omega t)}]^2 \\ &\quad + \tilde{\chi}^{(3)}[E_\omega(z,t)\mathrm{e}^{i(kz-\omega t)} + E^*_\omega(z,t)\mathrm{e}^{-i(kz-\omega t)}]^3 \\ &\quad + \ldots\ldots. \end{aligned} \tag{2.2}$$

where the quantities $\tilde{\chi}^{(2)}$, $\tilde{\chi}^{(3)}$, etc are the higher order susceptibilities, defined as

$$\tilde{\chi}^{(3)} = \sum_{\alpha\beta\gamma\delta} \chi^{(3)}_{\alpha\beta\gamma\delta} n_\alpha n_\beta n_\gamma n_\delta. \tag{2.3}$$

In perfectly isotropic medium (possessing centre of inversion) the even terms of susceptibility vanish.

Considering the contribution from $\chi^{(3)}$ alone we can write

$$P^{(\mathrm{NL})}_{(z,t)} = \tilde{\chi}^{(3)}[E_\omega(z,t)\mathrm{e}^{i(kz-\omega t)} + E^*_\omega(z,t)\mathrm{e}^{-i(kz-\omega t)3}]. \tag{2.4}$$

On expanding, terms in $\mathrm{e}^{-i3\omega t}$ appear which represent the third harmonic generation. If proper phase matching is not achieved the intensity of third harmonic wave will be very weak. Assuming that proper phase matching is not achieved, the terms representing third harmonic generation may be neglected. Thus,

$$P^{(\mathrm{NL})}_{(z,t)} = \tilde{\chi}^{(3)}3|E_\omega(z,t)|^2 E_\omega(z,t)\mathrm{e}^{i(kz-\omega t)}] + \mathrm{cc} \tag{2.5}$$

where cc denotes the complex conjugate term. Including $\tilde{\chi}^{(5)}$,

$$\begin{aligned} P^{(\mathrm{NL})}_{(z,t)} &= 3\tilde{\chi}^{(3)}|E_\omega(z,t)|^2 E_\omega(z,t)\mathrm{e}^{i(kz-\omega t)} \\ &\quad + 10\tilde{\chi}^{(5)}|E_\omega(z,t)|^4 E_\omega(z,t)\mathrm{e}^{i(kz-\omega t)} + \mathrm{cc}. \end{aligned} \tag{2.6}$$

In developing nonlinear quintic Schrödinger equation, the term containing $\tilde{\chi}^{(3)}$ in (2.6) is neglected and thus

$$P^{(\mathrm{NL})}_{(z,t)} = 10\tilde{\chi}^{(5)}|E_\omega(z,t)|^4 E_\omega(z,t)\mathrm{e}^{i(kz-\omega t)} + \mathrm{cc}. \tag{2.7}$$

Substituting (2.7) alongwith the values of second order derivatives of $E$ and $D$ in (2.1) we find

$$2i\left[k\frac{\partial E_\omega}{\partial z} + \frac{\omega}{c^2}\left(\varepsilon + \frac{1}{2}\omega\frac{\partial \varepsilon}{\partial \omega}\right)\frac{\partial E_\omega}{\partial t}\right] + \frac{\partial^2 E_\omega}{\partial z^2} - \frac{1}{c^2}\left[\varepsilon + 2\omega\frac{\partial\varepsilon}{\partial\omega} + \frac{1}{2}\omega^2\frac{\partial^2\varepsilon}{\partial\omega^2}\right]\frac{\partial^2 E}{\partial t^2}$$
$$= \frac{-40\pi\omega^2\tilde{\chi}^{(5)}}{c^2}|E_\omega|^4 E_\omega. \tag{2.8}$$

The group velocity and the phase velocity are respectively given by

$$V_{\mathrm{g}}(\omega) = \frac{\partial\omega}{\partial k} \quad \text{and}$$

$$V_{\mathrm{P}} = \frac{\omega}{k}. \tag{2.9}$$

The propagation constant $k$ is a function of frequency.

$$k^2(\omega) = \frac{\omega^2}{c^2}\varepsilon(\omega) \tag{2.10}$$

where $\varepsilon(\omega)$ is the permittivity of the medium which is numerically equal to the square of the index of refraction. Using the first and second derivatives of (2.10) with respect to $\omega$, we get the following identities

$$\frac{\omega}{c^2}\left(\varepsilon + \frac{1}{2}\omega\frac{\partial\varepsilon}{\partial\omega}\right) = \frac{k}{V_{\mathrm{g}}} \tag{2.11}$$

and

$$\frac{1}{V_{\mathrm{g}}^2} + k\frac{\partial(1/V_{\mathrm{g}})}{\partial\omega} = \frac{1}{c^2}\left(\varepsilon + 2\omega\frac{\partial\varepsilon}{\partial\omega} + \frac{1}{2}\omega^2\frac{\partial^2\varepsilon}{\partial\omega^2}\right). \tag{2.12}$$

Substituting (2.9), (2.11) and (2.12) in (2.8) and after simplification we get,

$$\left(\frac{\partial}{\partial z} + \frac{1}{V_{\mathrm{g}}}\frac{\partial}{\partial t}\right)E_\omega - \frac{i}{2k}\left(\frac{\partial^2}{\partial z^2} - \frac{1}{V_{\mathrm{g}}^2}\frac{\partial^2}{\partial t^2}\right)E_\omega$$
$$+ \frac{i}{2}\frac{\partial(1/V_{\mathrm{g}})}{\partial\omega}\frac{\partial^2 E_\omega}{\partial t^2} = \frac{i20\pi\omega V_{\mathrm{P}}}{c^2}\tilde{\chi}^{(5)}|E_\omega|^4 E_\omega. \tag{2.13}$$

We have the identity [4]

$$\left(\frac{\partial}{\partial z} + \frac{1}{V_{\mathrm{g}}}\frac{\partial}{\partial t}\right)E_\omega - \frac{i}{2k}\left(\frac{\partial^2}{\partial z^2} - \frac{1}{V_{\mathrm{g}}^2}\frac{\partial^2}{\partial t^2}\right)E_\omega$$
$$= \left[1 - \frac{i}{2k}\left(\frac{\partial}{\partial z} - \frac{1}{V_{\mathrm{g}}}\frac{\partial}{\partial t}\right)\right]\left(\frac{\partial}{\partial z} + \frac{1}{V_{\mathrm{g}}}\frac{\partial}{\partial t}\right)E_\omega. \tag{2.14}$$

Under the slowly varying envelope approximation (SVEA) the square bracket on the right hand side of (2.14) may be replaced by unity since the envelope function $E(z,t)$ varies little over a spatial region of the size of a wavelength and varies little over one cycle of the carrier wave frequency $\omega$.

Hence the term

$$\left[\frac{1}{2k}\right]\left[\left(\frac{\partial}{\partial z}\right)-\left(\frac{1}{V_g}\right)\left(\frac{\partial}{\partial t}\right)\right]$$

inside the square bracket makes only a small correction to unity and therefore may be neglected. Then (2.13) becomes,

$$\left(\frac{\partial}{\partial z}+\frac{1}{V_g}\frac{\partial}{\partial t}\right)E_\omega(z,t)+\frac{i}{2}\frac{\partial(1/V_g)}{\partial\omega}\frac{\partial^2 E_\omega}{\partial t^2}$$
$$=\frac{i20\pi\omega V_p}{c^2}\tilde{\chi}^{(5)}|E_\omega|^4 E_\omega. \tag{2.15}$$

Defining

$$\lambda=\frac{20\pi\omega V_p}{c^2}\tilde{\chi}^{(5)} \tag{2.16}$$

and

$$\frac{\partial(1/V_g)}{\partial\omega}=-\frac{i}{V_g^2}\frac{\partial V_g}{\partial\omega}=-\sigma\mu \tag{2.17}$$

where $\mu$ is always a positive number and $\sigma=\pm 1$. If $\partial V_g/\partial\omega$ is positive, $\sigma=+1$ and if $\partial V_g/\partial\omega$ is negative $\sigma=-1$. Substituting (2.16) and (2.17) in (2.15) and rearranging,

$$-\frac{1}{2}\sigma\mu\frac{\partial^2 E_\omega}{\partial t^2}-\lambda|E_\omega|^4 E_\omega=i\left(\frac{\partial}{\partial z}+\frac{1}{V_g}\frac{\partial}{\partial t}\right)E_\omega. \tag{2.18}$$

The variables $(z,t)$ may be changed to $(\xi,\tau)$

$$\tau=(t-(1/V_g)z) \text{ and } \xi=z.$$

Then (2.18) is transformed into

$$-\frac{1}{2}\sigma\mu\frac{\partial^2 E_\omega}{\partial\tau^2}-\lambda|E_\omega|^4 E_\omega=i\frac{\partial E_\omega}{\partial\xi}. \tag{2.19}$$

If $\lambda=0$, this has the form of the ordinary Schrödinger equation for a free particle, whose mass is inversely proportional to $\mu$. The variable $\tau$ is an effective spatial coordinate and $\xi$ is an effective time. The term $\lambda|E_\omega|^4$ represents a potential energy, the form of which depends on $\lambda$. Assuming $\tilde{\chi}^{(5)}$ to be positive, the parameter $\lambda>0$, and similarly for $\partial V_g/\partial\omega>0$, $\sigma=+1$, then (2.19) becomes

$$-\frac{1}{2}\mu\frac{\partial^2 E_\omega}{\partial\tau^2}-\lambda|E_\omega|^4 E_\omega=i\frac{\partial E_\omega}{\partial\xi}. \tag{2.20}$$

Writing $\tau=\sqrt{\mu}y$,

$$-\frac{1}{2}\frac{\partial^2 E_\omega}{\partial y^2}-\lambda|E_\omega|^4 E_\omega=i\frac{\partial E_\omega}{\partial\xi}. \tag{2.21}$$

Let $E_\omega = \lambda^{-1/4}u$. Then (2.21) becomes

$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u}{\partial y^2} + |u|^4 u = 0. \tag{2.22}$$

Equation (2.22) is the nonlinear quintic Schrödinger equation.

### 3. Soliton solutions of the NLQSE

A solution to (2.22) may be sought of the form

$$U(y,\xi) = \phi(y)e^{i\kappa\xi}. \tag{3.1}$$

Then (2.22) becomes

$$\frac{1}{4}\left(\frac{d\phi}{dy}\right)^2 - \frac{1}{2}\kappa\phi^2 + \frac{1}{6}\phi^6 = \text{constant}. \tag{3.2}$$

Applying the boundary conditions that $\phi(y)$ and its derivative $d\phi/dy$ vanish as $y \to \pm\infty$, the constant in (3.2) vanishes. Then we find

$$\frac{d\phi}{dy} = \pm\phi\left(2\kappa - \left(\frac{2}{3}\right)\phi^4\right)^{1/2}. \tag{3.3}$$

Hence we find

$$\int \frac{d\phi}{\phi\sqrt{(2\kappa - (2/3)\phi^4)}} = \pm y. \tag{3.4}$$

The solution is given by

$$\phi = \frac{(3\kappa)^{1/4}}{[\cosh(\sqrt{(8\kappa)}y)]^{1/2}} \tag{3.5}$$

or

$$U(y,\xi) = (3\kappa)^{1/4}[\operatorname{sech}(\sqrt{(8\kappa)}y)]^{1/2}e^{i\kappa\xi}. \tag{3.6}$$

Going back through all the previous transformations, we find,

$$E_\omega(z,t) = \left[\frac{3\kappa c^2}{20\pi\omega V_p\tilde{\chi}^{(5)}}\right]^{1/4} \frac{e^{i\kappa z}}{(\cosh[1/V_g)(8\kappa/\mu)^{1/2}(z - V_g t)])^{1/2}}. \tag{3.7}$$

This represents a pulse of stable shape which propagates through the medium with the group velocity $V_g$.

The solution to the NLQSE may be compared with the solution to the NLCSE given by [14]

$$E_\omega(z,t) = \left[\frac{\kappa c^2}{3\pi\omega V_p\tilde{\chi}^{(3)}}\right]^{1/2} \frac{e^{i\kappa z}}{\cosh[1/V_g(2\kappa/\mu)^{1/2}(z - V_g t)]}. \tag{3.8}$$

In both these equations $\kappa$ is the parameter which decides the width of the pulse with the only condition that $\kappa > 0$. Figure 1 shows the wave profile in the two cases against the same normalized values of the parameters.

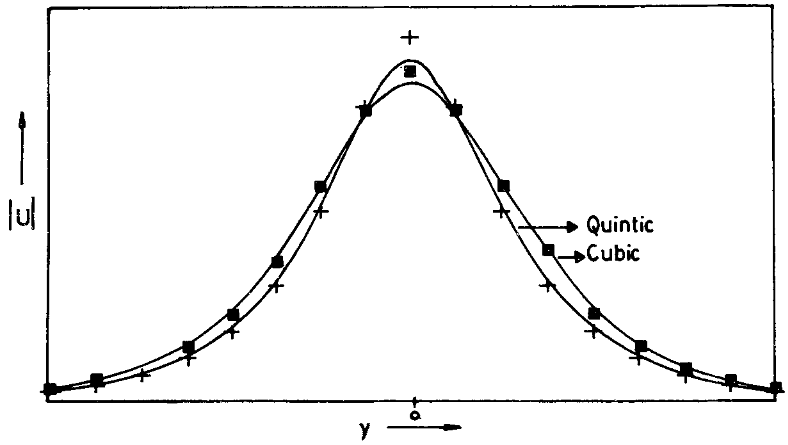


**Figure 1.** Pulse profile in the cubic and quintic materials.

## 4. Analysis using variational approach

Using the variational formulation [12] an approximate analytical expression for the self-trapped solutions to the NLQSE can be obtained.

Consider the NLQSE

$$iE_z + E_{tt} + \lambda |E|^4 E = 0 \tag{4.1}$$

where the suffixes $z$ and $t$ denote differentiation with respect to them.

The Lagrangian density corresponding to (4.1) is

$$L = \frac{i}{2}\left(E\frac{\partial E^*}{\partial z} - E^*\frac{\partial E}{\partial z}\right) + \left|\frac{\partial E}{\partial t}\right|^2 - \frac{\lambda}{3}|E|^6. \tag{4.2}$$

Since we are dealing with a one-dimensional confined pulse, a simple ansatz is

$$E(t,z) = A(z)e^{-(t^2/2\alpha^2)}e^{iat^2} \tag{4.3}$$

where $A(z)$, $\alpha(z)$ and $a(z)$ are parameter functions to be determined from the reduced variational problem.

The reduced Lagrangian is then obtained by inserting the trial function into the Lagrangian density and integrating from $-\infty$ to $+\infty$.

Substituting (4.3) in (4.2)

$$L = \frac{i}{2}e^{(-t^2/\alpha^2)}(AA_z^* - A_z A^*) + |A|^2 e^{-t^2/\alpha^2} t^2 a_z$$
$$+ |A|^2 e^{-t^2/\alpha^2} t^2 [4a^2 + (1/\alpha^4)] - (\lambda/3)|A|^6 e^{-3t^2/\alpha^2} \tag{4.4}$$

Defining

$$\langle L \rangle = \int_{-\infty}^{\infty} L\,\mathrm{d}t \tag{4.5}$$

$$\langle L\rangle = (i/2)(AA_z^* - A^*A_z)\sqrt{\pi}\alpha + |A|^2 a_z(\sqrt{\pi}/2)\alpha^3 + |A|^2[4a^2 + (1/\alpha^4)](\sqrt{\pi}/2)\alpha^3 - (\lambda/3)|A|^6(\sqrt{\pi}/\sqrt{3})\alpha. \quad (4.6)$$

The reduced variational problem is

$$\delta\int\langle L\rangle\,\mathrm{d}z = 0. \quad (4.7)$$

Using the variational principle [12] with the reduced Lagrangian $\langle L\rangle$ given by (4.6), the following variational equations are obtained:

$$\frac{\delta\langle L\rangle}{\delta A^*} = 0 \Rightarrow \frac{\mathrm{d}(i\alpha A)}{\mathrm{d}z} = -i\alpha A_z + \alpha^3 A a_z + \alpha^3 A[4a^2 + (1/\alpha^4)] - (2/\sqrt{3})\alpha\lambda|A|^4 A. \quad (4.8)$$

$$\frac{\delta\langle L\rangle}{\delta A} = 0 \Rightarrow \frac{\mathrm{d}(-i\alpha A^*)}{\mathrm{d}z} = i\alpha A_z^* + \alpha^3 A^* a_z + \alpha^3 A^*\left[4a^2 + \left(\frac{1}{\alpha^4}\right)\right] - \left(\frac{2}{\sqrt{3}}\right)\alpha\lambda|A|^4 A^*. \quad (4.9)$$

$$\frac{\delta\langle L\rangle}{\delta\alpha} = 0 = i(AA_z^* - A^*A_z) + 3\alpha^2|A|^2 a_z + 12\alpha^2|A|^2 a^2 - [|A|^2/\alpha^2] - \left(\frac{2}{3\sqrt{3}}\right)\lambda|A|^6. \quad (4.10)$$

$$\frac{\delta\langle L\rangle}{\delta a} = 0 \Rightarrow \frac{\mathrm{d}}{\mathrm{d}z}(\alpha^3|A|^2) = 8\alpha^3|A|^2 a. \quad (4.11)$$

Multiplying (4.8) by $A^*$, (4.9) by $A$ and then subtracting and adding we get the following equations

$$\frac{\mathrm{d}}{\mathrm{d}z}(\alpha|A|^2) = 0 \quad (4.12)$$

and

$$i(A^*A_z - AA_z^*) = |A|^2\left[2\alpha^2 a_z + 2\alpha^2\left(4a^2 + \left(\frac{1}{\alpha^4}\right)\right) - \left(\frac{4}{\sqrt{3}}\right)\lambda|A|^4\right]. \quad (4.13)$$

Equation (4.12) implies a constant of motion;

$$\alpha(z)|A(z)|^2 = \alpha_0|A_0|^2 = E_0 \quad (4.14)$$

where $E_0$ is the initial energy of the pulse which does not change.
By comparing (4.10) and (4.13) we get

$$\alpha^2 a_z = -4\alpha^2 a^2 + \frac{3}{\alpha^2} - \frac{10\lambda|A|^4}{3\sqrt{3}}. \quad (4.15)$$

From (4.11) and (4.12), we find

$$\frac{\mathrm{d}}{\mathrm{d}z}(\alpha^3|A|^2) = \frac{\mathrm{d}\alpha^2}{\mathrm{d}z}\cdot\alpha|A|^2. \tag{4.16}$$

Thus we find

$$\frac{\delta\langle L\rangle}{\delta a} = 2\alpha\alpha_z\alpha|A|^2$$

$$= 2\alpha\alpha_z E_0. \tag{4.17}$$

Comparing (4.17) with (4.11) we get

$$2\alpha\alpha_z E_0 = 8\alpha^3|A|^2 a = 8\alpha^2 E_0 a \tag{4.18}$$

i.e.

$$\alpha_z = 4\alpha a. \tag{4.19}$$

Combining the derivative of (4.19) with (4.15) we get

$$\frac{\mathrm{d}^2\alpha}{\mathrm{d}z^2} = \frac{12}{\alpha^3} - \frac{40}{3\sqrt{3}}\frac{\lambda E_0^2}{\alpha^3}. \tag{4.20}$$

Equation (4.20) may be considered to be derived from a potential such that

$$\frac{\mathrm{d}^2\alpha}{\mathrm{d}z^2} = -\frac{\mathrm{d}V}{\mathrm{d}\alpha} \tag{4.21}$$

where

$$V(\alpha) = \frac{6}{\alpha^2} - \frac{20}{3\sqrt{3}}\frac{\lambda E_0^2}{\alpha^2}. \tag{4.22}$$

Self-trapped solutions of (4.1) correspond to extrema of the potential, i.e., they correspond to $E_0$ and $\alpha$ values such that

$$\frac{\mathrm{d}V(\alpha)}{\mathrm{d}\alpha} = 0. \tag{4.23}$$

Applying this condition we find

$$36\sqrt{3} - 40\lambda E_0^2 = 0. \tag{4.24}$$

This implies

$$E_0^2 = \frac{9\sqrt{3}}{10\lambda}$$

$$= \frac{9\sqrt{3}}{200\pi\omega V_p\tilde{\chi}^{(5)}}. \tag{4.25}$$

It appears that there is a critical value for the energy for a self-trapped solution of (4.1) to exist. The critical value of energy is found to depend on the fifth order susceptibility of the fibre material. Figure 2 shows the variation of the critical energy $E_0$ with $\lambda$.

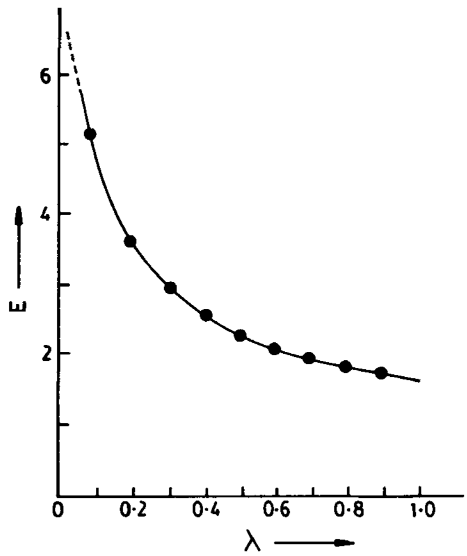


**Figure 2.** Variation of critical energy with the parameter $\lambda$.

From the Lagrangian formulation the stability analysis of the solutions can be carried out. Stable solutions correspond to local minima of the potential function

$$\frac{d^2 V}{d\alpha^2} = \frac{36}{\alpha^4} - \frac{120}{3\sqrt{3}} \frac{\lambda E_0^2}{\alpha^4}$$

$$= \frac{36}{\alpha^4} - \frac{40}{\sqrt{3}} \frac{\lambda E_0^2}{\alpha^4}. \qquad (4.26)$$

For a minimum, $(d^2 V/d\alpha^2)$ is positive which implies that $\lambda$ must be less than $(9\sqrt{3}/10E_0^2)$.

## 5. Conclusions

A remarkable result of considering the effect of $\tilde{\chi}^{(5)}$ alone to the soliton propagation in optical fibres is the reduction of pulse width and an increase in the peak value of intensity which is useful in optical communication.

The present study reveals the existence of a critical energy for soliton solutions. This fact may be conveniently used for any application where a cut-off is desirable in terms of energy of the incident radiation.

Recently Herrmann [13] studied the coefficient of cubic term which has a small value compared to that of the quintic term. In the present work we considered a situation where the cubic term is absent and quintic term alone is present. We found that by exciting the fifth order nonlinearity to the desired level, soliton pulses of much reduced pulse width may be transmitted at the critical input energy. This may find applications in optical switching, logic circuits and optical communication systems. Thus, if we can grow by suitable doping of a material, in which the fifth order nonlinearity alone is active, more advantageous soliton propagation may be possible.

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