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Numerical Studies on Soliton Propagation in the Dielectric Media
by the Nonlinear Lorentz Computational Model

Hirotsada Abe[†] and Hideo Okuda

Princeton Plasma Physics Laboratory, Princeton University,

P.O. Box 451

Princeton, N.J. 08543

Abstract - Soliton propagation in the dielectric media has been simulated by using the nonlinear Lorentz computational model, which was recently developed to study the propagation of electromagnetic waves in a linear and a nonlinear dielectric. The model is constructed by combining a microscopic model used in the semi-classical approximation for dielectric media and the particle model developed for the plasma simulations. The carrier wave frequency is retained in the simulation so that not only the envelope of the soliton but also its phase can be followed in time. It is shown that the model may be useful for studying pulse propagation in the dielectric media.

[†]Permanent address: Department of Electronics and Informatics,
Ryukoku University, 1-5 Yokotani, Oe-cho Seta, Otsu-shi 520-21, Japan.

I. INTRODUCTION

A new computer simulation model[1], called the nonlinear Lorentz computational model, was recently proposed to study electromagnetic wave propagation in linear and nonlinear dispersive solid-state media. The model is based on the Lorentz model of the atom[2], in which the atoms are assumed to be harmonic oscillators. The model well represents the linear dispersive properties of the dielectric media for the electromagnetic wave. A semi-classical description[3]-[5] is used to include the nonlinear response of a dielectric medium arising from the intrinsic quantum effects.

The electromagnetic properties of the model have been studied by using two examples of steady state wave propagation: one is a linear wave refraction and reflection at the dielectric boundary and the other is a nonlinear dependence of the wavelength on the wave amplitude in a uniform dielectric[6]. The simulation results show excellent agreement with the theoretical calculations.

It is well-known that study of the transient phenomena or the pulse propagation in the dielectric media is important: The femtosecond phenomena such as the envelope soliton propagation[7] is expected to be used in the communication engineering and the nanosecond phenomena such as the high-power soliton generation in ceramics[8] may be utilized in the electrical engineering.

Furthermore, an optical switching in a dielectric may be constructed which can be applied to the optical microelectronics. A number of nonlinear devices based on the optical fibers for ultra-fast switching and logic have been proposed in the literature[9]-[12]. Some of them are based on, for example, Mach-Zehnder configuration, nonlinear polarization rotation, or nonlinear coupling.

In this paper, we will study soliton propagation using our nonlinear Lorentz computational model. The study of soliton is important because it forms a basis of the nonlinearities in the dielectric media.

In order to simulate wave propagation in a linear and a nonlinear dielectric materials, we should mention that a different approach has been developed in which a finite-difference method in the time domain is used to solve Maxwell's equations directly together with linear and nonlinear susceptibilities given a priori as frequency-dependent functions[13]-[15]. In models Maxwell's equations are solved for the prescribed boundary conditions and any spatial non-uniformities of the dielectric media, however, are allowed including vacuum region. There are differences in these models, for example, our present model includes full nonlinearities within the framework of the semi-classical approximation of the dipole in the presence of the immobile nuclei, while the other model[13]-[15] employs a perturbation approximation valid for small electric field amplitude, while allowing to include the Raman effects[13],[14].

Both models are shown to be able to study the general behaviors of including the soliton for not only envelope but phase change in time and space[1],[13],[14]. One of two dielectric media simulated in this paper is similar to that used in the earlier works[13],[14]. The other, however, is a dielectric medium with two harmonic oscillators which has never been simulated.

II. THEORETICAL REVIEWS AND SIMULATION MODELS

A. The Nonlinear Lorentz Computational Model

Let us describe the mathematical method describing the nonlinear Lorentz computational model. Microscopically, the simplest dielectric material can be considered as an isotropic and locally uniform collection of a large number of electric dipoles. We, therefore, assume in our model that a large number of electric dipoles are uniformly distributed in the system, where the ions are assumed fixed spatially and the electrons oscillate around the ions.

The motion of the electrons in the presence of an electric field $\mathbf{E}$ and a magnetic field $\mathbf{B}$ is given by[5]

$$\begin{aligned} \frac{d\mathbf{x}_{\sigma j}}{dt} &= \mathbf{v}_{\sigma j} , \\ \frac{d\mathbf{v}_{\sigma j}}{dt} &= - \frac{e}{m} \left(\mathbf{E} + \mathbf{v}_{\sigma j} \times \mathbf{B} \right) - \omega_{0\sigma}^2 f_{\sigma j} (\mathbf{x}_{\sigma j} - \mathbf{x}_{0\sigma j}) - \Gamma_{0\sigma} \mathbf{v}_{\sigma j} \\ f_{\sigma j} &= 1 + \delta_{3\sigma} \frac{\omega_{0\sigma}^2}{c_m^2} (\mathbf{x}_{\sigma j} - \mathbf{x}_{0\sigma j}) \cdot (\mathbf{x}_{\sigma j} - \mathbf{x}_{0\sigma j}) , \end{aligned} \tag{1}$$

where $\mathbf{x}_{\sigma j}$ and $\mathbf{v}_{\sigma j}$ are the position and the velocity of the j -th electron for the σ -th species harmonic oscillator, respectively, $\mathbf{x}_{0\sigma j}$ is its equilibrium position, $\omega_{0\sigma}$ is its eigen frequency, $\Gamma_{0\sigma}$ is a small friction coefficient, $\delta_{3\sigma}$ is a numerical constant to control the cubic nonlinearity for the dielectric media. Here c_m is the speed of light in a dielectric defined by

$$c_m = \frac{c}{\sqrt{\epsilon_m}}, \quad (2)$$

where c is the speed of light in vacuum and ϵ_m is the dielectric constant relative to vacuum representing the contribution from the eigen frequencies much higher than those under consideration.

In the case of $\delta_{3\sigma} < 0$, it is clear that Eq. (1) is unstable for the large wave amplitude because the nonlinear force acts to increase displacement indefinitely. In order to stabilize the equation of motion for a negative $\delta_{3\sigma}$, $f_{\sigma j}$ is approximated by

$$f_{\sigma j} = \delta_{3r\sigma} + (1 - \delta_{3r\sigma}) \exp \left[\frac{\delta_{3\sigma}}{(1 - \delta_{3r\sigma})} \frac{\omega_{0\sigma}^2}{c_m^2} (\mathbf{x}_{\sigma j} - \mathbf{x}_{0\sigma j}) \cdot (\mathbf{x}_{\sigma j} - \mathbf{x}_{0\sigma j}) \right], \quad (3)$$

in the present model where $\delta_{3r\sigma}$ is a numerical constant satisfying $0 < \delta_{3r\sigma} < 1$. For a small displacement, Eq. (3) is reduced to Eq. (1).

While Eq. (1) is valid in three dimensions, for simplicity only a one-dimensional model was considered, in which all the electromagnetic fields vary with x only. Equation (1) is finite-differenced using the leapfrog

scheme and solved numerically together with Maxwell's equations self-consistently[16],[17].

B. Dispersion Relation in the Nonlinear Dielectric Medium

Extending the theory of the dispersion relation for the nonlinear dielectric medium with the single harmonic oscillator[6] to that with the multi-harmonic oscillators straightforwardly, the nonlinear dielectric constant $\varepsilon(\omega)$ is given by

$$\varepsilon(\omega) = n^2 \equiv \left(\frac{c k}{\omega} \right)^2 = \varepsilon_m \left[1 + \chi_m^{(1)}(\omega) + \chi_m^{(3)}(\omega) |E|^2 \right], \quad (4)$$

where $|E|$ is the absolute amplitude of the complex electric field and the linear and nonlinear susceptibilities $\chi^{(1)}(\omega)$ and $\chi^{(3)}(\omega)$ are given by

$$\begin{aligned} \chi_m^{(1)}(\omega) &= \frac{1}{\varepsilon_m} \chi^{(1)}(\omega) = \sum_{\sigma=1}^M \frac{\omega_{pm\sigma}^2}{\omega_{0\sigma}^2 - \omega^2 - i\omega\Gamma_{0\sigma}}, \\ \chi_m^{(3)}(\omega) &= \frac{1}{\varepsilon_m} \chi^{(3)}(\omega) \sim -\frac{3}{8} \sum_{\sigma=1}^M \delta_{3\sigma} \left(\frac{e \omega_{0\sigma}^2}{m c_m} \right)^2 \frac{\omega_{pm\sigma}^2}{(\omega_{0\sigma}^2 - \omega^2)^4}. \end{aligned} \quad (5)$$

Here M is the number of the species of the harmonic oscillators and $\omega_{pm\sigma}$ is the frequency defined by $\omega_{pm\sigma} = (n_{d\sigma} e^2 / \epsilon_0 \varepsilon_m m)^{1/2}$, with $n_{d\sigma}$ the number density of the σ -th dielectric dipole.

The dependence of $\varepsilon(\omega)$ on the electric field E is characteristic to the property of the solution to the Duffing equation[18]. The nonlinear refractive index can be approximated by

$$n(\omega, |E|^2) = n_0(\omega) + n_2 |E|^2, \quad (6)$$

where

$$\begin{aligned} n_0 &= \varepsilon_m^{1/2} \left[1 + \chi_m^{(1)}(\omega) \right]^{1/2}, \\ n_2 &= \varepsilon_m \frac{\chi_m^{(3)}}{2n_0}. \end{aligned} \quad (7)$$

The second term of the righthand side of Eq. (6) represents the high-frequency Kerr effect so that the balance between the nonlinearity and the linear dispersive properties in this wave dispersion equation may account for propagation of the envelope soliton[7].

C. The Nonlinear Schrödinger Equation

From the definition of the refractive index, the wave number k is related to the wave frequency ω by

$$k = \frac{\omega}{c} n(\omega) = \frac{\omega}{c} n_0(\omega, |E|^2) + \frac{\omega}{c} n_2 |E|^2. \quad (8)$$

Taylor-expanding both sides of Eq. (8) around the carrier wave frequency ω_{c0} and the carrier wave number k_{c0} , we find

$$k - k_{c0} = k_{c0}'(\omega - \omega_{c0}) + k_{c0}'' \frac{(\omega - \omega_{c0})^2}{2} \frac{\partial k}{\partial |E|^2} |E|^2 + i \gamma, \quad (9)$$

where

$$\begin{aligned} k_0' &= \frac{\partial k}{\partial \omega} \Big|_{\omega=\omega_{c0}, |E|=0}, \\ k_0'' &= \frac{\partial^2 k}{\partial \omega^2} \Big|_{\omega=\omega_{c0}, |E|=0}, \\ \gamma &= \frac{\omega_{c0}}{c} \text{Im}(n_0). \end{aligned} \quad (10)$$

Assuming a linearly polarized carrier wave with the frequency ω_{c0} and the wave number k_{c0} and the amplitude $q(x, t)$ varying slowly compared with the change of phase,

$$E_z = q(x, t) \exp(-i\omega_{c0}t + ik_{c0}x), \quad E_x = E_y = 0, \quad (11)$$

we find approximately

$$\begin{aligned} \frac{\partial q}{\partial x} &= i(k - k_{c0})q, \\ \frac{\partial q}{\partial t} &= -i(\omega - \omega_{c0})q. \end{aligned} \quad (12)$$

Multiplying the both sides of Eq. (9) by q and using Eq. (12), we get

$$i \left(\frac{\partial q}{\partial x} + k_{c0} \frac{\partial q}{\partial t} \right) - \frac{k_{c0}''}{2} \frac{\partial^2 q}{\partial t'^2} + \frac{\omega_{c0} n_2}{c} |q|^2 q = -i \gamma q. \quad (13)$$

In the frame ($t' = t - k'z$, $z' = z$) moving with the group velocity k' , we find

$$i \frac{\partial q}{\partial x} - \frac{k_{c0}''}{2} \frac{\partial^2 q}{\partial t'^2} + \frac{\omega_{c0} n_2}{c} |q|^2 q = -i \gamma q. \quad (14)$$

III. SIMULATION RESULTS

Two examples of dielectric media have been simulated to study transient phenomenon in which short electromagnetic pulses or solitons propagate in the presence of the cubic nonlinearity: the first one (Medium I)

corresponds to the dielectric medium consisting of a single oscillator and the second (Medium II) for a double oscillator.

In the simulations discussed in the following, we have introduced a characteristic frequency ω_N and a grid length Δ , which are used for normalization in simulation parameters and to scale the simulation results to those in various cases[6].

For Medium I, we simulated two cases with the different carrier wave frequencies ($\omega_{c0} = 8.61\omega_N$ and $\omega_{c0} = 2.0 \omega_N$) in the presence of an anomalous dispersion $k_{c0}'' < 0$ (Case IA) and a normal dispersion, $k_{c0}'' > 0$ (Case IB), while for Medium II (Case II) an anomalous dispersion with the same carrier wave frequency ($\omega_{c0} = 8.61\omega_N$) was simulated.

For Medium I, the eigen frequency ω_0 and the frequency $\omega_{pm} = \omega_p/(\epsilon_m)^{1/2}$ were chosen to be $4.0 \omega_N$ and $4.62 \omega_N$ and the friction coefficient Γ_0 was chosen to be $2.0 \times 10^{-5} \omega_N$. For Medium II the following parameters were chosen: two eigen frequencies were $\omega_{01} = 3.0 \omega_N$, and $\omega_{02} = 16.0 \omega_N$, two friction coefficients were $\Gamma_{01} = \Gamma_{02} = 2.0 \times 10^{-5} \omega_N$, and the frequency $\omega_p = \sqrt{\omega_{p1}^2 + \omega_{p2}^2}$ was $30 \omega_N$, where $\omega_{p1}^2/\omega_p^2 = 0.2$ and $\omega_{p2}^2/\omega_p^2 = 0.8$.

We have simulated three cases of soliton propagation in Medium I or II with different carrier wave frequencies ω_{c0} , which is explained in detail later. To generate a soliton, a pulse is excited at $x = L/8$ by a current $J_z = J_0 \text{sech}[(t - t_0)/\delta t] e^{-i\omega_{c0}t}$ where $t_0 = 10.0 \omega_N^{-1}$, $\delta t = 1.0 \omega_N^{-1}$,

and the carrier wave frequency ω_{c0} is $8.61 \omega_N$ or $2.0 \omega_N$. The dielectric medium is assumed to have a cubic nonlinearity so that $\delta_{3\sigma} = +2.2 \times 10^{+6}$ or $\delta_{3\sigma} = -2.2 \times 10^{+6}$.

For simplicity, we assume the characteristic frequency $\omega_N = 10^{14} \text{ rad/s}$ and dielectric constants $\epsilon_m = 2.25$ for Medium I and $\epsilon_m = 1.0$ for Medium II, respectively. The linear complex dielectric constants ϵ vs ω for these dielectric media are shown in Fig. 1.

Then the vacuum wavelengths for the carrier wave frequency $\omega_{c0} = 8.61 \omega_N$ for Cases IA and II and $\omega_{c0} = 2.0 \omega_N$ for Case IB become $\lambda_v = 2.19 \mu m$, $\lambda_v = 2.19 \mu m$, and $\lambda_v = 9.43 \mu m$, respectively. The velocity $c_m = c/\sqrt{\epsilon_m} = 2.0 \times 10^8 \text{ m/s}$ corresponds to $40.0 \omega_N \Delta$ and $20.0 \omega_N \Delta$ in Cases IA and IB and so their wavelengths $\lambda_m = \lambda_v/\sqrt{\epsilon_m}$ is 29.2Δ and 62.8Δ ($\lambda_v = 43.8 \Delta$ and 94.3Δ), which means $\Delta = 0.050 \mu m$ or $\Delta = 0.100 \mu m$, respectively. For Case II, the speed of light c is $40.0 \omega_N \Delta$. Thus, the vacuum wavelength λ_v is $29.2 \omega_N \Delta$ and so $\Delta = 0.075 \mu m$. These parameters are summarized in Table I. By using another characteristic frequency ω_N and ϵ_m , different dielectric materials can be studied.

The length of the one-dimensional system, L , is taken 2048 spatial grids, $L = 2048\Delta$, for all the runs. The absorbing boundary condition[19] is imposed on the electromagnetic waves so that it damps away in the ramp regions at the left and right edges ($0 \leq x \leq L/8$ and $7L/8 \leq x \leq L$).

by means of ramp functions or is numerically absorbed before reaching both the system boundaries. The dielectric medium is assumed to be placed between $x = L/16$ and $x = 15L/16$.

For all the runs, the normalized time step $c_m \Delta t / \Delta$ is chosen to be 0.8 and $\delta_{3r\sigma} = 1$ in Eq. (3) is used. The total number of the dipoles in the system is 25,600. For Medium II, the numbers of the dipoles are $N_1 = 5,120$ for the first species and $N_2 = 20,480$ for the second species.

As a method of the spatial interpolation for charge and current sharing and the field-quantity interpolation, the linear spline has been used. To calculate the field quantity[16],[17], We used the fast Fourier transformation (FFT) method with the k -space smoothing using the Gaussian filter with its radius $R = \Delta$.

A. Simulation Results of Case IA

Some of the simulation parameters in Case IA are close to those used in Ref. 13 and 14 where $\varepsilon(0) = 5.25$, $\varepsilon(\infty) = 2.25$ were assumed. In the present work, $\omega_{c0} = 8.61 \times 10^{14}$ was used as the carrier wave frequency of the pulse. Note $\delta_3 = -2.2 \times 10^6$ in the present work is different from that used in Refs. 13 and 14.

Shown in Figs. 2(a) and (b) are the pulse propagation in the linear dispersive medium ($\delta_3 = 0$), where the envelope of the pulse is found to spread out in time as it propagates away from the antenna. It is well

known that the nonlinear effect can prevent the pulse from spreading and lead to formation of solitons[1].

Shown in Figs. 2(c) and (d) are the simulation results with $\delta_3 = -2.2 \times 10^6$, where formation of the envelope soliton due to the high-frequency Kerr effect is clearly observed. The nonlinear term $\delta_3(\omega_0/c_m)^2 E_z^2$ is larger than that used in Refs. 13 and 14 and thus the soliton envelope is narrower.

Figures 3(a)-(d) show their corresponding wave number spectra at $x \sim 0.28L$, $\sim 0.43L$, $\sim 0.58L$, and $\sim 0.73L$, respectively. Unlike the works in Refs. 13 and 14, generation of the daughter wave is not observed in Figs. 2 and 3, because our present model does not include the Raman effects.

B. Simulation Results of Case II

Here we simulated Medium II where the parameters of two eigen frequencies are $\omega_{01} = 3.0 \omega_N$ and $\omega_{02} = 16.0 \omega_N$, two friction coefficients are $\Gamma_{01} = \Gamma_{02} = 2.0 \times 10^{-5} \omega_N$, and $\varepsilon(0) = 23.8$, $\varepsilon(\infty) = 1.0$. We chose the carrier wave frequency $\omega_{c0} = 8.61 \omega_N$, which is the same as that in Case IA. As seen in Fig. 1, the refractive index for this carrier frequency is close to that in Case IA.

Shown in Fig. (4) is the result of the soliton formation and propagation with $\delta_3 = -2.2 \times 10^6$. A small precursor and a radiation or a ripple are

born and propagate in front of the soliton and after it, respectively.

We also simulated collisions of the solitons using Medium II: In one case, two counter-propagating solitons have the polarization in the z -direction and in the other case two solitons have polarizations perpendicular with each other, one in the z -direction and the other in the y -direction.

First, the results of collision of the solitons linearly polarized in the same direction are shown in Fig. 5(a) at $t = 41.25 \omega_N^{-1}$. Shown in Fig. 5(b) are two solitons just before collision at $t = 67.50 \omega_N^{-1}$, in Fig. 5(c) during collision showing significant increase in the amplitude, and in Fig. 5(d) after the collision when the pulses separate and move away without distorting their general shapes which is a well-known characteristic of colliding solitons.

Next, we show the second case: one soliton is linearly polarized in the z -direction propagating from the left side and collides with the other soliton linearly polarized in the y -direction propagating from the right. Shown in Fig. 6(a) is the plot of E_z vs x during the collision at $t = 71.25 \omega_N^{-1}$. It is interesting to find that the solitons are little affected by the collision. After the collision, the soliton propagates to the right keeping its original shape before collision, as shown in Fig. 6(b). To see the effect of the collision on the shape of the soliton, Fig. 6(b) was compared with Fig. 4(b) at $t = 108.75 \omega_N^{-1}$ finding only a slight difference on the tail of the ripple

located around $x = L/4$. Incidentally, the shape of the soliton before the collision at $t = 41.25 \omega_N^{-1}$ is scarcely changed from that when a single soliton was used as shown in Fig. 4(a).

C. Simulation Results of Case IB

For this simulation, Medium I was used again. The carrier wave frequency of $\omega_{c0} = 2.0 \omega_N$ was used and thus the dispersion becomes normal, while it is anomalous for the carrier wave frequency of $\omega_{c0} = 8.61 \omega_N$ as explained in Sec. IIIA. For the stable propagation of the envelope soliton, the dispersive term [the second term of Eq. (14)] is balanced with the nonlinear term (the third term) so that $k_{c0}'' n_2$ must be positive. Then the sign of δ_3 must be positive. Therefore, $\delta_3 = +2.2 \times 10^6$ was chosen. Figure 7 shows the soliton propagation for the normal dispersion.

The pulse excited by the antenna is found to split into three solitons asymmetrically, as shown in Fig. 7(a). The splitted solitons have very narrow envelopes which are about one wavelength wide. They move away with time, as seen in Fig. 7(b). Correspondingly, the wave spectrum has three peaks or more as shown in Fig. 8.

General evolution of this soliton propagation is very similar to that of the solution to the modified nonlinear Schrödinger equation[20]. This equation is derived from Eq. (8) as well as the conventional nonlinear Schrödinger equation but it is extended to include a nonlinear correction

term with a time derivative of the pulse envelope. Usually, Eq. (8) holds well under two constraints: (i) the steady state and (ii) in the limit of small wave amplitude[6]. Surprisingly, the simulation result shown in Fig. 7(a) is very similar to the behavior governed by the modified nonlinear Schrödinger equation for the three-soliton bound state[20], although both constraints seem to be violated judging from the previous results[6].

IV. DISCUSSION AND CONCLUSION

While the model for the nonlinear dielectric media is assumed a simple form in the examples given here, it can be improved further depending on the goal of the simulations. This can be achieved by increasing the accuracy of the model to include the detailed microscopic structures of the dielectric media. For example, it is possible to include lattice oscillations of nuclei arising from the quantum mechanical effects by including the motion of the ions which are assumed frozen in this work. In this way, Raman scattering may be included within the classical approximation. Since our model follows the individual motion of the electrons, the model can be used to study, for example, light amplification caused by the population inversion. While we considered wave propagation in a dielectric medium, models for electromagnetic wave propagation in a metal or in a semi-conductor can be constructed by adopting the Drude model[21] or the free carrier model for the conducting current.

The present approach is numerically robust and should permit modeling two- and three- dimensional boundary-value problems with a complicated structure of the optical devices. In fact, our time step and the spatial grid length are about ten times larger than those reported in Ref. 13 and 14, respectively.

We note that Eq. (9) derived by the perturbative approach to the Duffing equation[18] is essentially the same order of approximation to the reduced equations such as the nonlinear Schrödinger equation[7], the modified nonlinear Schrödinger equation[22], and the generalized nonlinear Schrödinger equation[23]. The error of the perturbative expansion in Eq. (9) may be significant due to appearance of the higher order structure of nonlinearity and generation of the noises with higher frequency, if the amplitude of the electric field reaches a certain value on the limit of the perturbative approach. According to the results for the Case IB presented in Sec. IIIC, however, the soliton amplitude seems to exceed the limit of the perturbative approach reported in Ref. 6. In addition, the assumption of the slowly changing envelope approximation[22] used in the theory may not hold for these extremely short envelopes. Nevertheless the very short soliton is observed and its behavior is explained by the modified nonlinear Schrödinger equation[20].

In the presence of a strong nonlinearity, the Duffing equation[18] which governs the equation of motion of the dipole is well known to exhibit

quite interesting phenomena such as hysteresis and chaos. We expect that these nonlinear optical phenomena may be studied by our model. These possibilities should be further investigated extensively, by comparing the simulation results with the experimental and theoretical results. This in turn clarifies the modeling capability or the way to improve the model.

In conclusion, we have studied the propagation of the soliton by using the nonlinear Lorentz computational model for the dielectric medium. Both linear and nonlinear wave propagations have been studied in detail and the results are found to be in good agreement with the theoretical predictions verifying the validity of the model in the wider range of the parameters than our expectation in advance of this study.

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Table I

	Case IA	Case IB	Case II
ω_N	10^{14}	10^{14}	10^{14}
$\sqrt{\epsilon_m}$	1.5	1.5	1.0
c	3.0×10^8	3.0×10^8	3.0×10^8
c_m	2.0×10^8	2.0×10^8	3.0×10^8
ω_{c0}	8.61×10^{14}	2.0×10^{14}	8.61×10^{14}
λ_o	2.19	9.43	2.19
λ_m	1.46	6.28	2.19
Δ	0.050	0.100	0.075

FIGURE CAPTIONS

Fig. 1 Two linear dielectric constants relative to vacuum $\epsilon(\omega) = 1 + \chi^{(1)}(\omega)$: The solid lines are for Medium I with the parameters $\omega_0 = 4.0 \omega_N$, $\Gamma_0 = 2.0 \times 10^{-5} \omega_N$, $\epsilon(0) = 5.25$, and $\epsilon(\infty) = 2.25$. The broken lines are for Medium II with the parameters: two eigen frequencies are $\omega_{01} = 3.0 \omega_N$, and $\omega_{02} = 16.0 \omega_N$; two friction coefficients are $\Gamma_{01} = \Gamma_{02} = 2.0 \times 10^{-5} \omega_N$; the frequency $\omega_p = \sqrt{\omega_{p1}^2 + \omega_{p2}^2}$ is $30 \omega_N$, where $\omega_{p1}^2/\omega_p^2 = 0.2$ and $\omega_{p2}^2/\omega_p^2 = 0.8$. The normalized frequency ω_N is assumed 10^{14} /sec in the paper.

Fig. 2 Results of the electromagnetic pulse and soliton propagation for Case IA in the Medium I using the carrier frequency $\omega_{c0} = 8.61 \times 10^{14}$ /sec. The left and the right columns correspond to the normalized electric fields $eE_z/m\omega_N^2\Delta$ at $\omega_N t = 20$ and at $\omega_N t = 55$, respectively: $\delta_3 = 0.0$ for (a) and (b), $\delta_3 = -2.2 \times 10^6$ for (c) and (d).

Fig. 3 Wave frequency spectra of E_z measured at (a) $x \sim 0.28L$; (b) $\sim 0.43L$; (c) $\sim 0.58L$; (d) $\sim 0.73L$, for Case IA in the Medium I using the carrier frequency $\omega_{c0} = 8.61 \times 10^{14}$.

Fig. 4 Results of the soliton propagation. The electric fields is normalized by $eE_z/m\omega_N^2\Delta$: (a) at $\omega_N t = 41.25$; (b) at $\omega_N t = 108.75$, for

Case II in the Medium II using the carrier frequency $\omega_{c0} = 8.61 \times 10^{14}$.

Fig. 5 Results of the counter-propagating solitons for Case II in the Medium II using the carrier frequency $\omega_{c0} = 8.61 \times 10^{14}$: The electric fields is normalized by $eE_z/m\omega_N^2\Delta$: (a) at $\omega_N t = 41.25$; (b) at $\omega_N t = 67.50$; (c) at $\omega_N t = 71.25$; (d) at $\omega_N t = 116.25$.

Fig. 6 Results of the counter-propagating solitons for Case II in the Medium II using the carrier frequency $\omega_{c0} = 8.61 \times 10^{14}$. The electric fields is normalized by $eE_z/m\omega_N^2\Delta$: (a) at $\omega_N t = 71.25$; (b) at $\omega_N t = 108.75$.

Fig. 7 Results of the soliton propagation for the normal dispersion for Case IB in the Medium I using the carrier frequency $\omega_{c0} = 2.0 \times 10^{14}$. The electric fields is normalized by $eE_z/m\omega_N^2\Delta$: (a) at $\omega_N t = 30$; (b) at $\omega_N t = 90$.

Fig. 8 Wave frequency spectra of E_z measured at (a) $x \sim 0.28L$; (b) $\sim 0.73L$, for Case IB in the Medium I using the carrier frequency $\omega_{c0} = 2.0 \times 10^{14}$.

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