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COMPUTER SIMULATION ON THE LINEAR AND NONLINEAR PROPAGATION
OF THE ELECTROMAGNETIC WAVES IN THE DIELECTRIC MEDIA

BY

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Computer Simulation on the Linear and Nonlinear Propagation
of the Electromagnetic Waves in the Dielectric Media

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ABSTRACT

In this Letter, we first present a new computer simulation model developed to study the propagation of electromagnetic waves in a dielectric medium in the linear and nonlinear regimes. The model is constructed by combining a microscopic model used in the semi-classical approximation for the dielectric media and the particle model developed for the plasma simulations. The model was then used for studying linear and nonlinear wave propagation in the dielectric medium such as an optical fiber. It is shown that the model may be useful for studying nonlinear wave propagation and harmonics generation in the nonlinear dielectric media.

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Recently, soliton propagation¹ and harmonics generation² in the nonlinear dispersive solid-state media such as the glass have been studied extensively because of its importance in their applications to optical microelectronics and communication engineering.

In this Letter, we present a computer simulation model to study electromagnetic wave propagation in the nonlinear dispersive solid-state media. In order to solve Maxwell's equations for the fields and the equation of motion for particles numerically, we use the numerical techniques which have been developed in the particle simulation of plasmas, in which a spatial discrete grid is used to represent the fields and the force on a particle.^{3,4}

In order to model the wave propagation in a nonlinear dielectric medium, we use the semi-classical model to represent the electrical behaviors of the nonlinear dispersive solid-state media. The original Lorentz model for the dielectric media has been extended to include a nonlinearity arising from the intrinsic quantum effects.

Microscopically, the simplest dielectric material can be considered as an isotropic and locally uniform collection of a large number of electric dipoles with the eigen frequency ω_0 for the oscillating electric field. 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

$$\begin{aligned}\frac{d\mathbf{x}_{ej}}{dt} &= \mathbf{v}_{ej} , \\ \frac{d\mathbf{v}_{ej}}{dt} &= -\frac{e}{m} \left(\mathbf{E} + \mathbf{v}_{ej} \times \mathbf{B} \right) - \omega_0^2 (\mathbf{x}_{ej} - \mathbf{x}_{ej0}) - \Gamma_0 \mathbf{v}_{ej} \\ &\quad - \delta_2 \frac{\omega_0^3}{c} (\mathbf{x}_{ej} - \mathbf{x}_{ej0})^2 - \delta_3 \frac{\omega_0^4}{c^2} (\mathbf{x}_{ej} - \mathbf{x}_{ej0})^3 ,\end{aligned}\quad (1)$$

where $\mathbf{x}_{ej}$ and $\mathbf{v}_{ej}$ are the position and the velocity of the j -th electron, $\mathbf{x}_{ej0}$ is its equilibrium position, Γ_0 is the friction coefficient, δ_2 and δ_3 are numerical constants for the second and third order nonlinearity for the dielectric media.

The linear dispersion relation for the transverse electromagnetic waves ($\mathbf{k} \perp \mathbf{E}$) is given by

$$n^2 \equiv \left(\frac{ck}{\omega} \right)^2 = 1 + \frac{\omega_p^2}{\omega_0^2 - \omega^2 - i\omega\Gamma_0} , \quad (2)$$

where n is the refractive index of the dielectric media, c is the speed of light, and ω_p is the plasma frequency defined by $\omega_p = (n_0 e^2 / \epsilon_0 m)^{1/2}$. Here n_0 is the number density of the electric dipoles.

Equation (1) is finite-differenced using the leap-frog scheme and solved numerically together with Maxwell's equations self-consistently.^{3,4}

Two examples have been considered using the model: the first is the steady state wave propagation in a dielectric material placed in vacuum. The second is the transient state in which a short electromagnetic pulse or

a soliton propagates in the presence of cubic nonlinearity. While Eq. (1) is valid in three dimensions, only a one-dimensional model was considered for simplicity, in which all the electromagnetic fields vary with x only. The motion of the electrons, however, is followed in three directions.^{3,4}

In the simulations discussed in the following, the length of the one-dimensional system, L , is taken 1024 spatial grids, $L = 1024\Delta$, where Δ is the grid length. Δ is equal to $1/2.5$ of the skin depth c/ω_p . Electromagnetic waves are absorbed numerically at $x = 0$ and $x = L$ boundaries by means of ramp functions. The eigen frequency ω_0 was chosen to one half of the plasma frequency $\omega_0/\omega_p = 1/2$, and the friction Γ_0 was chosen zero for the examples given here. The total number of the dipoles in the system is 51,200. The speed of light c is $2.5\omega_p\Delta$. The normalized time step $\omega_p\Delta t$ is chosen to be 0.2.

In Fig. 1, results of the steady state wave propagation are shown, where an electromagnetic wave with its frequency of $\omega = 0.25\omega_p$ is excited in vacuum at $x = L/4$ by an oscillating current $J_z = J_0 e^{-i\omega t}$, where J_0 is the wave amplitude and is constant in time in this case. The linear dielectric media is located at between $x = 0.57L$ and $x = 0.75L$ ($\delta_2 = \delta_3 = 0$). In the dielectric region, the refractive index n is calculated to be 2.52 from Eq. (2) so that the wavelength becomes shorter as the wave propagates in the dielectric. The measured ratio of the wavelengths in vacuum and in the dielectric is about 2.45 which is close to this calculated value.

Shown in Fig. 2 are the results of the transient wave propagation. The pulse is excited at $x = L/4$ by a current $J_z = J_0 \operatorname{sech}[(t - t_0)/\delta t] e^{-i\omega t}$ where $t_0 = 80 \omega_p^{-1}$, $\delta t = 16 \omega_p^{-1}$, and $\omega = 0.25\omega_p$. In this case the dielectric medium is assumed to have a cubic nonlinearity so that $\delta_2 = 0$ and $\delta_3 \neq 0$.

Shown in Figs. 2(a) and (b) is the pulse propagation in the linear dispersive media ($\delta_3 = 0$), 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 effects can prevent the pulse from spreading and lead to formation of solitons.¹ Shown in Fig. 2(c) and (d) are the simulation results with $\delta_3 = 1.0$, where formation of the envelope soliton due to the high-frequency Kerr effect is clearly observed. With even a larger nonlinearity, $\delta_3 = 4.0$, we found generation of a modulational instability^{5,6} as shown in Figs. 2(e) and (f) in which the envelope is distorted progressively in time. In Figs. 2(g) and (h), the wave spectra measured at $x = 717\Delta$ are shown for $\delta_3 = 1.0$ and $\delta_3 = 4.0$, respectively. It is clearly seen in Fig. 2(h) that the double peaks corresponding to the modulational instability are accompanied by the smaller side bands.

We have also simulated a case with a negative $\delta_3 = -0.6$. As shown in Figs. 2(i) and (j), we found in this case broadening of the pulse envelope and formation of a bump at the tail part of the pulse.

We have also simulated a collision between two counter-propagating

solitons for $\delta_2 = 0.0$ and $\delta_3 = 1.0$. Although the detail of this result is not shown here, we observed that after the collision the pulses separate and move away without distorting their general shapes which is a well-known characteristic of colliding solitons.

We have developed a computer simulation model for the nonlinear dielectric media by using particle simulation techniques developed for plasma simulations. Both linear and nonlinear wave propagations have been studied and the results are found to be in good agreement with earlier works verifying the validity of the model. While the model for the nonlinear 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 an accuracy of the model for the 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. While we considered wave propagation in a dielectric medium, models for electromagnetic propagation in a metal or in a semi-conductor can be constructed by adopting the Drude model or the free carrier model for the conducting current. Results from these models will be reported in the future.

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FIGURE CAPTIONS

Fig. 1 Results of the simulation for the steady-state electromagnetic wave propagation in vacuum and in the dielectric located at $0.57L < x < 0.75L$.

Fig. 2 Results of the electromagnetic pulse and soliton propagation. The left and the right columns correspond to the normalized electric fields $eE_z/m_e\omega_p^2\Delta$ at $\omega_pt = 200$ and at $\omega_pt = 500$, respectively: $\delta_3 = 0.0$ for (a) and (b), $\delta_3 = 1.0$ for (c) and (d), and $\delta_3 = 4.0$ for (e) and (f). Figs. 2(g) and (h) represent the power spectra measured at $x = 717\Delta$ for $\delta_3 = 1.0$ (g) and for $\delta_3 = 4.0$ (h). Figs. 2(i) and (j) show the normalized electric fields for $\delta_3 = -0.6$.

FIG. 1

FIG. 2

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