Possibility of scanning of the frequency of a light-pulse field

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Scanning of the field frequency of an intense light pulse propagating in an optical waveguide is predicted and analyzed.

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The presently existing pulsed lasers produce, at pulse durations $\tau_p < 10^{-7}$ sec, radiation with a frequency that is fixed during a individual generation pulse. At the same time, an effective solution of a number of problems in modern physics (such as selected excitation of a specified vibrational level of a gas molecule and the associated photodissociation of the molecule, the change of the rate of a chemical reaction, isotope separation, and others) can be obtained (see[1]) by applying to the substance sufficiently short pulses in which the instantaneous generation frequency varies continuously in a sufficiently wide range during the time of the individual pulse. This paper proposes a method for such a variation (scanning) of the light frequency. This method is based on the passage of a light pulse with initially fixed field frequency through an optical waveguide (fiber), the material of which has a noticeable dependence of the refractive index on the light intensity.

It is known that for a medium linear in the field the complex amplitudes of the natural waves of an optical waveguide are written in the form (see, e.g.[2,3])

$$\mathbf{E}_m = \mathbf{g}_m(\mathbf{r}_\perp)\, e^{ik_m z}, \qquad k_m = \frac{\omega}{c} n_{m\,\mathrm{eff}} \tag{1}$$

where z and $\mathbf{r}_\perp$ are the longitudinal and transverse coordinates, respectively, and ω is the frequency of the propagating wave. For simplicity, we shall neglect henceforth the weak frequency dependence of the quantity[1)] $n_{m\,\mathrm{eff}}$ and assume also that only one mode is excited in the waveguide (say the fundamental wave), so that the subscript m takes on one value and can therefore be omitted, putting $\mathbf{E} = F(z, t)\mathbf{g}(\mathbf{r}_\perp)e^{ikz}$.

We now take into account the dependence of the refractive index n of the fiber material, including the peripheral sheath, on the radiation intensity (i.e., on $|E|^2$):

$$n = n_0\left(1 + \frac{1}{2} n_2 |E|^2\right) \quad (2)$$

and assume that $|E|^2$ is not too large, so that the following condition[2)] is satisfied for all $\mathbf{r}_\perp$, z, and t:

$$\Delta n_{nl} << \Delta n_0, \quad (3)$$

where $\Delta n_{nl} = \frac{1}{2} n_0 n_2 |E|^2$ and Δn_0 is the difference between the refractive indices at the center of the fiber and on its periphery (usually $\Delta n_0 \sim 10^{-2}$). Under the condition (3), the transverse function $\mathbf{g}(\mathbf{r}_\perp)$ of a wave of this type is practically independent of $|F|^2$. An important role is played by the now appearing dependence of n_{eff} on $|F|^2$. Taking (3) into account, we have

$$n_{\text{eff}} = n^{(0)}_{\text{eff}}\left(1 + \frac{1}{2} n^{(2)}_{\text{eff}} |F|^2\right), \quad (4)$$

where the coefficient $n^{(2)}_{eff}$ is determined by the value of $n_0 n_2(\mathbf{r}_\perp)$ and by the concrete character of the function $\mathbf{g}(\mathbf{r}_\perp)$ (in the typical case $\Lambda_\perp \gg \lambda$, where $\Lambda_\perp$ is the scale of localization of the function $\mathbf{g}(\mathbf{r}_\perp)$, normalized to $\Lambda_\perp^2$, and λ is the length of the light wave, we have $n^{(2)}_{eff} \sim n_2$). Taking (4) into account, we can obtain the following approximate expression for the amplitude $F(z, t)$:

$$2ik_0\left(\frac{\partial F}{\partial z} + \frac{1}{v_0}\frac{\partial F}{\partial t}\right) + k_0^2 n^{(2)}_{\text{eff}} |F|^2 F = 0, \quad (5)$$

where $k_0 = (\omega/c) n^{(0)}_{eff}$ and $v_0 = c/n^{(0)}_{eff}$. The general solution of Eq. (5) takes the form

$$F(z, t) = F_0\left(t - \frac{z}{v_0}\right) \exp\left[\frac{i}{2} k_0 z n^{(2)}_{\text{eff}} \left|F_0\left(t - \frac{z}{v_0}\right)\right|^2\right], \quad (6)$$

where $F_0(\theta)$ is an arbitrary given function. It is seen from (6) that if the initial light pulse (at $z = 0$) has a fixed carrier frequency ω, then in the section $z > 0$ the instantaneous field frequency $\Omega(t) = \omega + \Delta\Omega(t)$ depends on the time:

$$\Delta\Omega(t) = -\frac{1}{2} k_0 z n^{(2)}_{\text{eff}} \frac{\partial}{\partial t} \left|F_0\left(t - \frac{z}{v_0}\right)\right|^2 \quad (7)$$

and varies in the interval

$$\Delta\Omega_{\text{tot}} \sim \frac{1}{\tau_p} k_0 z n^{(2)}_{\text{eff}} |F_0|^2_{max}, \quad (8)$$

where τ_p is the duration of the incident pulse.

We present a numerical example. Assume $\lambda = 0.5 \times 10^{-4}$ cm, $z = 10^5$ cm (see[3]), $n^{(2)}_{eff} = 10^{-13}$ cgs esu, and $|F_0|^2_{max} = 10^9$ cgs esu (which corresponds at a typical value $\Lambda_\perp 5 \times 10^{-4}$ cm to a peak pulse power $P \sim 3 \times 10^4$ W). In this case we obtain from (8) $\Delta\Omega_{tot} \sim 10^6/\tau_p$, which in turn means frequency scanning in a wide range.[3)] For example, at $\tau_p = 10^{-8}$ sec we have $\Delta\Omega_{tot} \sim 10^{14}$ rad/sec.

We note in conclusion that the considered effect of scanning the frequency of light pulses in optical waveguide can exert an appreciable influence on various nonlinear phenomena in such waveguides, such as stimulated scattering, harmonic generation, etc.

[1)]In general, $n_{meff}(\omega)$ is determined by the optical dispersion of the refractive index $n(\omega)$ of the medium and by the function $\mathbf{g}_m(\mathbf{r}_\perp)$, and is usually weak. For a number of $n(\mathbf{r}_\perp)$ profiles realized by now, these factors cancel each other, so that n_{meff} is practically independent of ω with even greater accuracy.[3]

[2)]This condition means that the power of the considered light beam is much lower than the critical power at which a multifocus structure is produced in it.

[3)]We note that the considered frequency scanning differs in principle from phase modulation of the field of a light beam (see, e.g.,[4]) in a homogeneous nonlinear medium in that in the case of scanning in a waveguide the instantaneous frequency does not depend on the transverse coordinate $\mathbf{r}_\perp$, and the entire process is not subject to the diffraction limit $z < k\Lambda^2$. Similar limits in the case of phase modulation of the field in a homogeneous nonlinear medium do not make it possible to obtain frequency scanning in a pulse, since only values $\Delta\Omega_{tot} \lesssim 1/\tau_p$ can be attained with such modulation.

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