New type of optical parametric generator and amplifier

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A linearly-optical analog of the inverse Cerenkov effect is predicted. A parametric generator (amplifier) of light, based on this effect, is proposed and considered.

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Parametric generators (amplifiers) of light have been previously proposed by Akhmanov and Khokhlov[1] and by Kroll.[2] In these generators, the pump wave (with frequency ω_p and wave vector k_p) is converted into waves with new frequencies $\omega_{1,2}$ (and corresponding wave vectors $\mathbf{k}_{1,2}$), satisfying the conditions:

$$\omega_p = \omega_1 + \omega_2, \tag{1a}$$

$$\mathbf{k}_p = \mathbf{k}_1 + \mathbf{k}_2. \tag{1b}$$

In view of the dispersion of the refractive index of the medium, the wave spatial synchronism conditions (1b) is satisfied by using anisotropic crystals, in which different types of waves can interact, or else by using for this purpose multimode optical waveguides (see the review[3]). However, the precision requirement imposed on the waveguide by condition (1b) turn out to be so stringent, that the corresponding waveguide parametric generators and amplifiers have not yet been realized.[3]

We propose here an optical parametric generator (amplifier) of a new type, for which requirement (1b) is waived. We consider a single-mode optical waveguide with mirrors covering its end faces. We assume also that the substrate (shell) or material of the waveguide itself has an appreciable nonlinear susceptibility tensor $\hat{\chi}^{(2)}$. Assume further than a plane monochromatic pump wave is incident on this waveguide at a certain angle θ to its axis. This waveguide, bounded by the mirrors, is an optical resonator with a set of axial modes, and we consider two of these modes with natural frequencies $\bar{\omega}_{1,2}$ and satisfying the relation:

$$\omega_p \approx \bar{\omega}_1 + \bar{\omega}_2 \quad , \tag{2}$$

($\bar{\omega}_r = \pi c m_r / L n_{eff}(\bar{\omega}_r)$, m_r is an integer, L is the distance between the mirrors, and $n_{eff}(\omega)$ is the effective refractive index for the considered waveguide wave). Neglecting the reaction of the mode fields on the pump field, we obtain in analogy with[4,5] (where the interaction of axial modes is considered for stimulated Raman emission in an optical resonator) the following system of equations, which determines the complex amplitude $Y_{1,2}\exp(-i\Delta\omega t/2)$ of the field of these modes:

$$\dot{Y}_1 = -[\mu_1 - i(\Delta\omega/2)]Y_1 + (i\bar{\omega}_1 a/2N_1)Y_2^* + iF_1, \quad (3)$$

$$\dot{Y}_2^* = -[\mu_2 + i(\Delta\omega/2)]Y_2^* - (i\bar{\omega}_2 a^*/2N_2)Y_1 - iF_2.$$

Here

$$a = \int \mathbf{E}_1 \hat{\chi}^{(2)}(\bar{\omega}_1)\mathbf{E}_p\mathbf{E}_2 d\mathbf{r}, \quad (4)$$

$$\Delta\omega = \omega_p - \bar{\omega}_1 - \bar{\omega}_2, \quad N_\tau = (1/4\pi)\int \epsilon \mathbf{E}_\tau^2 \, d\mathbf{r}$$

μ_τ are the frequency half-widths of the considered mode of the passive resonator, the values of $F_{1,2}$ are determined by extraneous sources having frequencies $\bar{\omega}_{1,2}\mathbf{E}_\tau = \mathbf{g}_\tau(\mathbf{r}_\perp)\sin k_\tau z$ are the fields of the modes ($k_\tau = \pi m_\tau/L$, $\tau = 1, 2$), ϵ is the linear part of the dielectric constant of the medium, $\mathbf{E}_p = \mathbf{E}_0 \times \exp(ik_p x \sin\theta + ik_p z\cos\theta)$ is the complex amplitude of the pump field, and z is the waveguide axis. Equations (3) constitute a linear system whose characteristic polynomial is

$$\lambda^2 + \lambda(\mu_1 + \mu_2) + \left(\mu_1 - \frac{i\Delta\omega}{2}\right)\left(\mu_2 + \frac{i\Delta\omega}{2}\right) - \frac{\bar{\omega}_1\bar{\omega}_2}{4N_1N_2}|a|^2 \quad (5)$$

It is seen from (5) that, for example, at $\Delta\omega = 0$, the condition for self-excitation of optical oscillations at the frequencies $\bar{\omega}_{1,2}$ (at $F_{1,2} = 0$) takes the form

$$\frac{|a|^2}{4N_1N_2} \geqslant \frac{\mu_1\mu_2}{\bar{\omega}_1\bar{\omega}_2} \quad (6)$$

(it can also be verified, at $F_{1,2} \neq 0$, that when underexcited the system under consideration is an optical amplifier). Thus, self-excitation is possible if $|\alpha|$ is appreciable.[1)] It is seen from (4) that this takes place only under the conditions

$$k_1 \approx k_2 + k_p\cos\theta, \quad (7)$$

$$\lambda_p/2\sin\theta \gtrsim \Lambda_x, \quad (8)$$

where $\lambda_p = 2\pi/k_p$ and Λ_x is the scale of variation of the functions g_τ along x (we assume for the sake of argument $k_1 \geqslant k_2$). In this case $|\alpha|^2/4N_1N_2 \sim |\hat{\chi}^{(2)}|^2|\mathbf{E}_0|^2$. For example, at $|\hat{\chi}^{(2)}| \sim 3\times10^{-8}$ cgs esu, $L \sim 1$ cm, $\bar{\omega}_{1,2} \sim 3\times10^{15}$ rad/sec, and a mirror reflection coefficient $r \sim 0.9$ we obtain the threshold value of the pump field $|E_0|^2_{\text{thr}} \sim 10^3$ cgs esu.

Thus, in contrast to the requirement (1b), it is necessary to satisfy in the proposed generator the conditions (7) and (8), which impose no stringent limitations whatever on the dispersion of the effective refractive index and which does not require participation of different waveguide modes. They can be satisfied in the considered-case of a single-mode waveguide.[2)] The condition (7) determines the angle of incidence of the pump wave when the generation frequencies ($\bar{\omega}_{1,2}$) are given. By varying this angle, it is possible to tune the generated frequencies. We note that the results remain in force also for the case when the pump wave is reflected from the surface of the waveguide or the substrate.

We point out also that if two waves traveling in opposite directions and with frequencies $\omega_{1,2}$ were to be excited in the considered waveguide, then the condition (7) would determine the direction of the Cerenkov radiation of the nonlinear-polarization excited by the traveling waves at the frequency $\omega_1+\omega_2$ (the possibility of a similar nonlinear-optics analog of Cerenkov radiation for certain types of parametric interactions has been predicted in[6]; nonlinear-optic Cerenkov radiation of second harmonics was observed recently in a number of experiments[3]). Under the conditions considered by us, the inverse effect is produced (the nonlinear-optics analog of the inverse Cerenkov effect), wherein, under condition (7), a wave at frequency $\omega_1+\omega_2$ serves as a pump for waveguide waves at frequencies $\omega_{1,2}$.

1)The degenerate case $\bar{\omega}_1=\bar{\omega}_2$ is also included in consideration here. In this case the subscripts 1 and 2 pertain to one and the same axial mode of the resonator.

2)Of course, the generator and amplifier in question can be realized also in the case of a multimode waveguide and also if the material of this waveguide or of it substrate (envelope) is anisotropic, when waves of different types can interact. In this case the condition (7) can be written in the more general form $k_1\approx\pm k_2+k_p\cos\theta$.

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