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Generation of higher optical harmonics in focused beams

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An analysis is made of the influence of focusing on third, fourth, and fifth harmonic generation allowing for both direct and cascade processes taking place due to lower-order nonlinearities. It is found that as the focusing parameter increases under conditions of optimized wave mismatch, the fourth and fifth harmonic powers increase monotonically. It is also shown that in the case of phase-matched cascade processes, the harmonic power is highest for focusing on one of the faces rather than at the center of the nonlinear medium.

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In excitation of optical harmonics or other nonlinear parametric processes, an important part is played by the principle of optimal focusing of the waves in the nonlinear medium (crystal, liquid, or gas) in order to maximize the efficiency of the process. The influence of focusing on the power of the second optical harmonic excited by a Gaussian pump beam was analyzed in detail in Refs. 1–4. Calculations were made of the optimal focusing parameter $m = L/b$ (L is the length of the nonlinear medium, b is the confocal parameter) for which the harmonic energy is highest. Analyses have also been made of the dependence of the third harmonic power[5,6] and of nondegenerate four-wave parametric processes of the type $\omega = \omega_1 + \omega_2 + \omega_3$ (Ref. 7) on the focusing conditions.

Higher-order optical harmonics, fourth,[8] fifth,[9,10] and seventh,[11,12] have recently been obtained. These harmonics were obtained both under conditions of phase matching for the direct process, i.e., the process taking place due to a nonlinearity of the same order as the harmonic and under phase-matching conditions for the cascade processes taking place due to lower-order nonlinearities. It was confirmed experimentally that the harmonic generation efficiencies are similar in both cases. Some aspects of optimal focusing in fifth harmonic generation were analyzed in Refs. 13 and 14.

In optimal harmonic generation in crystals it is necessary to allow for the influence of birefringence on the conversion efficiency. The optimal focusing parameter allowing for birefringence was obtained for the second harmonic in Refs. 3 and 6 and for the third harmonic in Ref. 15.

The present paper analyzes the influence of focusing on third, fourth, and fifth harmonic generation, allowing for cascade processes taking place due to lower-order nonlinearities. Generation of higher harmonics is analyzed both with and without birefringence.

1. BASIC EQUATIONS

We shall describe generation of higher harmonics (third, fourth, and fifth) in focused Gaussian beams under conditions of tangential phase matching in a noncentrosymmetric medium using parabolic equations for the amplitudes, neglecting the influence of higher harmonics on the lower harmonics and allowing for cascade processes

$$\begin{aligned}
&\frac{\partial A_2}{\partial z} + \frac{i}{2k_2}\Delta_\perp A_2 = -i\sigma_2 A_1^2 e^{i\Delta_2 z},\\
&\frac{\partial A_3}{\partial z} + \frac{i}{2k_3}\Delta_\perp A_3 = -i\sigma_3 A_1^3 e^{i\Delta_3 z} - i\sigma_{11} A_1 A_2 e^{i\Delta_{11} z},\\
&\frac{\partial A_4}{\partial z} + \frac{i}{2k_4}\Delta_\perp A_4 = -i\sigma_4 A_1^4 e^{i\Delta_4 z} - i\sigma_{21} A_1^2 A_2 e^{i\Delta_{21} z} - i\sigma_{101} A_1 A_3 e^{i\Delta_{101} z}\\
&\qquad - i\sigma_{02} A_2^2 e^{i\Delta_{02} z},\\
&\frac{\partial A_5}{\partial z} + \frac{i}{2k_5}\Delta_\perp A_5 = -i\sigma_5 A_1^5 e^{i\Delta_5 z} - i\sigma_{31} A_1^3 A_2 e^{i\Delta_{31} z} - i\sigma_{201} A_1^2 A_3 e^{i\Delta_{201} z}\\
&\qquad - i\sigma_{1001} A_1 A_4 e^{i\Delta_{1001} z} - i\sigma_{12} A_1 A_2^2 e^{i\Delta_{12} z} - i\sigma_{011} A_2 A_3 e^{i\Delta_{011} z}
\end{aligned} \tag{1}$$

with the boundary conditions $A_n(x, y, 0) = 0$, $n = 2, 3, \ldots$, and the pump wave

$$A_1(x, y, z) = \frac{A_0}{a(1 - i\eta)} \exp\left\{-\frac{x^2 + y^2}{a^2(1 - i\eta)}\right\}. \tag{2}$$

Here, A_n are the wave amplitudes; z is the direction of propagation of the beams; $\Delta_\perp = \partial^2/\partial x^2 + \partial^2/\partial y^2$ is the transverse Laplacian; $\Delta_n = k_n - nk_1$, $\Delta_{pq} = k_{p+2q} - pk_1 - qk_2$, $\Delta_{pqr} = k_{p+2q+3r} - pk_1 - qk_2 - rk_3$, and $\Delta_{1001} = k_5 - k_1 - k_4$ are the wave mismatches of the direct and cascade processes; σ are the nonlinear coupling coefficients (the indices denote the nonlinear process, for example, σ_{pqr} refers to the process $p\omega_1 + q\omega_2 + r\omega_3$); a is the radius of a Gaussian beam; $b = k_1 a^2$ is the confocal parameter; $\eta = 2(z - z_0)/b$; z_0 is the coordinate of the center of the constriction.

We shall solve system (1) with its boundary conditions using Green's functions and we shall then convert to the total harmonic power $P_n = c/8\pi \int_{-\infty}^{\infty}\int_{\infty} A_n^* A_n dxdy$.

An analysis of the final expressions for P_n showed that the dependences of the fourth and fifth harmonic powers on the focusing parameters are approximately the same, so that we shall subsequently everywhere omit expressions for the fourth harmonic.

We shall introduce the notation:

$$\left.\begin{aligned}
h_n(\alpha, \Delta) &= \int_{-m(1+2l)}^{\alpha} \frac{\exp\left\{i\frac{b\Delta}{2}\eta\right\}}{(1-i\eta)^{n-1}} d\eta, \\
H_n &= i\sigma_n h_n[m(1-2l), \Delta_n]; \\
H_{pq} &= \sigma_{pq}\sigma_2^q b \int_{-m(1+2l)}^{m(1-2l)} \frac{\exp\left\{\frac{ib\Delta_{pq}}{2}\eta\right\}}{(1-i\eta)^p} h_2^q(\eta, \Delta_2)\, d\eta, \\
H_{pqr} &= -i\sigma_{pqr}\sigma_2^q\sigma_3^r b^2 \int_{-m(1+2l)}^{m(1-2l)} \frac{\exp\left\{\frac{ib\Delta_{pqr}}{2}\eta\right\}}{(1-i\eta)^{p+1}} h_2^q(\eta, \Delta_2)\, h_3^r(\eta, \Delta_3)\, d\eta, \\
H_{1001} &= \sigma_{1001}\sigma_4 b \int_{-m(1+2l)}^{m(1-2l)} \frac{\exp\left\{\frac{ib\Delta_{1001}}{2}\eta\right\}}{1-i\eta} h_4(\eta, \Delta_4)\, d\eta,
\end{aligned}\right\} \quad (3)$$

where $l = (2z_0 - L)/L$ is a prameter characterizing the position of the constriction of the pump beam in the nonlinear medium.

In this notation the expressions for the harmonic powers take the form

$$\left.\begin{aligned}
P_2 = c_2 b |H_2|^2, \quad P_3 = c_3 |H_3 + H_{11}|^2, \\
P_5 = c_5 b^{-2} |H_5 + H_{31} + H_{201} + H_{1001} + H_{12} + H_{011}|^2,
\end{aligned}\right\} \quad (4)$$

where c_n are coefficients independent of the focusing parameters. For centrosymmetric medium the expressions for the harmonic power are simplified since $\sigma_2 = \sigma_{11} = \sigma_{11} = \sigma_4 = \sigma_{101} = \sigma_{02} = \sigma_{31} = \sigma_{1001} = \sigma_{011} = 0$ and thus the amplitudes of even harmonics are zero.

The harmonic power increases with z when any of the wave mismatches in system (3) is small. For example, in third harmonic generation in a noncentrosymmetric medium for $\Delta = k_3 - 3k_1 \approx 0$, we have phase matching for the direct process whereas for $\Delta = k_2 - 2k_1 \approx 0$ or $\Delta = k_3 - k_2 - k_1 \approx 0$, we have phase matching for the cascade processes.[16]

We shall subsequently assume that if one of the mismatches Δ' is small ($|\Delta'| \sim 1/b$), the other mismatches are fairly large ($|\Delta| \gg 1/b$). System (3) consists of integrals of the type $\int_\alpha^\beta f(\eta)\exp(ib\Delta/2\eta)d\eta$. We shall find an expression for this integral for large $|\Delta|$. Successively integrating by parts and neglecting all terms of order $(b\Delta)^{-2}$, $(b\Delta)^{-3}$, and so on, we obtain

$$\int_\alpha^\beta f(\eta)\exp\left(\frac{ib\Delta}{2}\eta\right)d\eta \approx \frac{2}{ib\Delta} f(\eta)\exp\left(\frac{ib\Delta}{2}\eta\right)\Big|_\alpha^\beta. \quad (5)$$

2. PHASE MATCHING FOR THE DIRECT PROCESS

In this case, we have $|\Delta_n| = |k_n - nk_1| \approx 1/b$, and $a|\Delta_{pq}| \gg 1/b$, $|\Delta_{pqr}| \gg 1/b$. Transforming system (4), allowing for Eq. (5), and using the explicit relationships $\Delta_{p1} + \Delta_2 = \Delta_{p+2}$, $\Delta_{p01} + \Delta_3 = \Delta_{p+3}$, $\Delta_{1001} + \Delta_4 = \Delta_5$, $\Delta_{p2} + 2\Delta_2 = \Delta_{p+4}$, and $\Delta_{011} + \Delta_2 + \Delta_3 = \Delta_5$, we obtain

$$P_n = c_n b^{3-n} \sigma_{n\,\mathrm{eff}}^2 |h_n[m(1-2l), \Delta_n]|^2, \quad (6)$$

where $\sigma_{3\,\mathrm{eff}} = \sigma_3 + \sigma_{11}\sigma_2/\Delta_2$; $\sigma_{5\,\mathrm{eff}} = \sigma_5 + \sigma_{31}\sigma_2/\Delta_2 + \sigma_{201}\sigma_3/\Delta_3 + \sigma_{1001}\sigma_4/\Delta_4 + \sigma_2\sigma_{11}\sigma_{011}/\Delta_2\Delta_{11} + \sigma_2^2\sigma_{12}/\Delta_2^2$.

Thus, in the case of phase matching for the direct process, both the direct and cascade processes make contributions to the phase-matched increase in the harmonic, these contributions having exactly the same dependence on the focusing parameter m, position of the center of the constriction in the nonlinear medium, and wave mismatch Δ_n.

We shall analyze the dependence of the harmonic power on the focusing parameter for some typical cases. Figure 1 shows dependences of the second, third, and fifth harmonic powers on m for $\Delta_n = 0$ and focusing at the center of the nonlinear medium ($l = 0$). The integral in Eq. (6) between plus and minus infinity for $n \geq 3$ is zero, so that the powers of all the higher harmonics tend to zero. This is attributed to an additional phase shift of the pump and harmonic fields described by the factor $\exp\{-i\arctan[2(z - z_0)/b]\}$. As a result, the harmonic field generated by the region situated ahead of the constriction plane ($z < z_0$), is completely compensated by the harmonic field generated by the region situated beyond the constriction plane ($z > z_0$). We note that the second harmonic power for $m \to \infty$ also tends to zero[1] which is not due to the behavior of the integral in Eq. (6) but to the presence of the factor b in front of the integral. In the case of focusing at the boundary of the nonlinear

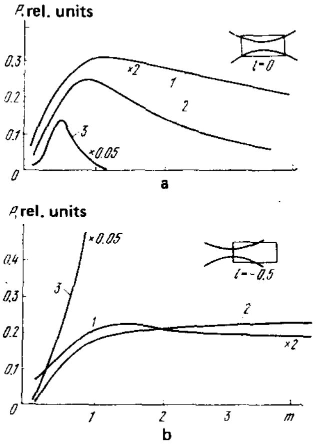

FIG. 1. Dependences of the harmonic power on the degree of focusing under conditions of exact phase matching for the direct process ($\Delta_n = 0$) with focusing at the center of the nonlinear medium (a) and at the front face (b) for the second (1), third (2), and fifth (3) harmonics.

medium, no such compensation is found and the character of the dependence changes: the third harmonic power reaches saturation and the fourth and fifth harmonic powers increase monotonically (Fig. 1b). Under these conditions, the second harmonic power tends to zero. This behavior of the harmonic powers is associated with the factor b^{3-n} in Eq. (6) and also with the fact that the integral in Eq. (6) between semiinfinite limits has a certain finite value, regardless of the number of the harmonic.

An additional diffraction phase shift of the pump and harmonic fields during focusing has the result that the wave mismatch $\Delta = 0$ is not generally optimal and in order to maximize the harmonic power, Δ must be optimized.

By replacing the limits of integration in Eq. (6) by infinite limits, an expression was obtained in Ref. 5 for the harmonic power in the case of strong focusing ($m \gg 1$) at the center of a nonlinear medium

$$P_n = \begin{cases} c_n \sigma_{n\,\mathrm{eff}}^2 b^{3-n} \exp(b\Delta_n)(b\Delta_n)^{2(n-2)}, & \Delta_n < 0, \\ 0, & \Delta_n \geq 0. \end{cases} \quad (7)$$

From this we can obtain the optimal mismatch: $\Delta_n^{\mathrm{opt}} = -2(n-2)/b$. Substituting this expression into Eq. (7), we obtain the dependence of the harmonic power on the degree of focusing for optimized Δ in the strong focusing approximation

$$P_n(\Delta_n = \Delta_n^{\mathrm{opt}}) \sim b^{3-n}. \quad (8)$$

In the case of weak focusing, Eq. (6) is reduced to give

$$P_n = c_n \sigma_{n\,\mathrm{eff}}^2 b^{3-n} \left| \int\limits_{-m(1+2l)}^{m(1-2l)} \frac{\exp\left\{\frac{ib\Delta_n}{2}\xi + i(n-1)\xi\right\}}{(1+\xi^2)^{\frac{n-1}{2}}} d\xi \right|^2 .$$

We then have $\Delta_n^{\mathrm{opt}} = -2(n-1)/b$ and the harmonic powers in the weak focusing approximation depend on the focusing parameters as follows:

$$\begin{aligned} P_2(\Delta_2 = \Delta_2^{\mathrm{opt}}) &\sim b \ln^2 \left[\frac{2m(l+1/2) + \sqrt{1+4m^2(l+1/2)^2}}{2m(l-1/2) + \sqrt{1+4m^2(l-1/2)^2}} \right], \\ P_3(\Delta_3 = \Delta_3^{\mathrm{opt}}) &\sim \{\operatorname{arctg}[2m(l+1/2)] - \operatorname{arctg}[2m(l-1/2)]\}^2, \\ P_5(\Delta_5 = \Delta_5^{\mathrm{opt}}) &\sim \frac{1}{b^2}\left\{ \frac{2m(1-4m^2l^2+m^2)}{[1+4m^2(l+1/2)^2][1+4m^2(l-1/2)^2]} + \operatorname{arctg}[2m(l+1/2)] \right. \\ &\quad \left. - \operatorname{arctg}[2m(l-1/2)] \right\}^2. \end{aligned} \quad (9)$$

Figure 2 shows dependences of the third and fifth harmonic powers on m in the case of focusing at the center of a nonlinear medium with optimized Δ. The continuous curve gives the results of calculations of the power in the weak focusing approximation (9), the dashed curves gives the results for the strong focusing approximation (8), and the circles give the results of direct calculations of the integral (6) by numerical techniques. It can be seen that the approximations fairly accurately describe the dependence of the power on the focusing and the character of these dependences is the same as those for focusing at the boundary of a nonlinear medium for $\Delta_n = 0$.

The power of the higher harmonics generated with optimized Δ is highest when the focal constriction is situated at the center of the nonlinear medium ($l = 0$) and decreases as the focus is shifted toward the boundary.

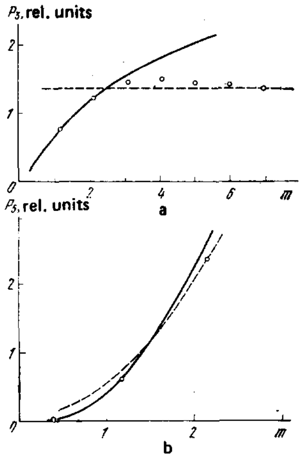

FIG. 2. Dependences of the harmonic power on the degree of focusing with optimized wave mismatch for direct processes ($\Delta_n = \Delta_n^{\mathrm{opt}}$ with focusing at the center of the nonlinear medium ($l = 0$) for the third (a) and fifth (b) harmonics; the continuous curves correspond to the weak focusing approximation; the dashed curves correspond to the strong focusing approximation; the circles give the results of direct calculations of the integral (6).

3. PHASE MATCHING FOR CASCADE PROCESSES

In this case, the wave mismatch for any stage of the cascade process is small and the other mismatches are large. Using Eq. (5), we can obtain from system (4) an expression for the harmonic power. For example, for third harmonic generation processes in a noncentrosymmetric medium we have

$$\left.\begin{aligned} P_3(\Delta_2 \approx 0) &= c_3 \frac{\sigma_2^2 \sigma_{11}^2}{\Delta_{11}^2 [1 + m^2(1-2l)^2]} |h_2[m(1-2l), \Delta_2]|^2, \\ P_3(\Delta_{11} \approx 0) &= c_3 \frac{\sigma_2^2 \sigma_{11}^2}{\Delta_2^2 [1 + m^2(1+2l)^2]} |h_2[m(1-2l), \Delta_{11}]|^2. \end{aligned}\right\} \quad (10)$$

For a cascade process in a centrosymmetric medium we have

$$\left.\begin{aligned} P_5(\Delta_3 \approx 0) &= c_5 \frac{\sigma_3^2 \sigma_{201}^2}{\Delta_{201}^2 [1 + m^2(1-2l)^2]^2} |h_3[m(1-2l), \Delta_3]|^2 \\ P_5(\Delta_{201} \approx 0) &= c_5 \frac{\sigma_3^2 \sigma_{201}^2}{\Delta_3^2 [1 + m^2(1+2l)^2]^2} |h_3[m(1-2l), \Delta_{201}]|^2. \end{aligned}\right\} \quad (11)$$

Figure 3 shows dependences of the third harmonic power on the parameter l in a noncentrosymmetric medium for two cases of phase matching: $\Delta_2 \approx 0$, $\Delta_{11} \approx 0$ (Δ is optimized for each value of l). It can be seen

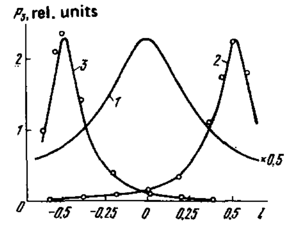

FIG. 3. Dependences of the third harmonic power on the position of the focus with optimized wave mismatches for the direct process (1, $\Delta_n = \Delta_n^{\mathrm{opt}}$), the second harmonic generation process (2, $\Delta_2 = \Delta_2^{\mathrm{opt}}$), and the synchronous summation process (3, $\Delta_{11} = \Delta_{11}^{\mathrm{opt}}$). The degree of focusing is $m = 5.4$ and the circles give the experimental results.

that the harmonic power does not reach a maximum for focusing at the center of the nonlinear medium, as in the case of phase matching for the direct process, but for focusing at the boundary, this being for $\Delta_{11} \approx 0$ at the front face and $\Delta_2 \approx 0$ at the rear face.

These dependences may be given the following physical interpretation. The phase matching $\Delta_{11} = k_3 - k_2 - k_{11} \approx 0$ may be considered to be synchronous mixing of a "free" second harmonic wave and a pump wave. The amplitude of the free second harmonic wave is governed by the amplitude of the pump wave at the front face of the nonlinear medium. In the case of fairly strong focusing on the rear face, the amplitude of the pump wave on the front face is small and thus the amplitudes of the free second harmonic wave and of the cascade third harmonic are also small.

In the case of $\Delta_2 = k_2 - 2k_1 \approx 0$ phase matching, nonsynchronous summation of the synchronous second harmonic and pump wave takes place, described by a relationship such as Eq. (5). In accordance with Eq. (5), the third harmonic power is governed by the difference between the products of the amplitudes of the pump and second harmonic waves at the entrance and exit faces of the nonlinear medium, respectively. One of these products is invariably zero since the second harmonic amplitude at the entrance face is zero. Thus, third harmonic generation is more efficient in the case of fairly strong focusing on the rear face.

These relationships were confirmed by experimental measurements of the dependence on the position of the focus for the power of the third harmonic excited in a KDP crystal in the phase-matching direction for cascade processes by pumping with the zeroth radiation mode of a Q-switched YAG:Nd^{3+} laser (Fig. 3). The KDP crystal was 4 cm long, the focal length of the lens was 8.3 cm, and the length of the focal constriction was 0.76 cm. For each position of the focus relative to the crystal, optimization of the wave mismatch was achieved by slightly rotating the crystal.

It should be noted that the difference between the harmonic powers when the pump wave is focused on the front and rear faces of the nonlinear medium increases as the degree of focusing m increases (Fig. 4) and also as the number of the harmonic increases [compare, for example, Eqs. (10) and (11)].

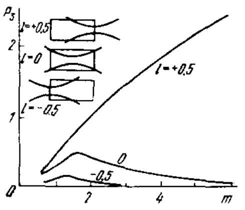

FIG. 4. Dependences of the third harmonic power on the degree of focusing under conditions of exact phase matching for the cascade process $\Delta_2 = 0$; similar dependences are obtained for the other phase-matched cascade process $\Delta_{11} = 0$, but in this case the upper curve corresponds to $l = -0.5$ and the lower curve corresponds to $l = +0.5$.

4. HARMONIC GENERATION BY FOCUSED BEAMS ALLOWING FOR BIREFRINGENCE

We shall analyze the excitation of harmonics by focused beams in a crystal using as an example the propagation of an ordinary pump wave in the phase-matching direction for the direct process (type $O_1 O_1 \ldots e_n$ interaction). Allowing for birefringence, the power of the n-th harmonic may be calculated from

$$P_n = c_n \sigma_{n\,\mathrm{eff}}^2 \frac{b^{7/2-n}}{\sqrt{2nk_1}} \int\limits_{-\infty}^{\infty} \exp\left\{-\frac{bk_x^2}{2nk_1}\right\} |F(k_x)|^2 \, dk_x, \tag{12}$$

where

$$F(k_x) = \int\limits_{-m(1+2l)}^{m(1-2l)} \frac{1}{(1-i\eta)^{n-1}} \exp\left\{\frac{ib\eta}{2}(\Delta + \beta k_x)\right\} d\eta,$$

k_x is the transverse component of the wave vector; β is the angle of birefringence.

For $\beta = 0$, Eq. (12) yields Eq. (6). The quantity $|F(k_x)|^2$ characterizes the conversion efficiency for the angular component defined by the transverse component of the wave vector k_x. For $\beta = 0$ the wave mismatch for all the angular components is Δ_n whilst in the presence of birefringence, this becomes $\Delta_n + \beta k_x$. The conversion efficiency of the whole beam is found as an integral over the conversion efficiencies of the individual angular components allowing for a Gaussian profile of the pump wave.

The results of calculations of the dependence of the third harmonic power on the focusing parameter for different angles of birefringence and focusing at the center of the crystal are plotted in Fig. 5. In the calculations, the wave mismatch was optimized. It can be seen from Fig. 5 that up to fairly large m, the influence of the birefringence is small and the third harmonic power tends to that for $\beta = 0$. The influence of birefringence becomes small when the aperture drift over the length of the constriction is smaller than the constriction diameter a ($b\beta \leqslant a$); since we have $b = ka^2$, this is found subject to the condition $b \leqslant 1/\beta^2 k$.

Similarly, for any harmonic the influence of birefringence decreases as the focusing parameter increases.

5. CONCLUSIONS

In terms of the dependence of their power on the focusing conditions, all harmonics with $n > 3$ are similar and differ substantially from the second harmonic, whilst the third harmonic occupies an intermediate position in this respect. The difference between the depen-

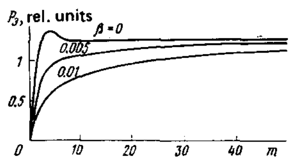

FIG. 5. Dependences of the third harmonic power on the degree of focusing with optimization of the direct process with respect to Δ_3 for different angles of birefringence β.

dences of the harmonic power as the confocal parameter b decreases is due to the influence of two factors: on the one hand, the effective length of the nonlinear medium, which makes the main contribution to the harmonic power, decreases and, on the other hand, the amplitude of the nonlinear polarization increases. For the second harmonic the first factor predominates over the second, for the third harmonic these factors compensate for each other, and for harmonics with $n > 3$ the second factor predominates.

For higher harmonics generated by cascade processes, there are two types of dependences of the power on the focusing conditions. If the phase-matching condition is satisfied for the direct process, the contribution of the cascade process to the total harmonic power depends on the main parameters in the same was as the contribution of the direct process. If the phase-matching condition is satisfied for any stage of the cascade process, we find a strong dependence of the power on the position of the constriction, asymmetric with respect to the center of the nonlinear medium, the asymmetry increasing sharply as the number of the harmonic increases.

In harmonic generation in crystals, the output power decreases due to birefringence. However, when focused pumping is used, the generation process takes place efficiently mainly near the constriction and thus the influence of birefringence may be neglected when the aperture drift over the length of the constriction does not exceed its diameter.

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Injection laser with an unstable resonator

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A report is given of the first ever investigations of an injection laser having an unstable resonator. It was found that in such a laser the transverse field distribution is stabilized and only one longitudinal mode is excited.

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An efficient method of selecting transverse oscillation modes and reducing the angular divergence of laser radiation is that in which an unstable resonator is used (see, for example, Ref. 1 and the review in Ref. 2). In a laser having an unstable resonator, the transverse field configuration is mainly determined by the resonator geometry and is to a lesser degree (than in lasers having a stable resonator) a function of the spatial variation of the complex permittivity ε (the refractive index and the gain) of the active medium. The transverse field distribution (configuration) therefore remains stable even when there is a complex and irregular change in the spatial dependence of ε. This situation is produced by the high degree of spatial coherence in lasers having an unstable resonator.

In injection lasers having a plane-parallel resonator the dependence of the transverse field configuration on the spatial variation of ε is stronger than for other types of laser (in practice, the configuration is given entirely by the variation of ε). The most unfavorable situation occurs for the direction parallel to the p–n junction. In this direction ε is almost constant, and all the changes are of a random nature. In addition, because of the inhomogeneous "depletion" of the inversion (the electron density) and the strong dependence of the refractive index on the electron density, an additional profile of ε appears which changes in a complex way