Coherent frequency doubling in nonlinear nonhomogeneous elements

N. F. Andreev, V. I. Bespalov, A. M. Kiselev, A. Z. Matveev, and G. A. Pasmanik
Institute for Applied Physics, USSR Academy of Sciences

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It is shown that in inhomogeneous crystals the frequency doubling can occur with a compensation for phase distortions. To achieve this, the wave front of the first harmonic must be inverted at the input of the nonlinear element relative to the wave front of the radiation that was transmitted through the crystal in the opposite direction.

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1. In the case of frequency doubling in inhomogeneous crystals, because of the differences of the optical paths in different regions of the beam cross section larger than the length of the light wave, the divergence of the second harmonic may increase substantially compared to the diffraction harmonic.[1] Similar peculiarities occur not only as a result of multiplication of harmonics, but also as a result of summation and subtraction of waves of different frequencies and other parametric transformations in inhomogeneous media.

In view of this, of particular interest are the investigations of the nonlinear processes in the field of laser beams that are phased in the cross section in such a way that, as a result of nonlinear transformation of these beams in an inhomogeneous medium, a radiation with previously determined (e.g., plane) wave front can be excited. In this work, we use the second harmonic to show that cross-section phased (coherent) frequency doubling can be achieved, if a low-power beam of the first harmonic is initially passed through a nonuniform crystal and then is amplified and reflected with inversion of the wave front (WFI) after passing through the amplifier in the opposite direction and attaining a sufficient power level for effective doubling of the frequency, the first-harmonic beam re-enters the crystal, where it excites the second harmonic whose field at the output of the system reproduces the square of the complex-conjugate field of the first harmonic prior to its passage through the nonuniform crystal. This result is of interest in connection with the problem of obtaining a single-mode, frequency-doubled emission in large-diameter beams, coupling the radiation to a small-size target for laser fusion, etc.[2]

2. We shall explain the effect of coherent-frequency doubling within the framework of a simple theoretical model. We assume that a weak power beam of the first harmonic passes initially along the Z axis through a layer with large inhomogeneities of the index of refraction ($-L_0 < Z < 0$) and then through an inhomogeneous nonlinear crystal ($0 < Z < L$) (Fig. 1). Thus, the first harmonic is amplified and reflected with WFI in the region $Z > L$ as a result of stimulated Mandel'shtam-Brillouin scattering (SMBS).[3] Neglecting the reflection from the nonlinear elements and the back scatter-

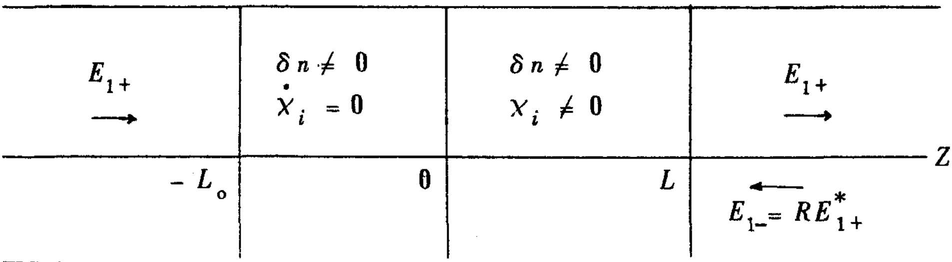

FIG. 1.

ing by the δn perturbations, the reflected-wave field E_{1-} in the $Z = L$ plane can be connected in the geometric approximation with the direct-wave field E_{1+} in the $Z = -L_0$ plane by the following relation:

$$E_{1-}(\mathbf{r}_\perp, L) = R\, E^*_{1+}(\mathbf{r}_\perp, -L_o) \exp(-ik_1 \int_{-L_o}^{L} \delta n(\mathbf{r}_\perp, Z) dZ), \quad k_1 = \frac{\omega_1}{c}, \qquad (1)$$

where R is the coefficient of reflection.

The reflected wave E_{1-} excites the second harmonic in the region $0 < Z < L$; the energy transfer to it is described in the same approximations by the set of equations

$$\frac{\partial E_{1-}}{\partial Z} + ik_1 \delta n E_{1-} = i\chi_1 E_{2-} E^*_{1-}; \qquad \frac{\partial E_{2-}}{\partial Z} + ik_2 \delta n E_2 = i\chi_2 (E_{1-})^2 \qquad (2)$$

$$k_2 = \frac{\omega_2}{c} = 2k_1$$

with the boundary conditions (1) and $E_{2-}(r_\perp, L) = 0$. We assume that dispersion of perturbations of the refractive index δn is negligible, which is valid if $\int_L^0 dZ\,[2k_1 \delta n(\omega_1) - k_2 \delta n(\omega_2)] < \pi$. We also assume that the Z axis coincides with the direction of the matching indices (synchronism) in the crystal $[n(\omega_1) = n(\omega_2)]$; all the spectral components of the first harmonic lie within the limits of the synchronism angle, and the reciprocal drift of the waves is insignificant.[4] The solution of Eq. (2) using the change of variables $E_1 = \widetilde{E}_{1-} \exp(ik_1 \int_L^0 \delta n dZ)$ and $E_2 = E_{2-} \exp(-ik_2 \times \int_L^Z \delta n dZ)$ allows us to determine the second-harmonic field E_{2-} in the planes $Z = 0$ and $Z = -L_0$:

$$E_{2-}(\mathbf{r}_\perp, 0) = \sqrt{2}\, \frac{[RE^*_{1+}(\mathbf{r}_\perp, 0)]^2}{|RE_{1+}(\mathbf{r}_\perp, 0)|}\, \mathrm{th}\,[\sqrt{2}\, |RE_{1-}(\mathbf{r}_\perp L)|\, \chi_1 L], \qquad (3)$$

$$E_{2-}(\mathbf{r}_\perp, -L_o) = \sqrt{2}\, \frac{[RE^*_{1+}(\mathbf{r}_\perp, -L_o)]^2}{|RE_{1+}(\mathbf{r}_\perp, L)|}\, \mathrm{th}\,[\sqrt{2}\, |R\widetilde{E}_{1-}(\mathbf{r}_\perp, L)|\, \chi_1 L] \qquad (4)$$

$$\times \exp[-L \frac{-\omega_2}{c} \int_0^{-L_o} (n(\omega_2) - n(\omega_1)] dZ].$$

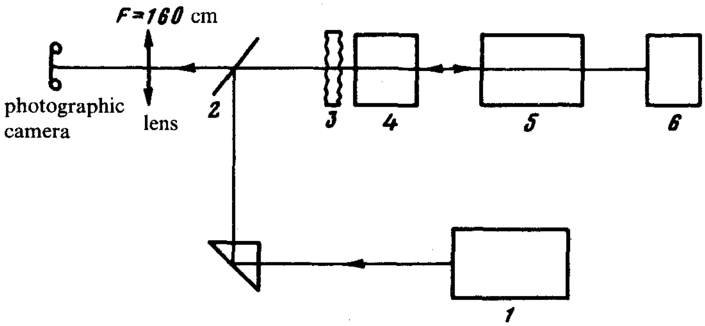

FIG. 2. 1—Source of the single-mode emission of the first harmonic with a Faraday decoupling (wavelength $\lambda = 1.06$ μm, beam diameter behind the 3 power telescope $d = 5$ mm, angular divergence $\theta = 1.5 \times 10^{-4}$ rad, duration and energy of the pulse: $\tau = 30$ nsec, $W = 5 \times 10^{-3}$ J); 2—beam splitter, reflecting 10% pulse energy; 3—phase plate; 4—doubling element; 5—optical amplifier; 6—SMBS mirror.

If the spread of the integral in the exponent at different points of the cross section is much less than π, then we can assume that the E_{2}- field reconstructs the square of the complex-conjugate field of the first harmonic. If, for example, the field of the first harmonic that propagates along the Z axis is a single-mode field in the $Z = -L_0$ plane and has a plane-wave front, then the field of the second harmonic in this plane will also be single-mode and will have a plane-wave front.

3. The experimental investigation was carried out according to the scheme illustrated in Fig. 2. A similar scheme without the doubling element was used by Basov *et al.*[5] A single-mode radiation $\lambda = 1.06$ μm with a divergence $\theta = 1.5 \times 10^{-4}$ rad at a beam diameter $d = 5$ mm is incident on the nonlinear element. This corresponds to a beam with a plane front that passes through the lens with an effective focal distance $F_{\text{eff}} = +74.5$ m. A homogeneous 1.35-mm-thick $LiIO_3$ crystal was used initially as the nonlinear element, which was sufficient to eliminate the mutual drift of the interacting waves and to achieve a synchronous doubling of the frequency within the limits of the angle $\theta \leqslant 2 \times 10^{-3}$ rad. The δn nonuniformities were simulated by the phase plate (PP) located in immediate proximity of the crystal (Fig. 2). If the crystal together with the PP is placed in the field of an amplified single-mode beam of the first harmonic (to do this, the crystal in Fig. 2 must be located on the left-hand side of the beam splitter 2), then the angular spectrum of the second-harmonic generation will be dis-

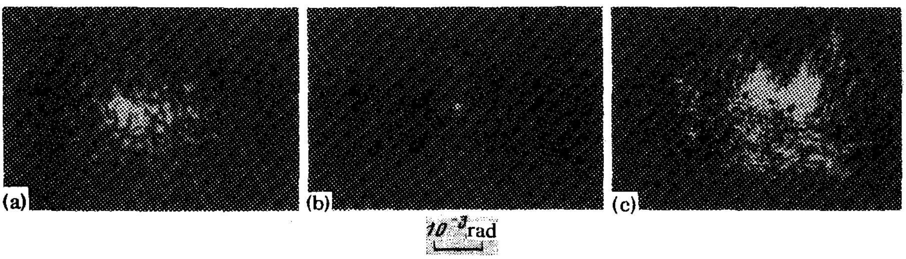

FIG. 3.

tributed in the angle $\theta_a \approx 1.1 \times 10^{-3}$ rad (Fig. 3a). However, as a result of placing the crystal in the path of the low-power, first-harmonic beam (on the right-hand side of the beam splitter 2), the angular emission spectrum at the doubled frequency, which was excited in the crystal by pumping that was reflected from the SMBS mirror 6 and transmitted twice through the amplifier 5 (in the absence of saturation), was reduced considerably to a width of $\theta_b \approx 1.3 \times 10^{-4}$ rad (Fig. 3b). This output corresponded to a beam with a plane front that was transmitted through a lens with $F_{eff} = -61.3$ m, which is in approximate agreement with the theoretical dependence $E_2 \sim E_1^{*2}$.

It is interesting to note that by increasing the distance between the PP and the crystal (to 60 cm), the angular spectrum can be narrowed slightly (by about 20%); however, this introduces a random modulation near the edges of the main lobe. This is apparently attributable to the fact that a certain compensation of the phase inhomogeneities of the second harmonic occurs at the PP, even if the distance between it and the crystal is comparable to that at which the phase distortions of the transverse-wave profile are converted to amplitude distortions. This problem, however, requires further study.

It should be pointed out that the conversion coefficients in all the cases were small compared to unity. It should also be noted that the coherent-doubling effect disappeared when the SMBS mirror 6 was replaced by an ordinary plane mirror (Fig. 3c, $\theta_c \sim 1.1 \times 10^{-3}$ rad) and also when longer nonlinear crystals were used. For example, by replacing the short $LiIO_3$ crystal by a 25-mm-long KDP crystal, we did not obtain the second harmonic with a divergence close to the diffraction harmonic.

To investigate the process of coherent-frequency doubling directly in an inhomogeneous element, we used a inhomogeneous $LiNbO_3$ crystal, which increased to $\theta' \sim 10^{-3}$ the divergence of the single-mode beam that was passed through it. However, as a result of a preliminary passage through it of low-power-emission, first-harmonic beam and subsequent doubling of the inverted and amplified radiation, the divergence of the second harmonic, which was close to the diffraction harmonic, was equal to $\theta'' \sim 1.8 \times 10^{-4}$ rad.

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