FREQUENCY DOUBLING OF LIGHT IN RUBY

T. P. Belikova and E. A. Sviridenkov
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 30 October 1966
ZHETF Pis'ma 5, No. 1, 29-32, 1 January 1967

Nonlinear effects arise in crystals placed in the focus of the emission beam from a powerful Q-switched ruby laser (flux density $W \sim 10^{10}$ W/cm^2). One such effect is emission of light at double the frequency, observed in crystals having no symmetry center [1], and also in fused quartz [2], which from the point of view of symmetry is a liquid, but whose molecules have no inversion center.

We observed emission of wavelength λ = 347 nm from the region of the focus of a ruby laser in a sample of ruby (ruby has an inversion center). The figure shows a spectrogram of the emission from ruby illuminated by a ruby laser. The spectrum consists of two broad bands [3] and a narrow line at double the ruby laser frequency (marked with arrow on the figure). At the bottom, for comparison, is shown the spectrum of a mercury lamp. The radiation was observed with (a) and without (b) damage to the ruby.

Fig. 1. Spectrum of emission from ruby illuminated by a ruby laser (the arrow denotes the emission at 347 nm wavelength).

The order of magnitude of this emission was estimated from the blackening of the film. 10^{-11} J of light energy is necessary to produce such a blackening in a spot measuring 0.1 mm^2. Ten exposures were made, i.e., 10^{-12} J was incident on the film following each flash. If it is assumed that the emission at the 2ω frequency is uniform in all directions, then 10^{-3} of all the energy entered the spectrograph. Thus, $\sim 10^{-9}$ J is converted into emission with λ = 347 nm when the incident energy is ~1 J.

As is well known [1], the most effective mechanism for optical frequency doubling is electric dipole interaction between light and a crystal having no symmetry center. The polarization at 2ω is given by

$$P_i(2\omega) = \chi^{e\text{-}dip}_{ikl} E_k(\omega) E_l(\omega). \qquad (1)$$

E_k and E_l are the field intensities in the laser beam, $\chi^{e\text{-}dip}_{ikl}$ is the nonlinear polarizability tensor in the electric-dipole interaction mechanism. The intensity of the doubled-frequency light emission is proportional to the square of the polarization and usually amounts to

$$I^{e\text{-}dip}(2\omega) \sim 10^{-4} - 10^{-5}\, I(\omega),$$

where $I(\omega)$ is the intensity of the incident radiation at a flux density $W \sim 10^{10}$ W/cm^2, if there are no accumulation and amplification effects. Relation (1) should be invariant against all symmetry transformations of the given crystal. It follows therefore, in particular, that $\chi^{e\text{-}dip}_{ikl} \equiv 0$ for all crystals having inversion centers. This means that there should be no double-frequency radiation in crystals with an inversion center if only electric dipole interaction is taken into account. Ruby is a crystal with an inversion center, and therefore the double-frequency radiation observed by us is of interest. Let us point to several possible causes of its occurrence. The first may be magnetic-dipole and electric quadrupole interaction between the laser light and the corundum lattice, similar to the mechanism considered by Askar'yan [4] and Pershan [5]. In these cases the polarization takes the form

$$P_i(2\omega) = \chi^{m\text{-}dip}_{ik\ell} E_k(\omega) H_e(\omega)$$

for magnetic-dipole interaction and

$$P_i(2\omega) = \chi^{e\text{-}q}_{ik\ell m} E\,(\omega) \frac{dEm(\omega)}{dr_k}$$

for electric quadrupole interaction. The components of the tensors $\chi^{m\text{-}dip}_{ik\ell}$ and $\chi^{e\text{-}q}_{ik\ell m}$ are not changed by the inversion transformation in crystals with symmetry centers.

It is well known [5] that the nonlinear polarization due to these interactions is smaller by three orders of magnitude than the polarization produced in the case of electric-dipole interaction. Therefore the intensity of the scattered light produced by this polarization should be smaller by six orders of magnitude than produced by electric-dipole interaction in similar crystals but without an inversion center. Thus, in this case

$$I(2\omega) \sim 10^{-6}\, I^{e\text{-}dip}(2\omega) \sim 10^{-10}\, I(\omega).$$

The second cause may be the distortion of the corundum lattice by chromium ions, which may lead to linear polarization proportional to the degree of lattice distortion and to the chromium concentration (in this case c = 0.03%). The intensity of the scattered light at double the frequency in ruby, due to this polarization, is

$$I(2\omega) \sim (3 \times 10^{-4})^2 I^{e\text{-}dip}(2\omega) \sim 10^{-7} \times 10^{-4} I(\omega) \sim 10^{-11} I(\omega).$$

In considering the foregoing effects, we must remember that the field at the frequency 2ω is correlated in phase with the field of the fundamental radiation. Interference may cause effective emission of light at 2ω from only a layer of thickness ~λ in the region of the caustic of the laser beam, or in inhomogeneities of the crystal [4,6].

Still another possible cause of the occurrence of 2ω-emission in ruby may be the anti-Stokes Raman scattering of the laser light by the chromium ions, which are in an excited state at the ^2E level. In this case account must also be taken of the magnetic-dipole and electric-quadrupole interactions. The lack of data on the values of the matrix elements does not make it possible as yet to estimate the contribution of each of these mechanisms to the production of 2ω-emission in ruby with the intensity $I(2\omega) \sim 10^{-9} I(\omega)$ observed by us. The disparity between the observed intensity and the estimates of the possible intensity may be due to the anisotropy of the 2ω-emission, resulting from interference effects.

The authors thank M. D. Galanin for interest in the work.

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VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

We assume that the baryon and muon conservation laws are not absolute and should be unified into a "combined" baryon-muon charge $n_c = 3n_B - n_\mu$. We put:

$n_\mu = -1$, $n_K = +1$ for antimuons μ_+ and $\nu_\mu = \mu_0$,

$n_\mu = +1$, $n_K = -1$ for muons μ_- and $\nu_\mu = \mu_0$,

$n_B = +1$, $n_K = +3$ for baryons P and N,

$n_B = -1$, $n_K = -3$ for antibaryons P and N

This form of notation is connected with the quark concept; we ascribe to the p, n, and λ quarks $n_c = +1$, and to antiquarks $n_c = -1$. The theory proposes that under laboratory conditions processes involving violation of n_B and n_μ play a negligible role, but they were very important during the earlier stage of the expansion of the Universe.

We assume that the Universe is neutral with respect to the conserved charges (lepton, electric, and combined), but C-asymmetrical during the given instant of its development (the positive lepton charge is concentrated in the electrons and the negative lepton charge in the excess of antineutrinos over the neutrinos; the positive electric charge is concentrated in