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EMISSION OF MONOPULSES OF COHERENT LIGHT BY A TWO-COMPONENT MEDIUM WITH NEGATIVE ABSORPTION

V. I. BORODULIN, N. A. ERMAKOVA, L. A. RIVLIN and V. S. SHIL'DYAEV

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Excitation of self-oscillations is considered for a medium located in a Fabry-Perot resonator. The medium contains two types of quantum oscillators with equal energy transitions. Such a medium emits monopulses of light for a certain relation between its parameters. The shape, energy, amplitude and duration of such pulses are determined. Monopulse emission from a medium consisting of ruby single crystals and KS-19 glass plates was observed experimentally. However, the applicability of the mechanism under consideration to these experimental results requires a special analysis.

1. MECHANISM OF EMISSION OF A MONOPULSE BY A TWO-COMPONENT MEDIUM

THE state of self-oscillations in an inverted medium, placed in a Fabry-Perot resonator, begins when the negative absorption in it exceeds all forms of losses, i.e., when

$$\gamma(\nu) \equiv -\alpha^* u + B_n(\nu) h\nu (n_2 - n_1) > 0, \qquad (1.1)$$

where ν is the light frequency, u is its velocity in the medium, n_2 and n_1 are the volume concentrations of quantum radiators at the upper and lower levels of the transition $2 \to 1$ with energy $h\nu_0$ and Einstein coefficient of stimulated emission $B_n(\nu)$, and the effective absorption coefficient $\alpha^* = \alpha + 2\pi\nu_0/uQ$ takes into account both the energy dissipation in a medium with absorption coefficient α and the losses at the mirrors of the resonator with quality factor Q.

The known methods of generation of "gigantic" monopulses by modulation of the Q of the resonator [1-4] lead to a sudden decrease in the second term of α^* and a corresponding sharp increase of $\gamma(\nu) > 0$ at the moment when the pump generates a sufficiently high level of overpopulation $n_2 - n_1$. Such a modulation is usually produced by means of some sort of optical shutter (which rotates a totally reflecting prism, Kerr cell, or the like) controlled externally.

It is evident that the ability to radiate monopulses of light lies in the mechanism of negative absorption itself if the medium contains quantum radiators of two types, n and m, with identical energy transitions in each (a two-component medium). The negative absorption in such a medium has a threshold character,[5] while the coefficient $\gamma(\nu)$ in (1.1) should be supplemented by the term $B_m(\nu) h\nu (m_2 - m_1)$, where the coefficient $B_m(\nu)$ and the concentrations m_2 and m_1 refer to radiators of type m. Radiators of both types are coupled with themselves and with each other only through the common radiation field.

The possibility of radiation of a monopulse is due to the fact that, after generation of self-oscillations (the start), the overpopulations $n_2 - n_1$ and $m_2 - m_1 < 0$ under the forcing action of the photons of the operating modes of the resonator approach saturation, but at different rates, determined by the values of the coefficients $B_n(\nu)$ and $B_m(\nu)$. If radiators of the m type approach saturation much more rapidly than those of the n type, then, for a definite relation of the parameters, the coefficient $\gamma(\nu) > 0$, and a while after the start it increases sharply, as in the methods of Q-modulation mentioned above.

After the start, the coefficient $\gamma(\nu_0)$ changes according to the law [5]

$$\gamma(\nu_0, E) = \alpha^* u \left\{ -1 + \frac{\exp(-b_n E)}{\beta_n} + \frac{\exp(-b_m E)}{\beta_m} \right\}, \qquad (1.2)$$

where

$$\beta_n = \frac{\alpha^* u}{B_n h\nu_0 n_0}, \quad \beta_m = \frac{\alpha^* u}{B_m h\nu_0 m_0}, \qquad (1.3)$$

$$b_n = \frac{QB_n}{\pi\nu_0 V}, \quad b_m = \frac{QB_m}{\pi\nu_0 V}, \qquad (1.4)$$

and E(t) is the energy radiated by the resonator, V is the volume filled by the working medium (an equilibrium distribution of all concentrations and energies is assumed for V), the coefficients B_n and B_m are taken for the common central frequency ν_0 for radiators of both types, and n_0 and m_0 are the initial values of the overpopulation.

The exponential dependence in (1.2) is valid if, after the start, one can neglect the effect of pumping and spontaneous decay, and also the action of photons which are not connected with the external mode space of the resonator, in comparison with the effect on the population of the levels on the part of photons of the operating mode.

The initial conditions at $E = 0$

$$\gamma(\nu_0) = 0, \qquad d\gamma(\nu_0)\,/\,dE > 0 \tag{1.5}$$

lead to the relations

$$(\beta_n)^{-1} + (\beta_m)^{-1} = 1, \tag{1.6a}$$

$$B_m / B_n > (1 - \beta_n)^{-1}, \tag{1.6b}$$

which coincide with the corresponding levels obtained in [5].

It is seen from (1.6a) that by selection of the values of B_m and $m_0 < 0$, one can bring the initial overpopulation n_0 to a level that is sufficient for the radiation of a "gigantic" monopulse.

The power $P = dE/dt$ radiated from the resonator is determined by the equation $dP/dt = \gamma(\nu_0)P$ which can, with account of (1.2) and integration over time, lead to a single function of E:

$$\frac{dE}{dt} = \alpha^* u\left\{ -E + \frac{1-\exp(-b_n E)}{\beta_n b_n} + \frac{1-\exp(-b_m E)}{\beta_m b_m} \right\}. \tag{1.7}$$

The process of radiation lasts from the start at $E = 0$ to the value $E = E_0$ for which $dE/dt = 0$. Thus the value E_0, which is determined as the non-zero root of the equation $dE/dt = 0$, is the total energy of the radiated monopulse; the total energy of the monopulse increases with increase in the initial population n_0, remaining less than the value

$$E_0 < \frac{n_0}{2} h\nu_0 V\eta \left[1 - \frac{B_n}{B}(1-\beta_n) \right] < \frac{n}{2} h\nu_0 V\eta \left[1 - \frac{B_n}{B_m}(1-\beta_{n0}) \right], \tag{1.8}$$

where $\eta = 2\pi\nu_0/\alpha^* uQ$ is the efficiency of the resonator, n being the total volume concentration of radiators of type n while β_{n0} is determined from (1.3) for $n_0 = n$.

The maximum amplitude of radiation $P_{peak} = dE/dt|_{peak}$ is reached at the energy $E = E_1$, which is determined from (1.7) by the condition $d^2E/dt^2 = 0$. Substitution of $E = E_1$ in (1.7) gives the peak value of the amplitude P_{peak} directly; this value increases upon increase in the initial overpopulation n_0, not exceeding a limiting value:

$$P_{peak} < \frac{n_0}{2} h\nu_0 V\eta\alpha^* u \left[1 - \frac{B_n}{B_m}(1-\beta_n) + \beta_n \ln \beta_n \right] < \frac{n}{2} h\nu_0 V\eta\alpha^* u \left[1 - \frac{B_n}{B_m}(1-\beta_{n0}) + \beta_{n0} \ln \beta_{n0} \right]. \tag{1.9}$$

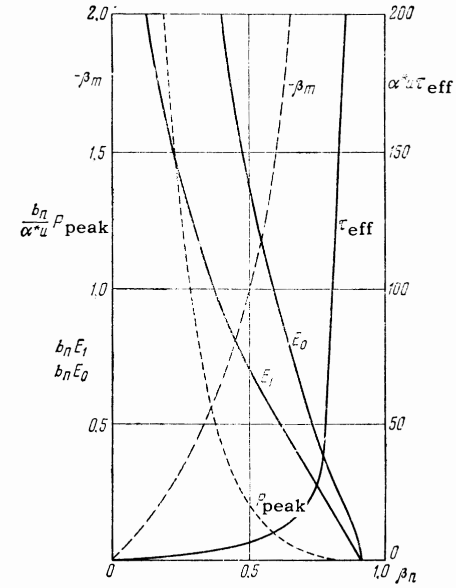

FIG. 1. Dependence of the normalized values of the total energy of the monopulse $b_n E_0$, the peak power $(b_n/\alpha^* u)P_{peak}$ and the energy corresponding to the peak, $b_n E_1$, the effective duration τ_{eff} ($\alpha^* u\, \tau_{eff} \to 1$ as $\beta_n \to 0$) and the parameter β_m on the parameter $B_m/B_n = 10$.

The dependences on the parameter β_n are given in Fig. 1 for the total energy of radiation E_0, the peak amplitude P_{peak} and the corresponding value of E_1 for the case $B_m/B_n = 10$. The same dependences are given for β_m and the effective pulse length, defined as the ratio $\tau_{eff} = E_0/P_{peak}$.

It must be noted that the entire present analysis is carried out in the quasimonochromatic approximation, in which case the spectral width of the radiated light pulse is much less than the width of the line $2\Delta\nu$ of spontaneous transition $2 \to 1$, which is valid so long as $\tau_{eff} \gg (\Delta\nu)^{-1}$. This approximation is suitable for a very high Q resonator ($\alpha^* u \ll \Delta\nu$), in which the reduction of the effective length of time τ_{eff} associated with an increase in the initial overpopulation n_0 has a limit $\tau_{eff} > (\alpha^* u)^{-1}$. In the opposite case of a low-Q resonator, any similar limitation is absent and the quasi-monochromaticity is violated at small values of τ_{eff}. Here, the reduction of the effective time τ_{eff} is limited to a quantity of the order $(\Delta\nu)^{-1}(\beta/(1-\beta))^{1/2}$ while the effectiveness of the process of stimulated emission falls as the result of the smearing out of the energy stored in the resonator (for a decrease of τ_{eff}) over the wings of the spectral line of the radiator.

The shape of the radiated monopulse obtained

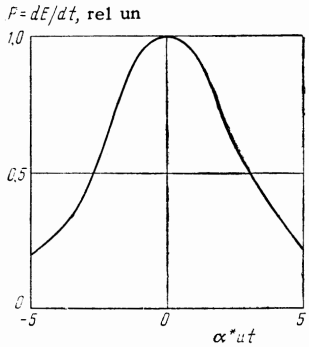

FIG. 2. Shape of the radiated monopulse for the case β_n = 0.05 and B_m/B_n = 10.

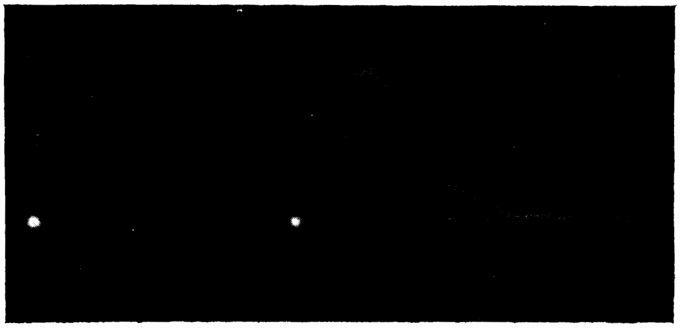

FIG. 3. Oscillogram of the monopulse at the output of the resonator (to the left) and after amplification (to the right). In the recording of the amplified pulse, an additional filter is used with a tenfold reduction. The time scale between the bright spots = 300 nanosec.

graphically by integration of Eq. (1.7) for the case β_n = 0.5 and B_m/B_n = 10 is shown in Fig. 2.

2. EXPERIMENT

In the experiment, the quantum radiators of type n and m need not be uniformly distributed in the medium. The two-component medium can be formed from two (or more) one-component specimens with radiators of different types, placed in a common Fabry-Perot resonator. In this case, the actual volume concentrations in the one-component media, n_0' and m_0', are connected with the quantities n_0 and m_0 obtained from the formulas of the previous section by the relations

$$n_0(l_n + l_m) = n_0' l_n, \qquad m_0(l_n + l_m) = m_0' l_m, \qquad (2.1)$$

where l_n and l_m are the lengths of specimens of the one-component media.

Experiments are known in which the two-component medium consisted of a single ruby crystal and a solution of metallophthalocyanin or a ruby and a uranium glass,[6] and also of a ruby and a glass colored with CdS : Se.[7] It is possible that the results of these experiments (or, at least, those set forth in [6]) can be interpreted from the positions set forth above.

This also applies in equal measure to the data of the following experiment, which in no way was aimed at selecting the optimal parameters for the system. The two-component medium consisted of a cylindrical ruby single crystal of length 75 mm with a chromium concentration of 0.05% and a plane parallel glass plate KS-19 (colored optical glass GOST 9411-60) of thickness 3 mm, placed in a resonator with a mirror transmission coefficients 0 and 30%. The pumping took place in a polished aluminum reflector by a pulsed discharge of a capacitor bank, with energy of 1600 joules, through two IFP-800 tubes. The output radiation was recorded by an F-5 photocell and was observed on an S-1-7 oscilloscope in the form of a monopulse of a duration 70-80 nanoseconds. The total energy of the monopulse was measured by a calorimetric method by the change in the resistance of a copper conductor of great length and was in the range 0.08-0.1 joule, which corresponded to a radiation amplitude of about 1.0—1.4 MW. Increase in the pump level or decrease in the thickness of the glass led to a repetition of the entire course of the phenomenon and to the appearance of second and third monopulses, which followed one another at intervals of about 70 microseconds.

The emitted monopulse underwent amplification in a single ruby crystal of length 240 mm with clear end surfaces, pumped by two IFP-5000 tubes with a total flash energy of 5400 joules. The output monopulse had an amplitude of about 10—14 MW. An intensive electric spark was produced in atmospheric air when the output radiation was focused by a lens with a focal length of 130 mm.

Figure 3 shows photographs of oscillograms of pulses at the output of the resonator and after amplification. Figure 4 gives the photographs of the electric spark in air at the focus of the lens.

Experiments with KS-17 and KS-18 glasses gave similar but somewhat weaker results (in energy and amplitude). The transmission coefficient of the KS-19 glass revealed a strong dependence on the intensity of the light incident upon it, which is shown in Fig. 5, data for which were obtained in the passage through the glass of monopulses of different energy and amplitude, but approximately the same duration. The quantitative results were compared with the dependence

$$kI = \ln(T / T_0) / (1 - T), \qquad (2.2)$$

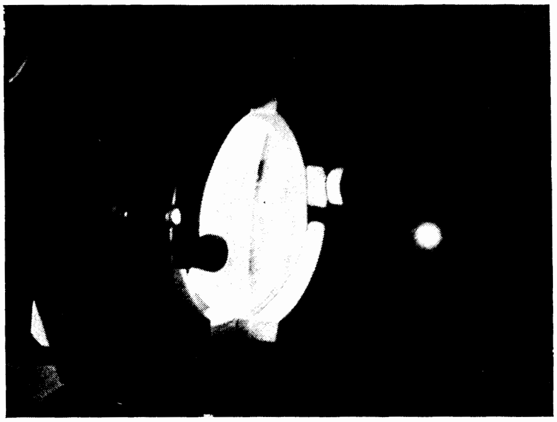

FIG. 4. Electric discharge of atmospheric air at the focus of the lens.

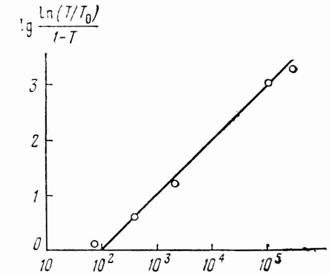

FIG. 5. Dependence of the transmission through KS-19 glass on the intensity of the incident light (in W/cm²).

where I is the light flux density incident on the glass, k is a coefficient of proportionality, T the transmission coefficient, T_0 its value at zero light intensity. Use of this formula is justified, based on the model of the previous section, if it is assumed that the process of saturation of the overpopulation $m_2 - m_1$ takes place so rapidly that one can consider it to be stationary during the experiment.

As is seen from Fig. 5, the points satisfactorily follow the straight line (2.2). It must be noted that, according to the conditions of the experiment, the energy of the pulses changes simultaneously with the light intensity and is proportional to it. Therefore, the dependence on I is essentially simultaneous and is a dependence on the transmitted energy of the light flux. This circumstance does not allow us to say uniquely whether or not the illumination of the KS-19 glass takes place under the action of the intense field of the passing light flux or under the action of its integral energy. The latter would be evidence in favor of the mechanism considered above.

Inasmuch as the transmission characteristics of the KS-19 are determined by the color pigment, which is a semiconductor formation of the type CdS and CdSe,[8] an alternative mechanism of illumination can show the shift of the edge of the absorption band under the action of the electric field of the light.[7]

Thus the problem of the applicability of the representations of the previous section to media of the type of the KS-19 glass underlies the fundamental consideration.

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121