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EFFICIENCY PARAMETRIC OSCILLATION USING OPTICAL RESONATOR

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A nonlinear wave theory that describes the parametric interaction of the Raman scattering component in an external resonator in a dissipative medium at the phase mismatch in the constant-intensity approximation is presented. This approximation takes into account the reverse reaction of the Stokes component on the exciting wave phase. It is shown that the conversion efficiency can be considerably increased by the choice of the resonator geometry. The high Stokes conversion efficiency is obtained under resonance phase condition. By a judicious choice of the parameters of the problem (phase mismatch, nonlinear length, mirror reflectivity coefficients, pump and anti-Stokes component intensities, absorption of interacting waves) the further increase in efficiency of the Stokes component can be achieved. The model is useful for optimization of parametric frequency conversion in the external resonator, and may be applied to different types of nonlinear interaction within the optical resonator.

1. INTRODUCTION

Lidar atmospheric sounding, laser spectroscopy, record and storage of the information, and also other problems, urgency of which is doubtless at the decision of the problems connected to ecology, multichannel systems of communication, system of medical diagnostics, demand development of more perfect methods and technical devices [1-2]. The part from them may be based on highly effective laser converters of frequency. The important stage of this way is the development of parametrical converters and definition of conditions necessary for the maximal conversion of frequency. On the other hand, the object of this investigation is the Raman scattering component generation – a powerful spectroscopic tool [3]. Except for that it is known, that the shifted wavelength of the Stokes beam can be exploited to make lasers of new wavelengths that can't be easily obtained by other methods [4].

With the purpose of increase of frequency conversion efficiency the nonlinear medium can be placed inside the optical resonator [5]. Recently, researchers at the Philips Center for Industrial Technology have developed a compact, optical interface for portable electronic equipment where the interaction of light waves within the internal laser cavity and external resonator have been used [6]. At frequency conversion in an optical resonator, due to the additional multifold passes of a medium, the effective length of a nonlinear interaction increases, and the energy exchange between the waves is mainly determined by the phase relationships. From here it is necessary to determine a role of phase effects on efficiency of the nonlinear optical processes occurring in the resonator.

To describe parametric interaction of Raman scattering components, the method of the coupled waves is used in particular [7]. In general case it is impossible to obtain the analytical solution in the close form. To solve this problem, the constant-field approximation is used more often [7-9]. In this approximation the phase changes of the interacting waves in the medium are not taken into account. However in real media the ignorance of the change of interacting wave phases results in the loss of information about specific properties of a nonlinear interaction. For this reason, for research of the behavior of Raman scattering components the use of the constant-intensity approximation is offered [10]. In this approximation the reverse reaction of the excited wave on the pump wave is taken into account. Furthermore the constant-intensity approximation, in contrast to the constant-field approximation, allows us to account the effect both of phase mismatch and the absorption of all the interacting waves in a nonlinear medium simultaneously. In Ref. [4] for obtaining of maximum conversion efficiency of the Stokes component the theory that describes the off-resonant continuous wave Raman laser to include the case of mismatched mirror reflectivities of the front and the back mirrors of the Raman laser cavity is presented. Research of conversion of frequency in the external resonator is carried out basically in the constant-field approximation [9, 11]. In the constant-intensity approximation the parametric interaction of waves and generation of the third harmonic were investigated in Refs. [12-14], intracavity parametric interaction of Raman scattering components was considered in Ref. [15].

The purpose of the present paper is determination of generation efficiency of Raman scattering component in the external resonator with account of dissipative medium and phase mismatch between the interacting waves in the constant-intensity approximation. The paper is divided into the following headings. Section 2 describes the analytical model of the external resonator filled with the Raman medium. In Section 3 the results of calculations for this theoretical model are reported and discussed. Finally, summary is given in Section 4.

2. THEORETICAL MODEL

Let us consider an external resonator containing a nonlinear dielectric medium of length d [16]. The pump wave is incident upon the front mirror I. The nonlinear medium is oriented for Stokes-anti-Stokes components generation at a laser frequency ω_p $\left(2\omega_p = \omega_s + \omega_a\right)$. Mirror I has reflectivity R_{po} at pump frequency ω_p and $R_{so,ao}$ at the Stokes-anti-Stokes components frequencies $\omega_{s,a}$, respectively, while mirror II has reflectivity R_p at pump frequency ω_p and $R_{s,a}$ at the Stokes-anti-Stokes components frequencies $\omega_{s,a}$, respectively at the incidence from a nonlinear layer. Following the first passage through the nonlinear medium the fundamental wave, owing to parametric interaction in it, generate the Stokes and anti-Stokes components. Then they are reflected by mirror II to parametric interact again at the nonlinear medium. The complex amplitudes $A_{p,s,a}$ of the fundamental, Stokes-anti-Stokes components waves follow the three reduced equations $\left(R_{po,ao} = R_{p,a} = 0\right)$ [9]. In Ref.16 the solution of this system for the Stokes component in the constant-intensity approximation ($I_{p,a}(z) = I_{p,a}(z=0) = I_{po,ao}$) at the output mirror of the resonator is given. As seen at $\gamma_p = 0$, we obtain the result of the constant-field approximation. From comparison of results in two approximations follows that the account of the depletion effects, i.e., of the reverse reaction of excited waves on the pump wave, conducts to the fact that the phase of the Stokes component depends not only on pump intensity but also on anti-Stokes component intensity.

3. RESULTS AND DISCUSSIONS

The analytical solution is performed to obtain the Stokes component intensity and the gain coefficient of the Stokes component in case of resonator given by ($\delta_s = 2\delta_p + \delta_a$)

$$\eta_s^r = \frac{I_s^+(z)\left(1-r_s^2\right)}{I_{s0}} = \exp(-2\delta_s d) \times$$

$$\times \frac{\cosh^2 q_3 d + \left(\frac{\Delta + 2f}{2q_3}\right)^2 \sinh^2 q_3 d}{1 - 2r_{s0} r_s \rho \cos\theta + r_{s0}^2 r_s^2 \rho^2}, \qquad (1)$$

where

$$q_3 = \Gamma_p^2 - 2\Gamma_a^2 - \frac{\Delta^2}{4};\ \Gamma_a^2 = \gamma_p \gamma_s I_{p0} I_{a0};\ \Gamma_p^2 = \gamma_a \gamma_s I_{p0}^2;$$

$$\rho^2 = \left[\cosh^2 q_3 z + \left(\frac{\Delta}{2q_3}\right)^2 \sinh^2 q_3 z\right] \exp(-2\delta_s z);$$

$$f = \gamma_s I_{p0} A_{a0}^* / A_{so};\ \theta = \varphi_{sr} + 2k_s z - \frac{\Delta_s}{2} + \theta_1;$$

$$\tan\theta_1 = \frac{\Delta}{2q_3} \tanh q_3 z;\ I_j = A_j A_j^*$$

At $r_s = 0$ from Eq. (1) we obtain the known result [15] for the single pass through nonlinear medium.

Calculations carried out using the constant-intensity approximation are demonstrated in Figs. 1-5. In Fig. 1 the gain coefficient of the Stokes component is plotted as a function of the reduced length of nonlinear medium $\Gamma_p z$.

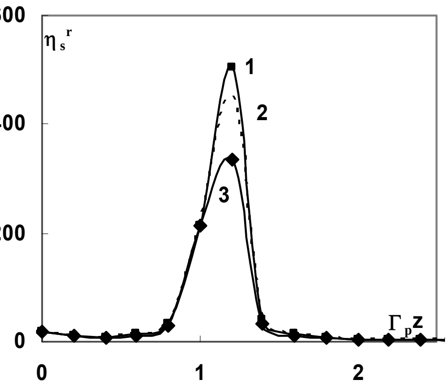

Fig.1. Dependence of the gain coefficient η_s^r on reduced length $\Gamma_p z$ at $\delta_s / 2\Gamma_p$=0.2, Γ_a / Γ_p=0.3, $\Delta / 2\Gamma_p = 0$ (curve 1), 0.1 (curve 2),0.15 (curve 3).

It can be seen that this has a clearly defined maximum. As the phase mismatch parameter $\Delta / 2\Gamma_p$ is increased, the gain coefficient deteriorates. An analysis of a similar dependence at the different values of the losses is shown in Fig. 2.

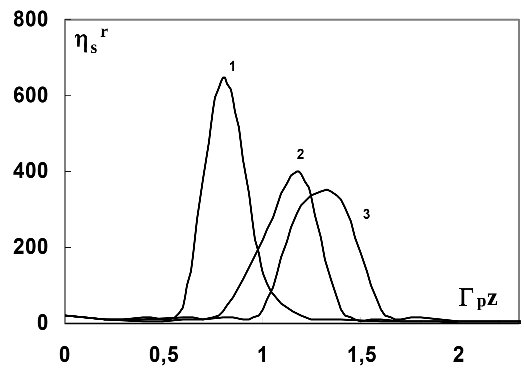

Fig.2. Dependence of the gain coefficient η_s^r on reduced length $\Gamma_p z$ at $\Delta / 2\Gamma_p = 0.1$, Γ_a / Γ_p=0.3, $\delta_s / 2\Gamma_p = 0.05$ (curve 1), 0.1 (curve 2), 0.14 (curve 3).

From comparison of curves 1, 2 and 3, we see that the gain drops while the optimal length of the medium appropriate to peak efficiency of conversion grows.

To analyze the role of the external resonator, we introduced concept of advantage due to use of the resonator determined as [16]

$$\eta_{advant} = \eta_s^r / \eta_s \,;\, \left(\eta_s = I_s(d)/I_{s0}\right) \quad (2)$$

where

$$I_s(d) = \exp(2\delta_s d)\left[\cosh^2 q_3 d + \left(\frac{\Delta+2f}{2q_3}\right)^2 \sinh^2 q_3 d\right]. \quad (3)$$

An analysis of Eq. (2) confirms that, owing to repeat pass through the Raman medium of the interacting waves, one can considerably increase the conversion efficiency or amplification of the Stokes component.

In our calculations we have taken $r_{so} = 1$. Then, using the Eq. (2) we obtain the following expression:

$$\eta_{advant} = \frac{1 - r_s^2}{1 + r_s^2 \rho^2 - 2 r_s \rho \cos\theta} \quad (4)$$

Analysis has shown that the further increase in efficiency can be achieved by the choice of the optimal parameters of the problem. It can be seen that the advantage due to use of the resonator decreases with the increasing of the pump intensity (see Fig. 3).

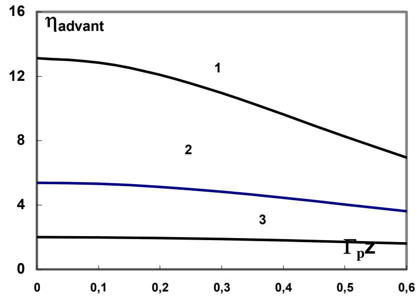

Fig.3. Dependence of η_{advant} on reduced pump intensity $\Gamma_p z$ at Γ_a / Γ_p=0.5, $\Delta z / 2 = 3$, $\delta_s z = 0$ (curve 1), 0.02 (curve 2), 0.04 (curve 3).

From here in case of frequency conversion of low-power lasers the application of resonator geometry is favorable. From Eq. (4) condition between parameters of a problem at which application of the converter of frequency is expedient follow ($\eta_{advant} > 1$). At the certain values of other parameters of a problem this condition imposes restrictions on reflection coefficient of the Stokes component

$$r_s < 2\rho\cos\theta / \left(1 + \rho^2\right) \quad (5)$$

Non-fulfillment of this condition conducts to absence of advantage due to use of the resonator geometry. The maximal value η_{advant} (see Eq. (7)) turns out at the following optimum value of reflection coefficient

$$r_s^{opt} = \frac{1 + \rho^2 - \sqrt{\left(1 + \rho^2\right)^2 - 4\rho^2 \cos^2\theta}}{2\rho\cos\theta} \quad (6)$$

The gain coefficient η_s^r given by Eq. (1) versus the reflection coefficient r_s is plotted in Fig. 4.

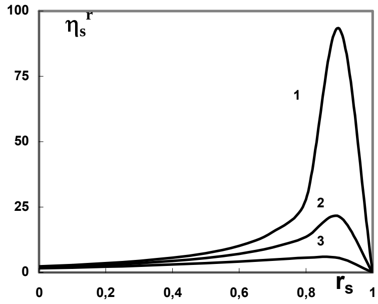

Fig.4. Dependence of the gain coefficient η_s^r on the reflection coefficient r_s at $\Gamma_p z$ =1.2, $\Delta / 2\Gamma_p = 0.1$, $\delta_s / 2\Gamma_p = 0.12$ (curve 1), 0.15 (curve 2), 0.2 (curve 3).

If the other parameters of the problem are kept constant with the rising of the losses the gain coefficient decreases. Simultaneously with it r_s^{opt} is displaced aside small optimum values of reflection coefficient. From this figure follows that in comparison with a case of absence of the resonator, at amplification of waves in the resonator it is possible to achieve significant efficiency of conversion. It follows from the Eq. (4) that the efficiency of the optic parametric generator achieves the maximum value when we have

$$\theta = 2\pi m, \quad m = 1,2,... \quad (7)$$

From Eq. (7) [16] the resonance phase condition depends on such parameters of the problem as the pump and anti-Stokes component intensities, the length of the nonlinear medium and the phase changes of the Stokes component at the reflection from the mirrors.

It is seen from the obtained Eqs. (6) and (7) that in the constant-intensity approximation, in contrast to the constant-field approximation, conditions of the maximal conversion of frequency depend on anti-Stokes component intensity. r_s^{opt} decreases with growth of pump intensity (see Fig. 5).

According to Eqs. (6) and (7), the maximal value of η_{advant} is determined as follows $\eta_{advant}^{\max} = 1/\left(1 - \rho^2\right)$.

As seen, the $\eta_{advant}^{\max}$ decreases with growth of the losses in the medium.

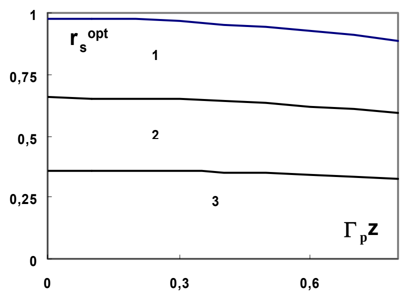

Fig.5. Dependence of r_s^{opt} on reduced pump intensity $\Gamma_p z$ at Γ_a / Γ_p=0.5, $\Delta z / 2 = 3$, $\delta_s z = 0$ (curve 1), 0.02 (curve 2), 0.04 (curve 3).

4. SUMMARY

Thus, the investigation of parametric generation in a nonlinear medium must be carried out with account both of the phase changes and of the losses in the medium, the use of optical resonator allows to increase the generation efficiency considerably.

Moreover, if amplification on the given laser transition isn't high enough, for increase of conversion efficiency the arrangement of the nonlinear medium is expedient namely in the Fabry-Perot type external resonator in contrast to arrangement inside the laser cavity.

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