Influence of intracavity stimulated Raman scattering on self-modulation of a ring laser emitting ultrashort pulses

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(Submitted May 15, 1991)
Kvantovaya Elektron. (Moscow) 18, 1359–1361 (November 1991)

An investigation is made of the generation of ultrashort pulses in a ring laser in the presence of intracavity nonlinear losses due to stimulated Raman scattering. A numerical analysis of the attractors of the problem is used in a study of typical lasing regimes: stable, unstable regular, and unstable irregular (optical turbulence). A change in the nonlinearity parameter reveals also "intermittence" regions. An analysis is made of the influence of feedback provided by the Stokes radiation on the localization of an instability region.

Characteristics of the operation of lasers with intracavity nonlinear-optical frequency conversion have been investigated on many occasions. The attention has been usually on the attainment of the maximum conversion efficiency. On the other hand, the resonator losses due to nonlinear optical conversion of the fundamental frequency have a very strong influence on the lasing regimes. For example, a theoretical investigation of the operation of a ring picosecond laser with nonlinear losses, which are due to intracavity second harmonic generation, was investigated theoretically.[1] In particular, it was found that stable, unstable regular, and stochastic self-modulated lasing regimes are possible. Another example is provided by the results of Ref. 2, which deals with multistablity and chaotic operation of a ring laser with nonlinear losses resulting from multiphoton transitions in the active medium. The study reported in Ref. 3 was concerned with spatial–temporal instabilities of optical beams in ring systems with a cubic nonlinearity in liquid crystals (confirming once again the occurrence of the optical turbulence).

Subsequently, the influence of delay of feedback in a ring laser resonator on the instability of lasing was investigated.[4] Intracavity stimulated Raman amplification introduces considerable nonlinear losses and affects both the nature of formation of ultrashort pulses and the lasing regime.[5]

We shall report a theoretical investigation of the characteristics of the operation of a ring picosecond laser with intracavity stimulated Raman amplification of Stokes pulses and we shall allow for a positive feedback at the Stokes frequency. We shall adopt the following approximations:

1) the pulses going around the resonator retain their profiles and the round-trip time in the resonator is constant;

2) the spatial length of the pulses is considerably less than the resonator perimeter, but it exceeds considerably the thickness of the active and nonlinear media;[1]

3) only the pulses at the fundamental frequency are amplified (the interaction between the pulses at the fundamental and Stokes frequencies occurs solely in the nonlinear medium);

4) the nonlinear losses (for example, those induced by a semitransparent mirror) are different for the two waves.

Under these approximations the energies V and W of the pulses during the nth and $(n+1)$th passes are linked by the following recurrence relationships:

$$a_{n+1}=r_1 f_n \varphi_n,\quad b_{n+1}=r_2 b_n \varphi_n e^{c_n}, \tag{1}$$

where $\varphi_n = [1+(b_n/c_n)(e^{c_n}-1)]^{-1}$; $c_n = b_n + g f_n$, $f_n = a_n/(1+a_n)$. The normalized variables used above are defined as follows: $a_n = V_n/V_0$, $b_n = W_n GL$, $g = V_0 GLK$, $r_1 = KR_1$, and $r_2 = R_2$.

Here, V_n and W_n are the energies of the pulses at the fundamental and Stokes frequencies, respectively; V_0 is the saturation parameter of the active laser medium; K is the gain of the active medium; G is the gain of the stimulated-Raman-active medium, normalized to the unit energy of a pump pulse; L is the length of the stimulated-Raman-active medium; R_1 and R_2 are the reflections of the semitransparent mirror at the fundamental and Stokes frequencies, respectively (this allows for the linear losses).

The relationships in Eq. (1) describe the general case of a feedback affecting both waves. The ranges of the values of a_n and b_n in the limit $n\to\infty$ (attractors) are independent of the initial ("unrenormalized") values a_0 and b_0. However, before we analyze the process in its general form, we shall consider first lasing in the absence of feedback in respect of the Stokes wave ($r_2 = 0$), but in the presence of an external constant Stokes illumination ($b_n = \varepsilon$).

We shall investigate an attractor $\hat{a}(g) = \lim_{n\to\infty} a_n(g)$ describing our problem. In particular, if $G = 0$, we find that $\hat{a}(0) = r_1 e^{-\varepsilon} - 1$. Figures 1 and 2 give the results of a nu-

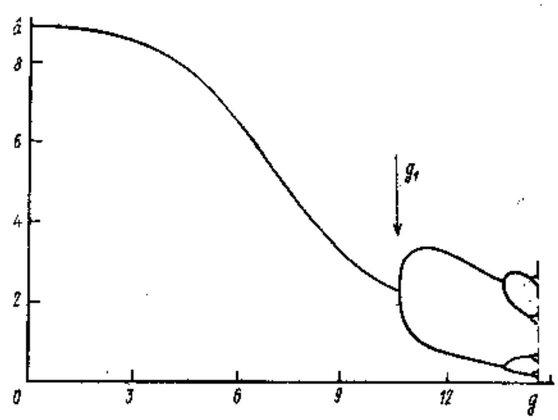

FIG. 1.

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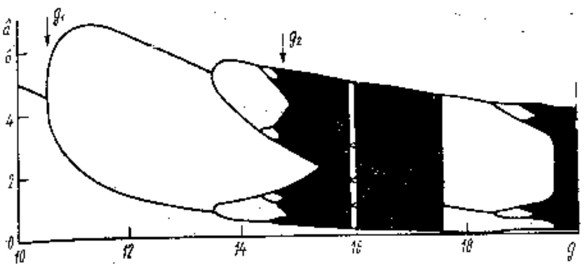

FIG. 2.

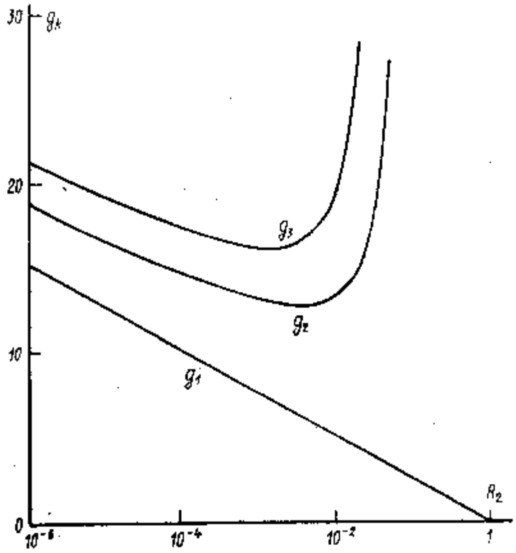

FIG. 4.

merical calculation of the structure of the attractor $\hat{a}(g)$ when $\varepsilon = 0.01$ and $r_1 = 10$. We can see that in the range $0 < g < g_1$ for each value of g there is one stable point and an increase in g causes $\hat{a}$ to fall monotonically, which is to be expected (because of the increase in the nonlinear losses). When we go over to the range $g > g_1$, the attractor structure becomes much more complex because lasing is now unstable. Initially, when $g = g_1$, we encounter the first bifurcation of the solution and then (on increase in g) the familiar frequency-doubling effect[6] creates consecutive bifurcations for each of the branches. However, right up to $g = g_2$ the attractor consists of a discrete even set of points. Finally, beginning from $g = g_2$ the attractor has its own special topological structure corresponding to transition to the optical turbulence region. A further increase in g gives rise to significant intermittence involving the reverse transition from the optical turbulence to the instability with a discrete (odd) number of states.

This type of development of an instability on increase in the nonlinear parameter is quite familiar (see, for example, Ref. 1). The characteristic features of the case under discussion are manifested primarily in the numerical values of the bifurcation points and in the turbulence structure. However, if the Stokes wave is included among their dynamic variables (because of the feedback), the situation becomes much more complex, because the recurrence relationship is now two-dimensional.

Figure 3 shows the structure of an attractor obtained directly by numerical calculations carried out using the expressions in Eq. (1) and assuming that $r_1 = 10$ and $r_2 = 0.001$. Comparing Fig. 3 with Figs. 1 and 2, we can see that there is a qualitative difference because, firstly, a region $0 < g < g_0$ appears where $\hat{a}(g) = \text{const}$ and, secondly, there is a considerable "smearing out" of the attractor in the optical turbulence region. The region appears because the losses experienced by the Stokes wave exceed its gain and the operation of the laser is practically free of nonlinear losses. If $g \gg g_0$, the threshold of generation of the Stokes wave is reached and the subsequent stages of changes in the nature of lasing are similar to those discussed above (stable point, discrete instability region, optical turbulence). Broadening of the attractor in the turbulence region [right up to disappearance characterized by $\hat{a}(0)$] is due to the fact that the limitations on the Stokes intensity are now lifted. A change in the feedback r_2 naturally alters considerably the structure of the attractor. Figure 4 gives the dependences of the singular points of the attractor (g_k, $k = 0,1,2$) on r_2. The dependence $g_0(r_2)$ falls monotonically on increase in r_2 (i.e., the threshold of generation of the Stokes wave falls on increase in the feedback strength, which is to be expected). However, the nonmonotonic behavior of the dependences of g_1 and g_2 on r_2 is unexpected. Initially (in the region $0 < r_2 < 0.005$) an increase in r_2 reduces the parameters $g_{1,2}$ (i.e., an increase in the nonlinearity results in an "earlier" onset of the instability). However, a further increase in r_2 causes $g_{1,2}$ to rise again. The physical explanation of the latter is at present

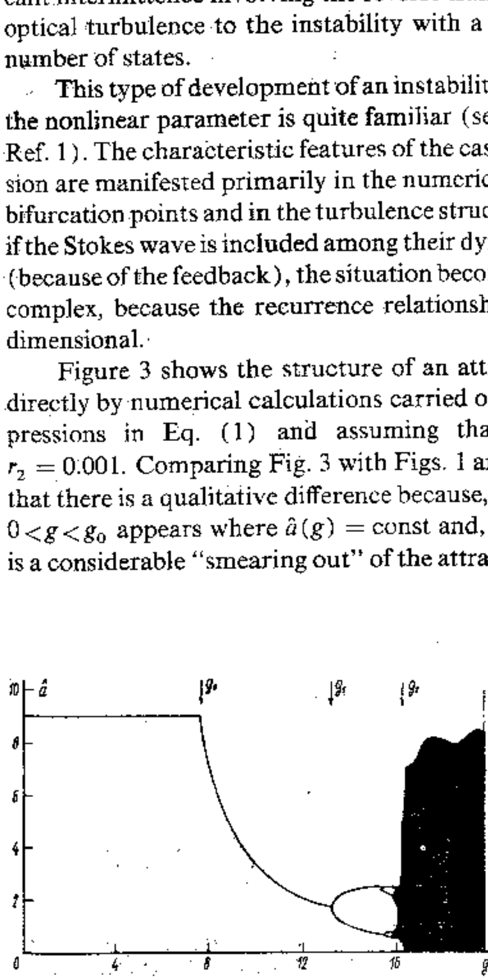

FIG. 3.

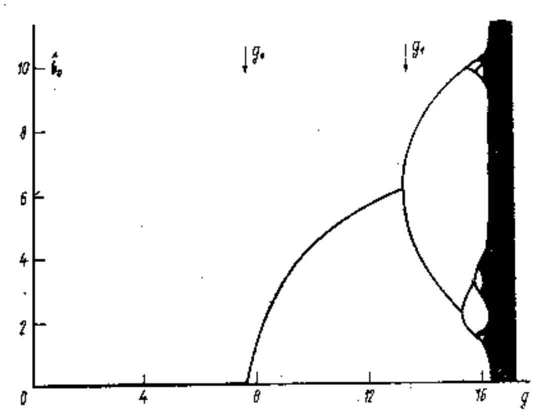

FIG. 5.

difficult to provide. It is necessary to investigate additionally the statistical properties of a sequence of pulses.

If the investigated ring laser system is regarded as a source of Stokes pulses, then it is interesting to consider an attractor of the $\hat{b} = \lim_{n\to\infty} b_n$ type. By way of example, Fig. 5 shows the dependence $\hat{b}(g)$ for $r_1 = 10$ and $r_2 = 0.001$. This dependence effectively includes practical recommendations on the selection of the conditions that ensure the maximum Stokes wave generation rate under stable conditions ($g < g_1$), etc.

The reported results should be useful in an analysis of the experimental data and in the development of ring lasers generating ultrashort pulses and experiencing nonlinear losses due to the Raman effect.

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Translated by A. Tybulewicz