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Enhancement of the efficiency of second-harmonic generation in a microlaser

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Abstract. It is shown that the use of a doubly resonant cavity provides a considerable increase in the intracavity SHG efficiency in microlasers in the case of small nonlinearity parameters.

Advances in laser miniaturisation put forward a problem of designing miniature laser frequency converters. Conventional schemes used to increase the efficiency of nonlinear optical processes are either inefficient, when applied to microlasers, or cannot be realised in small-size laser systems.

Consider, for example, frequency doubling. In conventional schemes, when limitations on the length of a cavity and a nonlinear element are absent, the SHG efficiency is achieved either by placing a nonlinear crystal inside a laser cavity [1 – 3] or by injecting laser radiation with frequency ω into an external cavity, which has a high Q factor for radiation with frequency ω [4, 5] or frequencies ω and 2ω [6, 7].

Of considerable interest from the standpoint of miniaturisation are the schemes with nonlinear crystals inside a laser cavity [1 – 3], particularly schemes with frequency self-doubling in an active medium itself [8 – 10]. It is common to use only one cavity with a high Q factor (the cavity of a laser itself at the frequency ω) in such schemes, and the cavity for the second harmonic is absent because the corresponding transmission of cavity mirrors (or one of them) is close to unity.

Unfortunately, it is impossible to obtain a high SHG efficiency in microlasers under such conditions. One can overcome this problem (see below) by using a doubly resonant cavity with a high Q factor, i.e., a cavity whose Q factor is high at both frequencies ω and 2ω.

Consider a microlaser with frequency self-doubling in an active element with selective mirrors on its faces. One of the mirrors is assumed to be totally reflecting for both frequencies ω and 2ω. The reflectivities of the second mirror at these frequencies are r_ω and $r_{2\omega}$. For simplicity, we ignore distributed linear loss for the second harmonic.

The dynamics of lasing in a system with a doubly resonant cavity can be described by the following system of rate equations:

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$$\dot{a}_1 = \frac{a_1}{2T_c}[k_1(N-1) - \sqrt{\varepsilon}\, a_2 \sin\psi], \tag{1}$$

$$\dot{a}_2 = -\frac{k_2}{2T_c}a_2 + \frac{\sqrt{\varepsilon}}{2T_c}a_1^2 \sin\psi, \tag{2}$$

$$\dot{\psi} = \frac{\sqrt{\varepsilon}}{2T_c}\left(\frac{a_1^2}{a_2} - 2a_2\right)\cos\psi, \tag{3}$$

$$\dot{N} = \frac{1}{T_1}\left[(1+\eta) - N\left(1 + a_1^2\right)\right]. \tag{4}$$

Here, $\psi = 2\varphi_1 - \varphi_2$; $a_{1,2} = (I_{1,2}/I_s)^{1/2}$ are dimensionless amplitudes of intracavity fields at the fundamental frequency and the second harmonic, respectively; $\varphi_{1,2}$ are their phases; $I_{1,2}$ are the intensities of these fields; I_s is the saturation intensity of an active medium; $k_{1,2}$ are coefficients of linear loss in the doubly resonant cavity; T_c is the cavity round-trip time; $\varepsilon = \chi l^2 I_s$ is the nonlinearity parameter; χ is the nonlinearity factor; l is the length of an active (nonlinear) element; T_1 is the inverse-population relaxation time; N is the ratio of the inverse population to the threshold value; and $1+\eta$ is the ratio of the pump power to the threshold value. Equations (1) – (4) are written under the assumption that the detuning of the fundamental frequency from the gain line centre is small and that the natural cavity frequencies ω_{1c} and ω_{2c}, which correspond to the fundamental frequency and the second harmonic, satisfy the condition $\omega_{2c} = 2\omega_{1c}$.

The intracavity SHG in a laser with a doubly resonant cavity was theoretically studied in Refs [11 – 13], where stationary lasing regimes and their stability were analysed. However, a detailed analysis of the effect of the Q factor of a doubly resonant cavity on the intracavity SHG was not carried out.

System of equations (1) – (4) has two stationary solutions. In accordance with (3), one solution takes place for $\cos\psi = 0$, and the other one is obtained for $a_1^2 = 2a_2^2$. In the first case, the intracavity field amplitudes are determined by the formulas

$$a_1^2 = \frac{-B + \left(B^2 + 4A\eta\right)^{1/2}}{2A}, \quad a_2^2 = \varepsilon\left(\frac{a_1^2}{k_2}\right)^2, \tag{5}$$

where $A = \varepsilon/k_1k_2$; $B = 1 + A$. In the second case, we have

$$a_2^2 = \left(\eta - \frac{k_2}{2k_1}\right)\left(2 + \frac{k_2}{k_1}\right)^{-1}, \quad a_1^2 = 2a_2^2. \tag{6}$$

The second solution is always stable and exists for

$$\eta = -\frac{k_2}{2k_1} > 0, \quad \frac{k_2}{\sqrt{\varepsilon}} > 2a_2. \tag{7}$$

In the domain of parameters specified by inequalities (7), the first solution [formulas (5)] is unstable. Solutions (5) and (6) have a common stability boundary on which, as follows from the analysis, bistability exists. Bistable regimes will be analysed elsewhere.

On the basis of the formulas presented above, we analysed the dependencies of the SHG efficiency $q = P_2/P$ on k_2 (P_2 is the output power of the second harmonic and P is the pump power). This dependence is shown in Fig. 1 for different k_1 and P/P_{th} (P_{th} is the threshold power of a Nd^{3+} : $LiNbO_3$ microlaser considered here for 1% loss at the fundamental frequency). The calculations were made for a Nd^{3+} : $LiNbO_3$ laser with $\varepsilon = 10^{-7}$, which corresponds to an active element 0.5 mm long. The pumping efficiency was assumed to be 50%.

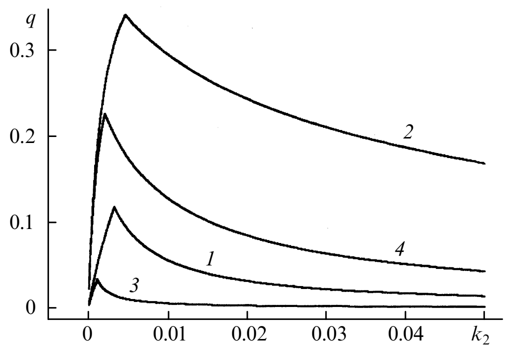

Figure 1. Dependence of the SHG efficiency q on the transmission coefficient $k_2 = 1 - r_{2\omega}$ of a doubly resonant cavity at the second harmonic for the loss coefficient at the fundamental frequency $k_1 = 0.1$ (*1, 2*) and 0.5% (*3, 4*) and pump powers $P = 1.5P_{th}$ (*1, 3*) and $10P_{th}$ (*2, 4*).

One can see from the figure that the use of a cavity with a high Q factor at the frequency 2ω allows us to increase the second-harmonic intensity by a factor as large as several dozens (when a cavity at the frequency 2ω $\eta_{2\omega} = 0$ is absent and $q \ll 0.1$). This increase is caused by the fact that when a cavity for the second harmonic is absent, lasing at the frequency 2ω takes place in nonoptimal conditions, and, therefore, the second-harmonic efficiency is low. An optimum choice of the Q factor at the frequency 2ω enables one to increase the efficiency of intracavity SHG.

Note that in the case of small ε, an increase in efficiency can be obtained only for the cavities having a rather high Q factor for the fundamental frequency. Under actual conditions, the Q factor is limited by loss mechanisms that cannot be completely eliminated (distributed loss in an active element, mirror loss, loss caused by the presence of interfaces in a cavity). If the limiting loss k_1 exceeds ε, i.e., the condition of optimum lasing $k_1 = \varepsilon$ [14] is not fulfilled, the use of a cavity with a high Q factor for the second harmonic provides a considerable increase in the SHG efficiency.

Thus, the use of a doubly resonant cavity for intracavity SHG in microlasers results in a considerable increase in the SHG intensity. Optimum characteristics of concrete frequency converters on the basis of microlasers with a doubly resonant cavity can be calculated using the formulas obtained above.

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