Pramāṇa – J. Phys., Vol. 25, No. 6, December 1985, pp. 713–718. © Printed in India.

Study of synchronously mode-locked and internally frequency-doubled CW dye laser

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MS received 27 February 1985; revised 30 September 1985

Abstract. The analysis of the characteristics of a synchronously mode-locked and internally frequency-doubled dye laser is presented. Dependence of dye laser pulse characteristics on the cavity length mismatch of the pump laser and dye laser is studied. Variation of the minimum pulsewidth with intracavity bandwidth and the harmonic conversion efficiency is presented in the form of graphs.

Keywords. Dye laser, frequency-doubling, mode-locking; cavity mismatch; pulsewidth; peak intensity.

PACS No. 42·55; 42·60

1. Introduction

The synchronously pumped mode-locked dye laser has been studied extensively (Kim *et al* 1978; Minami and Era 1980; Ausschnitt *et al* 1979) because of its ability to produce continuous trains of picosecond and subpicosecond pulses tunable in the visible region. In addition, its power conversion efficiency is so high that simultaneous operation of two dye lasers is possible in tandem (Kuhl *et al* 1977; Heritage and Jain 1978) or in parallel configuration to generate two independently tunable pulse sources (Jain and Heritage 1978). Recently a synchronously mode-locked laser has been employed for the study of fast chemical reactions of molecules (Taylor *et al* 1979) by producing continuous trains of UV picosecond pulses from a synchronously mode-locked and intracavity frequency-doubled (SMLFD) CW dye laser (Yamashita *et al* 1980, 1982). The SMLFD dye laser has been studied both experimentally (Welford *et al* 1980; Yamashita *et al* 1980) and theoretically (Yamashita *et al* 1982).

The pulse characteristics of the usual synchronously mode-locked (SML) CW dye laser were theoretically considered by Kim *et al* (1978) and Ausschnitt *et al* (1979) independently. Kim *et al* followed a self-consistent approach describing the steady-state pulse properties in terms of the system parameters where it was shown that the pulse duration is determined by 1/3 power of the duration of pumping pulse and inverse 2/3 power of the bandwidth of a frequency tuning element. Following the steady-state approach of Haus (1975), Ausschnitt *et al* showed that the pulse duration is proportional to 1/2 power of the duration of pumping pulse and inverse 1/2 power of the bandwidth of the tuning element.

Yamashita *et al* (1982) extended the model of Kim *et al* to include the effects of nonlinear losses due to the second harmonic generation (SHG) process, the birefringent filter effect due to the intracavity SHG crystal, and the insertion losses of the crystal. The main drawback of Ausschnitt *et al*'s model is that it does not reproduce well the experimental result of the broadening of the pulse duration in the region where the cavity length is shorter than the optimum. However, since this model is based on the well-tested theory of Haus which has been extensively used in the analysis of mode-locking of lasers including semiconductor lasers (van der Ziel 1981) it is convenient and worthwhile to utilise this model to study the properties of SMLFD CW dye laser. In the present paper we study the SMLFD CW dye laser by extending the work of Ausschnitt *et al* so as to include the nonlinear effects of intracavity SHG process. The effects of cavity detuning, intracavity bandwidth and the harmonic conversion efficiency of the nonlinear crystal on the characteristics of the dye laser pulses are obtained from the present analysis.

Derivation of the basic governing equations of the analysis is presented in the following section. The results are discussed in § 3 and the conclusions in § 4.

2. Governing equations

The mode-locked laser system in question consists of a amplifier which is repetitively pumped by the output pulses from an external mode-locked laser, an SHG crystal and an optical filter used for wavelength tuning inside a Fabry-Perot resonator. Rewriting the steady-state equation (1) of Ausschnitt *et al* (1979), we have

$$[G(t) - L - A_{SHG}(t) + \delta T \mathrm{d}/\mathrm{d}t + 1/W_c^2 \mathrm{d}^2/\mathrm{d}t^2]\, V(t) = 0, \tag{1}$$

where $G(t)$ is the round-trip gain of the dye laser amplifier, L the constant cavity loss, W_c the intracavity bandwidth determined by the optical filter and $V(t)$ the time-dependent electric field pulse envelope of the dye laser pulse. The parameter δT, the timing mismatch between the pump pulse period and the cavity round-trip time of the dye laser pulse, is defined as

$$\delta L = -c(\delta T/2), \tag{2}$$

where δL is the cavity length mismatch between the SMLFD dye laser and the pump laser and c is the velocity of light.

The round-trip gain of the laser amplifier is assumed to be of the form (Ausschnitt *et al* 1979)

$$G(t) = G_{s_0}\left(1 - \int_{-\infty}^{0} I(t)\,\mathrm{d}t\right) + \left(\frac{1}{\tau_r} - I_0 G_{s_0}\right)t - \left[\frac{1}{\tau_c^2} + \frac{I_0}{2}\left(\frac{1}{\tau_r} - I_0 G_{s_0}\right)\right]t^2, \tag{3}$$

where

$$G_{s_0} = \frac{G_m E_{p_0}}{2}\left[1 + \tan\mathrm{h}\frac{t_0}{\tau_p}\right], \tag{4a}$$

$$\frac{1}{\tau_r} = \frac{G_m E_{p_0}}{2\tau_p}\sec\mathrm{h}^2\frac{t_0}{\tau_p}, \tag{4b}$$

$$\frac{1}{\tau_c^2} = \frac{G_m E_{po}}{\tau_p^2} \operatorname{sec h}^2 \frac{t_0}{\tau_p} \tan h \frac{t_0}{\tau_p}. \tag{4c}$$

In the above equations $G_m = \sigma_p Nl/2$ is the maximum available gain expressed in terms of absorption cross-section of the dye at the pump wavelength σ_p, the total population density of the dye N, and length of the gain medium l. The parameter t_0 is the advance of the pump pulse relative to the dye pulse, τ_p is the pump pulsewidth and E_{p_0} is the total energy in the pump pulse normalized to the saturation energy of the dye absorption. For the gain of the form given in (3) equation (1) has a gaussian pulse solution of the form

$$I(t) = I_0 \exp(-\gamma t^2), \tag{5}$$

with the pulse duration $\tau = (2 \ln 2/\gamma)^{1/2}$. The photon intensity of the dye pulse is $I(t) = \sigma |V(t)|^2 / h\nu A$, where σ and $h\nu$ are, respectively, the optical cross-section and photon energy of the lasing transition, and A is the cross-sectional area of the beam at the dye jet.

Substitution of (3) and (5) in (1) gives the following characteristic equations:

$$\frac{G_m E_{p_0}}{2}\left(1 + \tan h \frac{t_0}{\tau_p}\right)\left(1 - \frac{\sqrt{\pi}}{2} \frac{\tau}{(2 \ln 2)^{1/2}} I_0\right) - L - \alpha_l - \sqrt{2}\alpha_s = \frac{2 \ln 2}{W_c^2 \tau^2}, \tag{6}$$

$$\left(\frac{G_m E_{p_0}}{2\tau_p} \operatorname{sec h}^2 \frac{t_0}{\tau_p}\right)\tau - I_0 \tau \left[\frac{G_m E_{p_0}}{2}\left(1 + \tan h \frac{t_0}{\tau_p}\right)\right] = (\delta T/\tau) 2 \ln 2, \tag{7}$$

$$2(1 - \sqrt{2}\alpha_s) + \frac{2\tau^2}{2 \ln 2}\left(\frac{G_m E_{p_0}}{\tau_p^2} \operatorname{sec h}^2 \frac{t_0}{\tau_p}\right) + I_0 \delta T = \frac{4 \ln 2}{W_c^2 \tau^2}. \tag{8}$$

The effect of intracavity frequency-doubling crystal, given by the term $A_{\mathrm{SHG}}(t)$, is considered in the above derivation by assuming that the doubling crystal modifies a gaussian pulse of the form given in (5) into $I_0 \exp(-\sqrt{2}\alpha_s/2 - \alpha_l) \exp -(1 - \sqrt{2}\alpha_s)\gamma t^2$. Here, α_l is the linear insertion loss due to the SHG crystal and α_s is the SHG conversion efficiency coefficient of the nonlinear crystal.

Equations (6)–(8) describe three unknown dye pulse parameters τ, I_0 and t_0 in terms of the measurable system parameters G_m, E_{p_0}, τ_p, L, δT, α_l, α_s, and W_c. These equations reduce to equations (9) of Ausschnitt *et al* (1979) for $\alpha_l = \alpha_s = 0$ except for the factor $(2 \ln 2)^{1/2}$ which is due to the difference in the definition of the mode-locked pulsewidth.

3. Results and discussion

The three characteristic equations (6)–(8) are solved numerically and the results are presented in the form of graphs. Figure 1 shows the variation of the pulse duration and relative peak intensity of the fundamental pulse as a function of cavity mismatch for various values of conversion efficiency α_s. From this figure we see that with increase of the conversion efficiency (longer crystals) the pulse duration is broadened and the intensity is decreased. The pulse broadening due to the increase of α_s is due to the following process. During the SHG process the power of the fundamental wave is mostly converted to the SH wave at the pulse peak of the fundamental one and is only converted

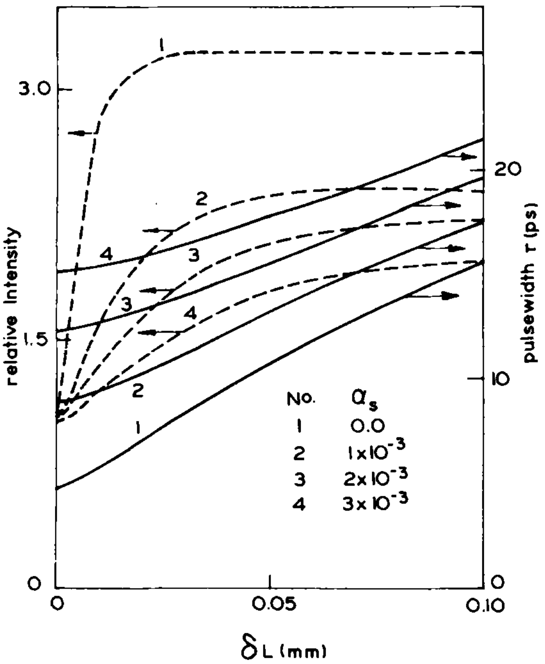

Figure 1. Pulsewidth and peak intensity of pulse as functions of cavity mismatch for different conversion efficiencies.

very slightly at its extremes, which ultimately results in the broadening of the fundamental pulse. In addition to the increase of nonlinear losses α_s due to the SHG process, the increase in the length of the nonlinear crystal results in the decrease of the effective intracavity bandwidth due to birefringent effect of the crystal. The effect of both these changes is to broaden the fundamental dye laser pulse as shown in figure 1.

The dependence of the minium pulsewidth on the conversion efficiency by keeping the intracavity bandwidth constant is presented in figure 2, while the dependence of the minimum pulsewidth on the intracavity bandwidth for constant conversion efficiency is presented in figure 3. It is seen that the increase in pulse duration is more rapid for the increase in the conversion efficiency above $\alpha_s \geqslant 1 \times 10^{-3}$ and for the decrease in intracavity bandwidth less than $W_c \leqslant 1{\cdot}5 \times 10^{13}\ \mathrm{sec}^{-1}$. The present results are similar to those of Yamashita *et al* (1982) except for the results presented in figure 1. As mentioned earlier the present model predicts the results only in the region where δL is positive as given in figure 1 and these results cannot be compared with those of Yamashita *et al* (1982) which are given for the negative δL values.

4. Conclusion

In this paper we have presented the analysis of the characteristics of a SMLFD CW dye laser. The variation of the pulsewidth and the peak intensity of the fundamental dye laser pulse as a function of cavity mismatch for different harmonic conversion efficiencies (different crystal lengths) is studied. Furthermore, the dependence of the

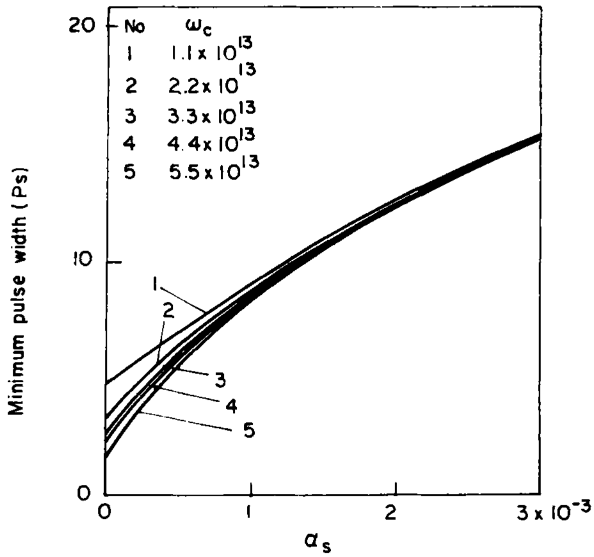

Figure 2. Variation of minimum pulsewidth with harmonic conversion efficiency for constant intracavity bandwidth.

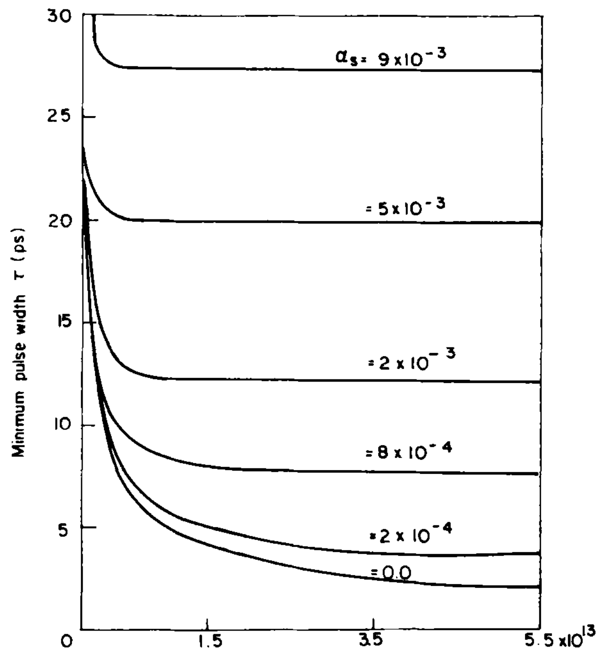

Figure 3. Variation of minimum pulsewidth with intracavity bandwidth for constant harmonic conversion efficiency.

minimum pulse duration on the harmonic conversion efficiency and intracavity bandwith is analysed and the results are presented in the form of graphs.

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