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Femtosecond pulse generation in a cw pumped passive mode-locked linear rhodamine 6G—DODCI dye laser

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ABSTRACT: The femtosecond pulse generation in a cw pumped linear passive mode-locked rhodamine 6G - DODCI dye laser is studied. The laser is operated without and with a prism pair. The DODCI concentration is varied and the absorber jet is detuned from the CPM postion. The influence of the prism pair positioning is investigated. A fast partial absorption recovery of DODCI is necessary for sufficient background suppression. With the prism-pair balanced oscillator soliton-like stable pulses of 50 fs duration were generated independent of detuning the absorber jet out of the CPM position.

1. INTRODUCTION

The femtosecond pulse generation in cw laser pumped colliding pulse mode-locked (CPM) ring dye lasers is well established (Shank 1988). Antiresonant ring linear CPM dye lasers were operated with similar performance data as ring CPM dye lasers (Diels 1990). Here a cw argon ion laser pumped linear rhodamine 6G - DODCI femtosecond dye laser is investigated experimentally and theoretically. The schematic experimental setup is shown in Fig.1. Colliding pulse mode-locking is achieved by placing the DODCI loss jet in the center of the resonator. The laser is detuned from the CPM - position by moving mirror M1.

2. THEORETICAL ANALYSIS

The pulse development and background suppression in multiple transits through the saturable absorber is illustrated in Fig.2. The pulse shaping action of the saturable absorber and of the gain medium are considered. The dotted line shows the input pulse shape. The saturable absorption dynamics of DODCI is discussed by Penzkofer and Bäumler (1991). At the laser wavelength of $\lambda_L = 620nm$ thermally elevated N-isomers and P-isomers of DODCI contribute to the absorption. The $S_1 - S_0$ relaxation times are $\tau_N = 1.3ns$ and $\tau_P = 1.4ns$ (Bäumler and Penzkofer 1990). A fast partial absorption recovery (time constant τ_{rec}) is present in both isomers, because in the P-isomers there occurs a fast relaxation ($\tau_{rec} = 0.95ps$, Angel et al 1989) out of the populated Franck Condon state, and in the N-isomers there occurs a fast refilling of the emptied S_0-state by spectral cross-relaxation. In Fig.2 the solid curve is calculated for $\tau_{rec} = 1ps$ while the dashed curve is calculated for $\tau_{rec} = 10ns$ (100 round-trips, small-signal transmission of

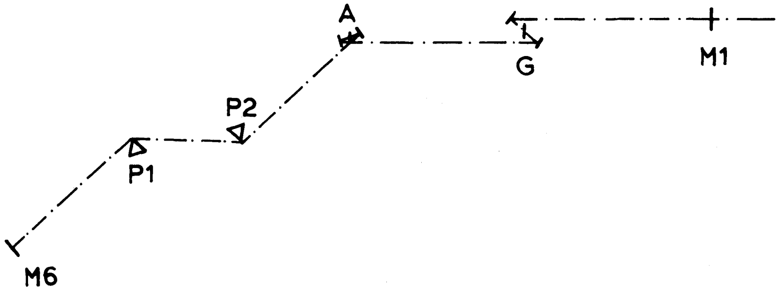

Fig. 1. Schematic laser arrangement.

absorber $T_0 = 0.95$). The fast partial absorption recovery of the slow saturable absorber is necessary for sufficient background suppression and the formation of femtosecond pulse trains.

The steady-state pulse duration is determined by equating the pulse shortening and pulse broadening within a single round-trip. Pulse shortening is caused by saturable absorption of the mode-locking dye. The gain depletion of the lasing dye acts slightly pulse broadening. Without a prism pair in the resonator the pulse broadening is caused mainly by the positive group velocity dispersion (GVD) of the positive self-phase modulated (SPM) pulses in the gain and loss jet. The solvent contributions (ethylene

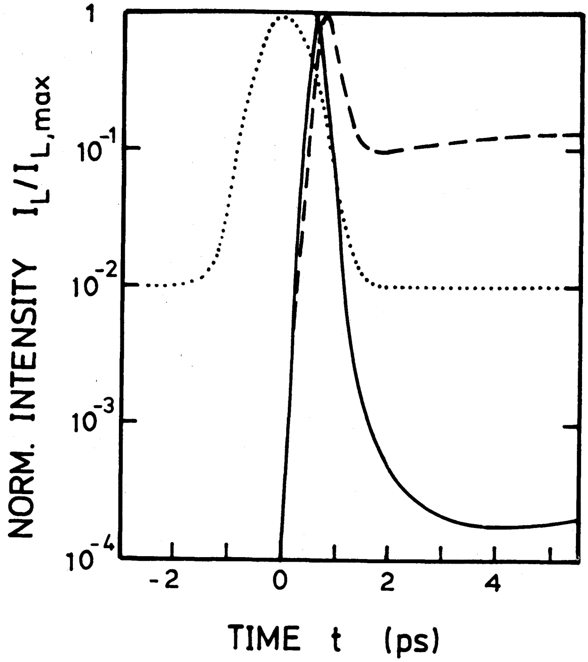

Fig. 2. Transient pulse shortening and background suppression.

glycol are dominant for the GVD (dispersion of refractive index) and the SPM (optical Kerr effect, $n_2 > 0$). With a prism pair in the resonator the laser performance depends on the prism separation (30 cm in our case) and on the apex heights h_1 (0.68 mm in our case) and h_2 of the laser beam passing through the prisms. The behaviour is illustrated in Fig.3. The spectral transit time lags per round-trip for the prism pair, $\partial t_{pr}/\partial\tilde{\nu}_L$, and of the total resonator, $\partial t_{tr}/\partial\tilde{\nu}_L$, including the GVD of the gain and loss jet (thicknesses $d_A = 35\mu m$ and $d_G = 250\mu m$) are shown by the dashed and solid curves in Fig.3a, respectively. The laser pulse duration is given by

$$\Delta t_L \approx \mid \Delta t_{ini} + \delta t_{tr} - \delta t_{AG} \mid$$

where Δt_{ini} is the inital pulse duration, $\delta t_{tr} \approx (\partial t_{tr}/\partial\tilde{\nu}_L)\Delta\tilde{\nu}_L[ln(\rho_1^{-1})]^{-1}$ is the total transit time lag (ρ_1 is output mirror reflectivity), and δt_{AG} is the combined temporal pulse shortening of the absorber and the gain medium. The spectral width of the laser is given by $\Delta\tilde{\nu}_L \approx [(\Delta\tilde{\nu}_L^{bwl})^2 + (\delta\tilde{\nu}_c)^2]^{1/2}$ where $\delta\tilde{\nu}_c$ is the frequency chirp caused by the SPM ($\delta\tilde{\nu}_c \propto \Delta t_L^{-1}$).

The steady-state condition requires $\Delta t_L = \Delta t_{ini}$. Three regions have to be distinguished:
(i) In the soliton-like pulse formation region I (Martinez et al 1985) the negative GVD interacts with the positve SPM and it is $\delta t_{tr} = -2\Delta t_L + \delta t_{AG}$. Stable femtosecond pulse trains are generated. At the prism-pair balanced position h_{2m} it is $\Delta t_{ini} = \Delta t_{min} \approx 0.5/\Delta\nu_{AMP}$, where $\Delta\nu_{AMP}$ is the spectral width of the amplification profile. The shortest stable pulses are generated.
(ii) In region II the pulse compressive negative GVD tries to generate pulses of $\Delta t_L < \Delta t_{min}$ and $\Delta\tilde{\nu}_L > \Delta\tilde{\nu}_{AMP}$. The laser falls below threshold and restarts again (self-quenching laser operation). At $h_2 = h_{2c}$ it is $\delta t_{tr} = 0$.
(iii) In region III the pulse broadening by the positive group velocity dispersion is counteracted by the saturable absorber pulse shortening, i.e. $\delta t_{tr} = \delta t_{AG}$. The laser stability is moderate.
In the transient femtosecond pulse formation start-up process the initial pulse duration is approximately given by $\Delta t_{ini} = \Delta t_{min}$ (duration of statistical fluctuating spontaneous emission, Glauber 1972). It is modified to the steady-state value by the laser build-up process.

3. EXPERIMENTAL STUDIES

Without the prism pair in the resonator pulse durations of 140 fs were obtained for a DODCI small-signal transmission of T_0=0.97 at the lasing wavelength of $\lambda_L = 620nm$. Detuning the loss jet from the center position resulted in the formation of trailing pulse tails of duration up to 900 fs.

The dependence of the femtosecond laser pulse duration and spectral width on the prism pair positioning is illustrated in Fig.3b and 3c for T_0=0.97. At the prism-pair balanced position h_{2m} stable pulses of 50 fs duration were generated ($\lambda_L = 620nm$) independent of the absorber jet detuning from the resonator center over distances of many centimeters. Decreasing the DODCI concentration from $3 \times 10^{-4} mol/dm^3$ to $3 \times 10^{-5} mol/dm^3$, the pulse duration increased from 50 fs to 110 fs and the peak laser wavelength shifted from 620 nm to 610 nm.

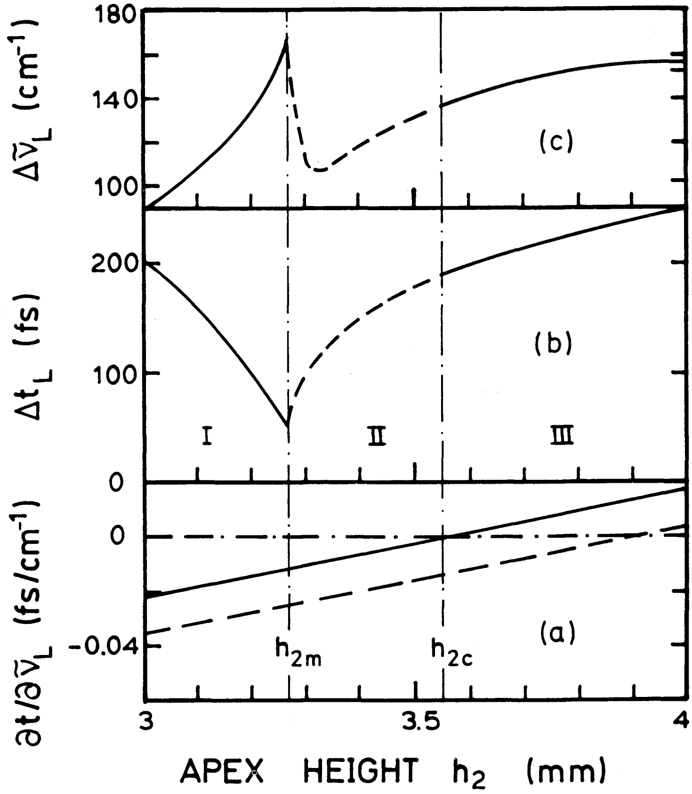

Fig. 3. Dependence of laser performance on prism pair positioning.

The advantages of the described linear femtosecond dye laser compared to the ring CPM dye laser are its easy alignment and the reduced number of optical components.

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