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Properties of a Distributed Feedback Dye Laser with Integrated Amplifier

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Abstract. Several properties of a compact laser light source built up by a distributed feedback dye laser (DFDL) and an amplifier realized with only one dye solution cuvette are discussed. It is shown that in this arrangement the region of single pulse generation with respect to the pump energy applied to the DFDL is extended in comparison with a pure DFDL oscillator set-up. This effect is mainly caused by the radiation coupled back from the amplifier into the DFDL oscillator. The results of numerical simulations are discussed and compared with some experimental facts published in a previous paper.

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The distributed feedback dye laser (DFDL) is a useful device for the generation of ultrashort light pulses in an inexpensive way. In the last few years it has attracted increasing attention [1–12]. Using the conventional arrangement as shown in Fig. 1 the generation of single pulses is possible only for pump energies exceeding the threshold values by no more than 30% when subnanosecond pump pulses, e.g. of a N_2-laser, are applied. The behaviour of a DFDL immediately at threshold was especially investigated in our previous paper [13].

In order to get more intense single pulses several arrangements for the selection of single pulses out of a pulse train usually emitted by the DFDL were investigated [14–17]. Further enhancement of the intensity and energy is obtained by subsequent amplification [18–21].

An essential disadvantage of the oscillator-amplifier arrangements usually proposed is the large experimental expense especially for the adjustment of many optical elements. A compact oscillator-amplifier set-up containing only one cuvette for the active medium was proposed and experimentally investigated in [22]. It is depicted in Fig. 2.

Whereas in conventional oscillator-amplifier systems the influence of amplified spontaneous emission (ASE) generated in the oscillator on the amplifier is suppressed by certain means (e.g. diaphragms, saturable absorbers,

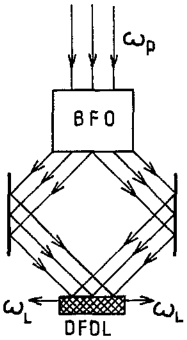

Fig. 1. DFDL oscillator set-up. The beam forming optic (BFO) contains a cylindric lens for focusing the pump radiation with frequency ω_p on a line in the dye solution and a beam splitter (semitransparent mirror or grating)

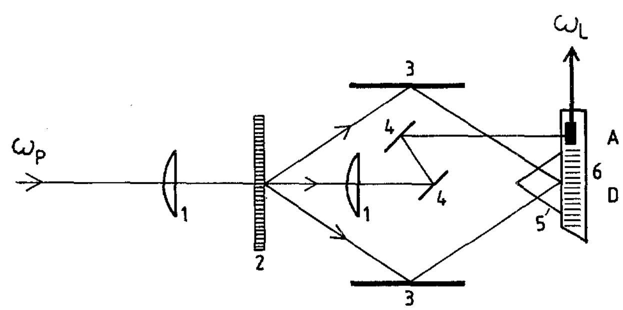

Fig. 2. Oscillator-amplifier arrangement used in the experiments [22] (*1* cylindrical lenses, *2* holographic grating, *3*, *4* mirrors, *5* quartz prism, *6* dye cuvette, *D* oscillator (DFDL) region, *A* Amplifier region). The amplifier pump pulse can be delayed with respect to the oscillator pumping by a suitable movement of the mirror pair 4

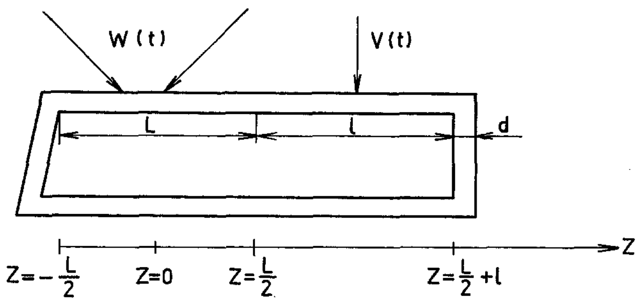

Fig. 3. Scheme of the dye cuvette in the oscillator-amplifier set-up shown in Fig. 2

such a suppression is impossible in our compact set-up. Therefore, only laser oscillators with a short pulse formation time and a fast intensity increase in the leading pulse edge are suitable for this arrangement. These properties leading to a low ASE content in the laser output are proven to be valid for DFDL [23].

Besides the simplified adjustment and compactness, a further advantage of our arrangement is the depletion of the population inversion in the oscillator by the backward propagating amplifier radiation suppressing the generation of further pulses and extending the dynamic range for single pulse generation in the oscillator. In this way the effect of inversion depletion observed by using an external mirror [15] is enhanced.

In the present paper we give a theoretical description of the emission properties of the DFDL-amplifier arrangement shown in Fig. 2 and compare the theoretical with the experimental results reported in [22].

1. Basic Equations

The basic equations for pulse generation by a DFDL were derived and discussed in [11, 13]. It was shown that a spontaneous emission source term is only relevant within a small range in the vicinity of the laser threshold and in the minima between the pulses emitted by the DFDL. The ASE source term can be neglected in evaluating both the peak intensity and the FWHM of the laser pulses. Using the equations derived in [11, 13] and neglecting the source term the pulse generation by the DFDL in its fundamental mode is described by the following equations:

$$\frac{dI_L}{dt}=u(b-\varrho)I_L\,, \tag{1}$$

$$\frac{db}{dt}=-\alpha\kappa I_L+\varrho_L W(t)n\,, \tag{2}$$

Where $I_L(t)$ is the normalized laser output intensity; $b(t)$ marks the normalized population inversion; $W(t)$ is the pump rate and n the total number density of dye molecules. κ denotes the nonresonant losses in the laser medium. The deviation of the real laser threshold from κ is determined by ϱ, and α is a constant depending on the spatial field strength behaviour of the fundamental DFDL mode (cf. [11]).

Now, we consider the oscillator amplifier arrangement as shown in Fig. 2. We assume that the oscillator is located in the region between $z=-L/2$ and $z=L/2$ and that the amplifier extends between $z=L/2$ and $z=L/2+l$ (Fig. 3). Since radiation with the photon flux density I_B (note that I_B is again normalized with respect to the laser emission cross section σ_L) is coupled back from the amplifier into the oscillator we must add in (2) a term $-(\kappa+b)I_B$ describing the depopulation of the upper laser level by the left propagating amplifier radiation. This process can lower the density of the dye molecules in the upper laser level to well below the threshold value. Therefore, the exact density $\bar{N}=(\kappa+b)/\sigma_L$ must be taken into consideration. Instead of (2) the equation of motion for $b(t)$ now reads

$$\frac{db}{dt}=-\alpha\kappa I_L-(\kappa+b)I_B+\sigma_L Wn\,. \tag{3}$$

Denoting the normalized photon flux densities propagating in the amplifier in the $\pm z$ direction with $I^{\pm}$ we find the following equations of motions:

$$\left(\frac{1}{u}\frac{\partial}{\partial t}\pm\frac{\partial}{\partial z}\right)I^{\pm}(z,t)=(\sigma_L N-\kappa)I^{\pm}(z,t)\,, \tag{4}$$

where $N(z,t)$ describes the density of the dye molecules in the upper amplifier level. N obeys the equation

$$\frac{\partial N}{\partial t}=-I_s N+V(t)n\,, \tag{5}$$

with

$$V(t)=\sigma_p F_p^A\,. \tag{6}$$

F_p^A is the photon flux density of amplifier pump radiation, and I_s denotes the total photon flux density in the amplifier.

$I_{\pm}(z,t)$ fulfills the following boundary conditions (Fig. 3):

$$I^{+}\left(z=\frac{L}{2},t\right)=I_L(t)\,, \tag{7}$$

$$I^{-}\left(z=\frac{L}{2}+l,t\right)=RI^{+}\left(z=\frac{L}{2}+l,t-\frac{2\eta d}{c}\right). \tag{8}$$

As the index of refraction η of the quartz cuvette and that of the dye solution itself are approximately the same, we take into account only the reflection at the boundary between the quartz glass and the air. The Fresnel reflectivity is $R=0.035$. Corresponding to our experimental arrangement we use in the numerical calculations for the cuvette thickness $d=3.6$ mm. The normalized output laser intensity is given by

$$I(t)=(1-R)I^{+}\left(z=\frac{L}{2}+l,t-\frac{\eta d}{c}\right). \tag{9}$$

Since the ASE in the DFDL is strongly suppressed [23, 24] it can be assumed that relevant ASE is only generated in the amplifier. The spectral photon flux densities $F_\omega^{\pm}$ of the ASE radiation propagating in the directions $\pm z$ are determined by the following equations [24, 25]:

$$\left(\frac{1}{u}\frac{\partial}{\partial t}\pm\frac{\partial}{\partial z}\right)F_\omega^\pm=(\sigma_L(\omega)N-\kappa)F_\omega^\pm+\bar{g}E(\omega)\Gamma_2 N\,. \quad (10)$$

The first term on the right-hand side of (10) describes the stimulated emission; the second represents the source term caused by spontaneous emission. $E(\omega)$ is the fluorescence spectrum normalized to the fluorescence quantum yield $\int E(\omega)d\omega=\Phi$.

In our further considerations we assume $\Phi\approx 1$. Γ_2 is the relaxation rate of the upper amplifier level and $\bar{g}$ a geometry factor determining the portion of spontaneously emitted photons entering the solid angle of propagation of the laser photons; it is assumed to be approximately constant.

To obtain the total ASE intensity we use the following approximation for the spectral integration in (10):

$$\int\sigma_L(\omega)F_\omega^\pm d\omega\approx K\sigma_L(\omega_L)F_{\mathrm{ASE}}^\pm\,. \quad (11)$$

where K^{-1} is a measure of the extent to which $\sigma_L(\omega_L)$ exceeds the average value $\frac{1}{\Delta\omega}\int\sigma_L(\omega)d\omega$ ($\Delta\omega$ is the bandwidth of the laser transition). Since one usually works near the center of the laser line, K is assumed to be a number smaller than one. Using again the normalization $I_{\mathrm{ASE}}^\pm=\sigma_L(\omega_L)F_{\mathrm{ASE}}^\pm$ we obtain from (10):

$$\left(\frac{1}{u}\frac{\partial}{\partial t}\pm\frac{\partial}{\partial z}\right)I_{\mathrm{ASE}}^\pm=(K\sigma_L N-\kappa)I_{\mathrm{ASE}}^\pm+\bar{g}\Gamma_2(\kappa+b)\,. \quad (12)$$

The total normalized flux density $I_s(z,t)$ within the amplifier [see (5)] is then given by

$$I_S=I^++I^-+K(I_{\mathrm{ASE}}^++I_{\mathrm{ASE}}^-)\,. \quad (13)$$

The normalized photon flux density in (3) which is coupled back from the amplifier into the oscillator is determined by

$$I_B(t)=I^-\left(z=\frac{L}{2},t\right)+KI_{\mathrm{ASE}}^-\left(z=\frac{L}{2},t\right). \quad (14)$$

2. Results and Discussion

For the evaluation of the intensity $I(t)$ emitted by the oscillator amplifier set-up, the solution of the coupled system of Eqs. (1, 3–5, 12) taking into account (13, 14) is necessary. We assume a Gaussian pump pulse with the same pulse duration $T_P=\sqrt{\ln 2}\,t_p$ for the oscillator and the amplifier. Therefore, we obtain for the pump rates

$$W(t)=\frac{\varepsilon}{\sqrt{\pi}t_P}\exp\{-(t/t_p)^2\}\,, \quad (15)$$

$$V(t)=\frac{\varepsilon_A}{\sqrt{\pi}t_p}\exp\{-[(t-\Delta t)/t_p]^2\}\,. \quad (16)$$

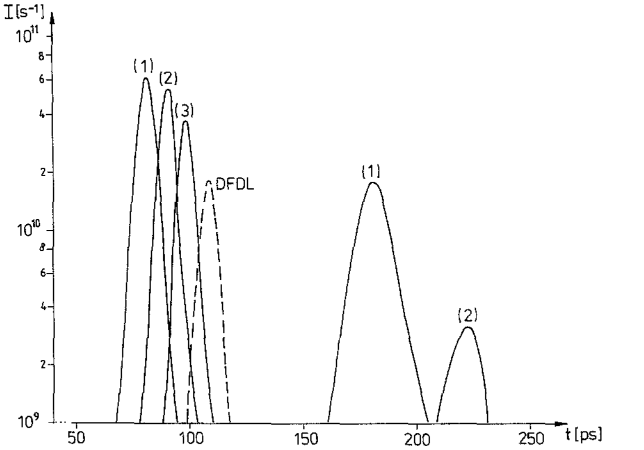

Fig. 4. Emission of the DFDL-amplifier set-up for the pump pulse delay time $\Delta t=100$ ps (curve *1*), $\Delta t=125$ ps (curve *2*), and $\Delta t=150$ ps (curve *3*) with the normalized pump energies $\varepsilon^D=0.06$ and $\varepsilon^A=0.1$

Δt describes a variable time delay of the pump of the amplifier relative to the pump of the oscillator. ε^D and ε^A are the normalized pump energies of the oscillator and the amplifier, respectively:

$$\varepsilon_D=\sigma_p E_P^D/Lb_D\hbar\omega_P\,, \quad (17)$$

$$\varepsilon_A=\sigma_p E_p^A/lb_A\hbar\omega_p\,. \quad (18)$$

The corresponding absolute pump energies are E_p^D and E_p^A, respectively.

The laser pump illuminates an area $b_D L$ for the oscillator and an area $b_A l$ for the amplifier. Using (1, 15, 16) we find the time t_{th}^D, t_{th}^A for which the threshold is exceeded in the DFDL and the amplifier, respectively:

$$\kappa+\varrho=\tfrac{1}{2}\sigma_L n\varepsilon^D\{1+\Phi(\sqrt{2}t_{th}^D/t_p)\}\,, \quad (19)$$

$$\kappa=\tfrac{1}{2}\sigma_L n\varepsilon^A\{1+\Phi(\sqrt{2}(t_{th}^A-\Delta t)/t_p)\} \quad (20)$$

where $\Phi(x)$ denotes the error function.

To evaluate the influence of macroscopic parameters on the laser emission we solved the system of Eqs. (1, 3–5, 12) numerically. The results are given for a solution of the dye coumarine 1 as the active medium. The arrangement is characterized by the following parameters: $N=1.6\times 10^{19}\,\mathrm{cm}^{-3}$, $\chi=460$ nm, $\sigma_L=2.5\times 10^{-16}\,\mathrm{cm}^2$, $\sigma_p=1.2\times 10^{-17}\,\mathrm{cm}^2$, $K=0.9$, $\kappa=120\,\mathrm{cm}^{-1}$, $L=l=4$ mm, $b_D=b_A=0.2$ mm, $\gamma=0.15$, $t_p=300$ ps.

For the numerical integration a step width in space-time of $\delta z=u\delta t=0.2$ mm was used.

We first want to discuss the dependence of the output intensity on the pump pulses delay time Δt fixing the pump energies at $E_p^D=20\,\mu$J ($\varepsilon^D=0.06$) for the oscillator and $E_p^A=34\,\mu$J ($\varepsilon^A=0.1$) for the amplifier. For these pump energies we find for $\Delta t=0$ the threshold times $t_{th}^A=-68$ ps, $t_{th}^D=37$ ps.

To minimize the ASE: in principle, the threshold of the amplifier should not be earlier than that of the oscillator. Therefore, in that special case Δt should not be less than 100 ps. The time behaviour of $I(t)$ is depicted in Fig. 4 for three different parameters $\Delta t\geq 100$ ps. Moreover in Fig. 4 the photon flux density emitted by the DFDL (without an interaction with the amplifier) is shown (dashed line). It

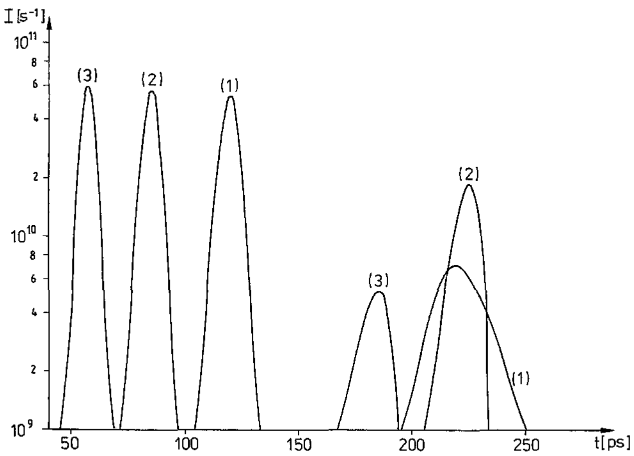

Fig. 5. Influence of pump energy fluctuations on the emission of the DFDL-amplifier arrangement. The parameters are $\Delta t = 110$ ps and curve *1*: $\varepsilon^D = 0.054$, $\varepsilon^A = 0.09$; curve *2*: $\varepsilon^D = 0.060$, $\varepsilon^A = 0.10$; curve *3*: $\varepsilon^D = 0.066$, $\varepsilon^A = 0.11$

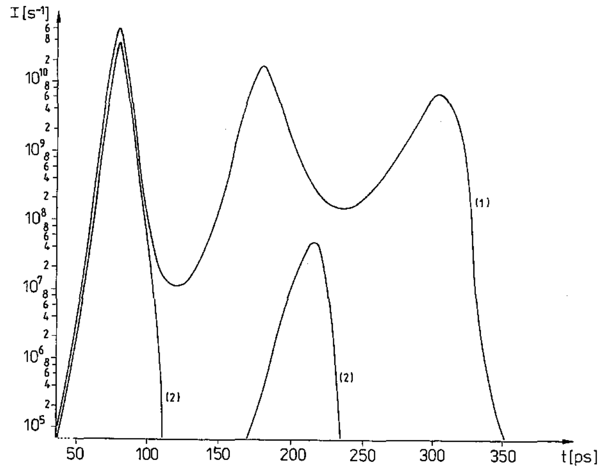

Fig. 6. Emission of the DFDL-amplifier set-up for $R = 0.037$ (curve *1*) and $R = 0.4$ (curve *2*) with the parameters $\varepsilon^D = 0.04$, $\varepsilon^A = 0.1$, and $\Delta t = 100$ ps

can be seen that in local time the maximum of the amplified pulse is emitted earlier than that of the oscillator pulse. Very important for practical use is the result that the oscillator-amplifier set-up still emits single pulses even when the oscillator pump energy exceeds the DFDL threshold pump energy (12 μJ) by nearly a factor of two. This proves the effect of extending the single pulse regime as a consequence of the depletion the DFDL population inversion by the radiation coupled back from the amplifier into the oscillator.

For the generation of single pulses the cases (2) ($\Delta t = 125$ ps) and (3) ($\Delta t = 150$ ps) in Fig. 4 are favoured. On the other hand, the ASE increases from 1% (1) to 24% (2), and 30% (3), and for $\Delta t = 200$ ps the ASE dominates the emitted laser radiation.

Nitrogen lasers are often used for pumping. The energies of the N_2-laser pulses are not very stable. Therefore, we simulated numerically the influence of fluctuations of the pump pulse energy on the output intensity I; the result is shown in Fig. 5. We assumed a fluctuation of $\pm 10\%$ around the mean values $\varepsilon^D = 0.06$ and $\varepsilon^A = 0.1$. It is obvious that the intensity of the second pulse and its distance in time from the first pulse are sensitively dependent on the pump energy, whereas the intensity of the main pulse depends more weakly on the pump energy.

With increasing pump energy the ASE also increases from 1% (curve 1) to 11% (curve 2) and 28% (curve 3).

The increasing ASE also causes the lowest energy of the second pulse for the highest pump energy.

As already stated, the intensity coupled back from the amplifier into the DFDL leads to a shortening of the emitted pulse train. Therefore further favouring of the single pulse regime should be obtained by a higher reflectivity of the laser output area of the dye cuvette. For a DFDL oscillator alone this effect was experimentally proven in [26]. This effect should be still more effective for an oscillator-amplifier arrangement. The result of the numerical simulation confirms this expectation. In Fig. 6 the calculated emission for the DFDL-amplifier arrangement is shown for the case of pure Fresnel reflection $R = 0.035$ between quartz and air and for a mirrored output area with a reflectivity of $R = 0.4$.

Finally let us relate the results of the numerical evaluation to the experimental results given in [22]. We again consider a solution of the dye coumarine 1. In the experiment published in [22] several parameters deviate from those used in the foregoing numerical examples, these are: $L = l = 7$ mm, $N = 9.6 \times 10^{18}$ cm^{-3}, $\gamma = 0.4$, $\kappa = 50$ cm^{-1}, $t_p = 400$ ps. The delay time Δt was measured to be $\Delta t = 50$ ps. The results are summarized in Table 1.

Table 1. Results of numerical simulation together with experimental results [22]] for comparison

Pump energy		Output energy		FWHM of the laser output [ps]		Number of pulses within the FWHM	
Oscillator [μJ]	Amplifier [μJ]	Experiment [μJ]	Theory [μJ]	Experiment	Theory	Experiment	Theory
12	18	0.25	0.15	40	25	1	1
40	30	0.45	0.21	100	15	1...2	1
24	36	0.7	0.58	160	150	2	2
30	45	1.0	0.81	250	145	2...3	2

Taking into account the error interval of the experimental results and the approximations of the theoretical model, the agreement of the theoretical and experimental results can be accepted. The FWHM of the laser emission is evaluated as the FWHM of the envelope of the pulse train emitted or, in the case of single pulse emission, as the FWHM of this pulse. The experimental results are averaged values over 50 shots. The energy of the N_2-laser pump fluctuates around $\pm 10\%$ in the experiment. Remembering the results above, such a fluctuation causes relevant fluctuations of the temporal distance of the pulses in the train. In principle, the theoretical results provide somewhat smaller laser energies and a wider distance in time between two pulses following one another in the case of the emission of more than one pulse compared with the experimental measurements. This effect should be caused by the inhomogeneous distribution of the pump laser intensity over the area of illumination in the experiment, whereas in theory we assumed a spatially constant pump intensity distribution on the amplifier surface and a constant visibility of the pump radiation interference pattern in the DFDL. Thus in the experiment areas exist which are illuminated with a higher laser pump intensity than that considered in the numerical evaluation. In these regions of the DFDL there is a stronger distributed feedback leading to a lower threshold and a faster intensity increase. But the exact theoretical treatment of the situation is fairly complex.

3. Conclusions

We have investigated a simple oscillator-amplifier arrangement with a dye as the active medium, which is contained in a single cuvette. The oscillator is a DFDL with a low ASE content. It can be expected that the emission properties of this system are superior in comparison with a DFDL oscillator alone.

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