# STABILITY OF DISTRIBUTED FEEDBACK DYE LASER EXCITED BY AN EXCIMER LASER

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FOR EXCIMER LASER PUMPING, THREE POSSIBLE REASONS FOR THE FLUCTUATION IN THE DFDL OUTPUT PULSE ENERGY WERE STUDIED: THE FLUCTUATION IN THE VISIBILITY OF THE AMPLITUDE—PHASE GRATING IN THE DYE SOLUTION, THE CHANGE IN THE PUMP PULSE SHAPE ON THE 100 ps – 4 ns TIME SCALE, AND THE CHANGE IN THE PUMP BEAM INTENSITY DISTRIBUTION ALONG THE EXCITED VOLUME.

## *Introduction*

Distributed feedback dye lasers (DFDLs) are simple sources of transform–limited picosecond pulses [1]. Both the pulse duration and the stability of the output pulse energy are relevant properties of DFDLs. The stability of a DFDL pumped by a low–pressure $N_2$ or an excimer laser has been measured and calculated [2,3]. The fluctuation in the exciting beam intensity was presumed to cause the fluctuation in the DFDL pulse energy. This energy fluctuation was determined from the fluctuation in the pumping laser energy and the slope of the calculated output–input energy characteristic of the DFDL. For low–pressure $N_2$ laser pumping, the calculations gave good agreement with the measurements [2]. However, for both TEA $N_2$ and excimer laser pumping, the measured fluctuation in the output energy was significantly larger than the calculated one. TEA $N_2$ and excimer lasers differ from low–pressure $N_2$ lasers in many properties:

a) The bandwidths of TEA $N_2$ lasers and excimer lasers are much larger than those of low–pressure $N_2$ lasers. The spatial coherences of TEA $N_2$ and excimer lasers are small. These two differences can cause a significant fluctuation in the visibility of the amplitude–phase grating in the DFDL.

b) There are a few streaks on the cross–section of the TEA $N_2$ laser beam, so the intensity of the pumping varies along the excited volume of the DFDL, and therefore the amplification is modulated in space. The positions of the streaks change from shot to shot. Such a streaky structure can not be seen in the beam of a low–pressure $N_2$ laser.

c) Exciting pulses from excimer lasers usually have a modulation in time [3], some peaks can be observed in the pulse shape. The phase of this modulation can change from shot to shot without changing the pulse energy.

The effects of these properties on the stability of the DFDL are studied in this paper by using a time–space–dependent differential equation system to describe the lasing of the DFDL.

## *Theoretical model*

The behaviour of the DFDL can be described by the following system of equations [4]:

$$-\frac{\partial R(x,t)}{\partial x} + \frac{\eta}{c}\frac{\partial R(x,t)}{\partial t} = \frac{1}{2}\,\sigma_e n(x,t)\left[R_o + R(x,t) + \frac{V}{2}S(x,t)\right] - \frac{1}{2}\rho R(x,t), \tag{1}$$

$$\frac{\partial S(x,t)}{\partial x} + \frac{\eta}{c}\frac{\partial S(x,t)}{\partial t} = \frac{1}{2}\,\sigma_e n(x,t)\left[S_o + S(x,t) + \frac{V}{2}R(x,t)\right] - \frac{1}{2}\rho S(x,t), \tag{2}$$

$$\frac{\partial n(x,t)}{\partial t} = I_p(x,t)\,\sigma_p\left[N-n(x,t)\right] - \frac{n(x,t)}{\tau} - \frac{\sigma_e \epsilon \lambda}{h\eta}\left[|R|^2+|S|^2\right]n(x,t). \tag{3}$$

The meanings of the symbols are as follows:

| | |
|---|---|
| x: | the distance along the excited volume [cm] |
| N: | the total concentration of dye molecules [$9\cdot10^{18}$ cm$^{-3}$] |
| n(x,t): | the concentration of molecules in the $S_1$ excited state [cm$^{-3}$] |
| $\tau$: | the fluorescence lifetime of the $S_1$ state [4 ns] |
| $\eta$: | the refractive index of the dye solution [1.32] |
| c: | the speed of light in vacuum [$3\cdot10^8$ m.s$^{-1}$] |
| V: | the visibility of the amplitude–phase grating in the excited volume [0.4] |
| $\sigma_p$: | the absorption cross–section of the dye molecules at the 308 nm pump wavelength [$1.15\cdot10^{-17}$ cm$^2$] |
| $\sigma_e$: | the emission cross–section of the dye molecules at the DFDL wavelength [$1.1\cdot10^{-16}$ cm$^2$] |
| R(x,t): | the electric field of the DFDL light propagating in the –x direction [V.m$^{-1}$] |
| S(x,t): | the electric field of the DFDL light propagating in the +x direction [V.m$^{-1}$] |
| $\epsilon$: | the permittivity of the dye solution [$\eta^2$ $8.854\cdot10^{-12}$ AsV$^{-1}$m$^{-1}$] |
| $\lambda$: | the wavelength of the DFDL [555 nm] |
| b: | the height of the excited volume [0.25 mm] |
| h: | Planck's constant [$6.616\cdot10^{-34}$ Js] |
| L: | the length of the pumped volume [3 mm] |
| $\rho$: | the non–saturable loss of DFDL energy in the excited volume [≈1 cm$^{-1}$] |

$a = \left[N\ \sigma_p\right]^{-1}$, is the penetration depth of the pump light into the dye solution [$\approx$ 0.1 mm]

$R_0 = S_0 = \sqrt{\frac{\hbar c}{ab\epsilon\lambda L}}$ , describes the spontaneous emission.

The system of equations (1)–(3) was solved on an IBM AT computer, using a numerical method. Typical excimer laser parameters were used for the calculations. The output energy of the DFDL was calculated from the formula:

$$E = \int \frac{\epsilon cba}{\eta} |R(L,t)|^2\, dt \tag{4}$$

*Results of calculations*

a) The exciting beam is split into two beams by a holographic grating in the DFDL arrangement. These two beams are reflected on the surfaces of a quartz parallelepiped. After reflection, these two beams interact in the dye solution, creating an amplitude–phase grating. In this pattern, the surfaces of the constant phase and amplitude are planes. These are perpendicular to the surface of the dye cell. For the ideal case, the visibility of the interference pattern is 1 everywhere in the excited volume. In reality, the visibility is smaller than 1. The reason for this, the bandwidth and the divergence of the excimer laser beam are not infinitely small. Therefore, the time and spatial coherence length of the exciting laser are small:

where $\Delta\lambda \approx 0.3$ nm and $\Theta \approx 0.01$ for the excimer laser. The depth of the excited

$$L_{time} = \frac{\lambda^2}{\Delta\lambda} \approx 300\ \mu m \tag{5}$$

$$L_{spatial} = \frac{\lambda}{\Theta} \approx 30\ \mu m \tag{6}$$

volume is ≈ 100 μm, which is significantly larger than the spatial coherence length. Therefore, the visibility is smaller than 1 and it can differ from point to point in the excited volume. A visibility value of ≈ 0.4 was estimated from the measurement of the amplified spontaneous emission background of the excimer laser pumped DFDL [5]. The visibility of the amplitude–phase grating can also change from shot to shot.

As an about ±10% fluctuation of the visibility seems realistic, the calculations were carried out with visibility values between 0.36 and 0.44. The results of calculations are shown in Figures 1 and 2. The output energy of the DFDL is represented as a function of pump intensity in Fig. 1. This Figure indicates that the threshold pump intensity for $V = 0.4$ is $I_p = 3.29 \cdot 10^{23}\ cm^{-2}s^{-1}$. For an 8% higher intensity of this threshold, the output energy is represented as a function of the visibility (see Fig. 2). (According to Fig. 3 in [5], the DFDL creates a single pulse only if the pump intensity does not exceed the threshold intensity by more than 8%.) As it can be seen in Fig.2 a±10% fluctuation of the visibility results a±14.3% fluctuation in the DFDL pulse energy. Therefore, the fluctuation in the visibility can be the reason for the fluctuation in the DFDL output energy.

b) The cross–section of the TEA $N_2$ laser beam has a streaked structure; the intensity of the beam is modulated in space. This beam is focused by a cylindrical lens into a line. Because of the streaked structure of the beam, the intensity changes along the line and therefore the amplification is modulated in space. To investigate the effect of this, we described the pump intensity as a function of and time variables with the following formula:

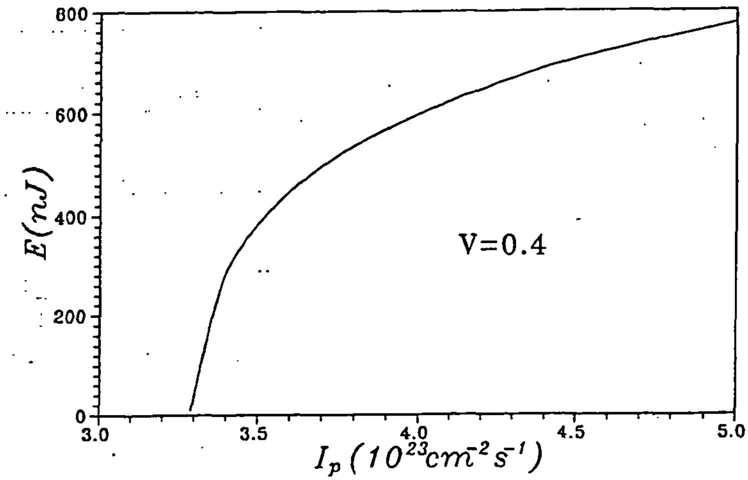


*Figure 1*: Single–pulse energy of the DFDL as a function of the pump intensity

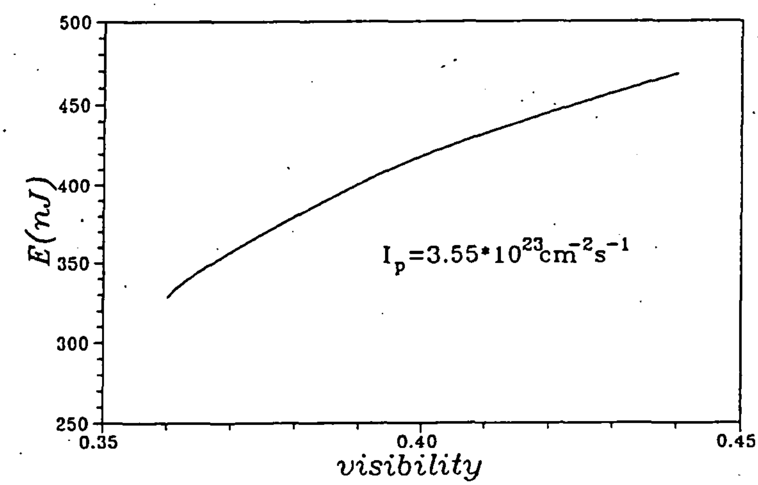


*Figure 2*: Single–pulse energy of the DFDL as a function of the visibility

$$I_p(x,t) = I_0 \left[1+u \sin\left[\frac{2\pi n}{L} x+\varphi\right]\right]\exp\left[-4 \ln(2)\left[\frac{t-t_p}{T}\right]^2\right] \tag{7}$$

where

$t_p$: the position in time of the maximum of the exciting pulse

T: the duration of the exciting pulse [9 ns]

u: the depth of the spatial modulation [0.5]

$$u = \frac{I_{max}-I_{min}}{I_{max}+I_{min}} \tag{8}$$

n: the number of streaks in the excited volume.

Usually, a small part of the focused beam is used to illuminate the dye cell, and therefore there are only a few streaks in the excited volume. The cases n = 1 and n = 2 were studied in our calculations. The results of the calculations are shown in Figures 3 and 4. The output energy is seen to depend only slightly on the spatial modulation of the pump intensity. This dependence is more significant for larger losses.

c) The exciting pulse may have a modulation in time. Such an exciting pulse was described as

$$I_p(x,t) = I_0 \left[1+u \sin\left[\frac{2\pi}{T_h} t+\varphi\right]\right]\exp\left[-4 \ln(2)\left[\frac{t-t_p}{T}\right]^2\right] \tag{9}$$

where $T_h$ is the period of the modulation.

We chose u = 0.5. The calculations (see Fig. 5) revealed that the output energy depends on the phase of the modulation. This phase was changed by $\varphi$. The exciting intensity was chosen to be 8% higher than the threshold intensity. The measured fluc–

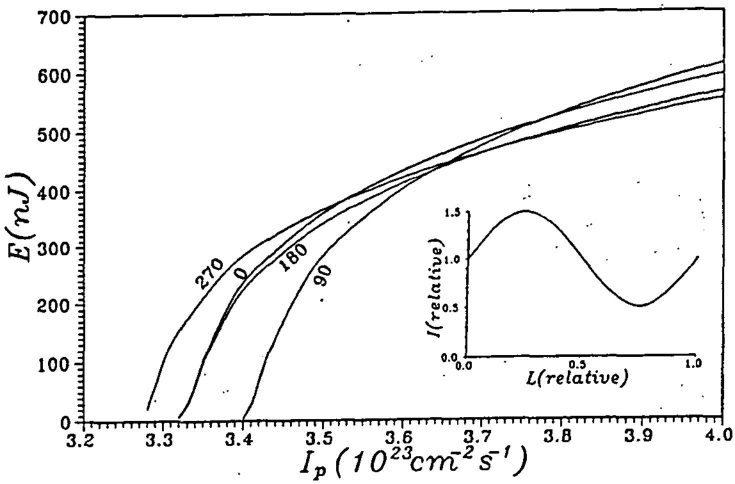


*Figure 5*: Single–pulse energy of the DFDL as a function of the pump intensity for different $\varphi$. The number of streaks is 1

tuation in the exciting pulse intensity was ±1%. This value was used in the calculations. For $T_h$ = 400 ps, the results of the calculations are depicted in Fig. 5 for a few values of the phase of the modulation. It can be seen from this Figure that there is a situation (for the used parameter–set at $\varphi$=90°) such that the energy of the DFDL fluctuates to a larger extent than ±8%, even if the phase of the modulation of the pump pulse is constant and the fluctuation in the pump intensity is only ±1%. This

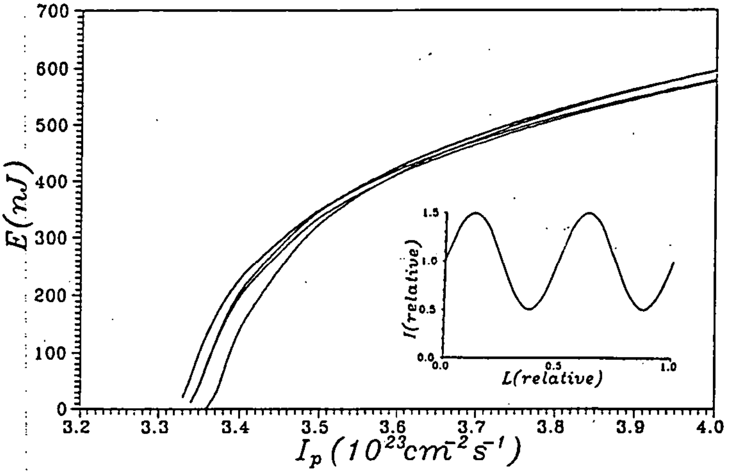


*Figure 4*: Single–pulse energy of the DFDL as a function of the pump intensity for different $\varphi$. The number of streaks is 2.

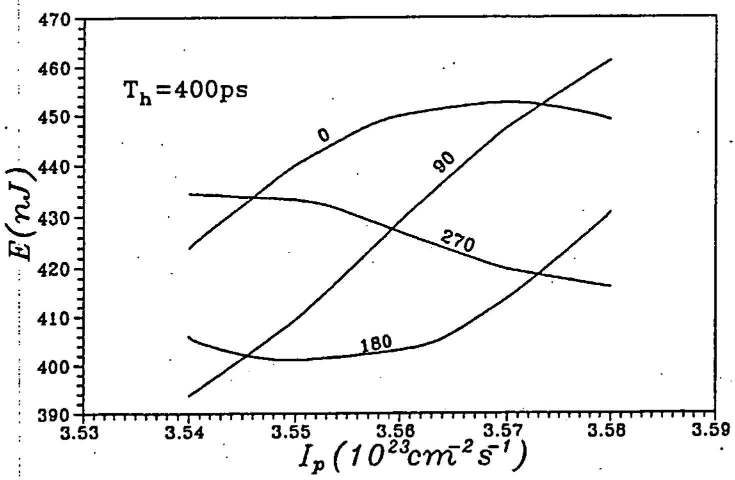


*Figure 5*: Fluctuation in the single–pulse energy of the DFDL at different phase $\varphi$.

sensitivity for the fluctuation in the pump intensity is about twice as large as in the case of unmodulated pumping. On the other hand, with constant pump intensity, the DFDL energy can change considerably if the phase of the modulation of the pump intensity changes from shot to shot.

Figure 6 shows the dependence of the DFDL energy fluctuation on the value ofthe modulation period. It can be seen that the fluctuation is significant if $T_h$ is larger than 300 ps. The fluctuation is larger than 25% for $T_h$ values between 1.4 and 2 ns. For a period time ($T_h$) of the modulation larger than 1 ns, the fluctuation does not decrease below 15%. Therefore, the calculations indicate that the time modulation of the pump pulse can be the reason for the fluctuation in the output energy.

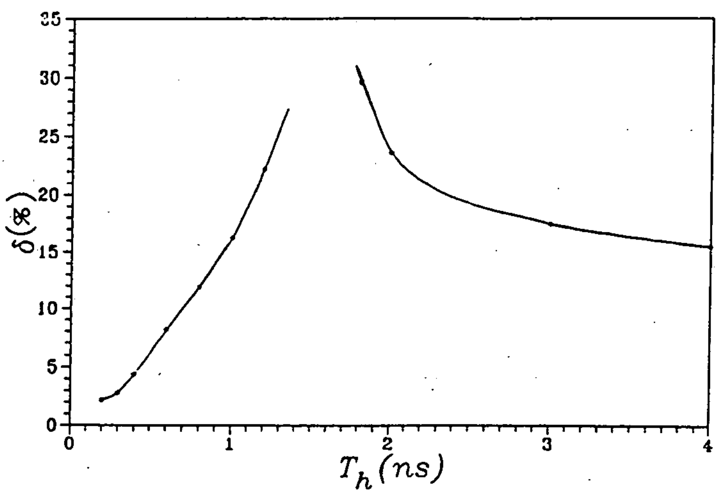


*Figure 6*: DFDL pulse energy fluctuation as a function of the period of the pump pulse modulation in time.

## *Conclusion*

For TEA $N_2$ and excimer laser pumping, we have studied the reasons for the fluctuation in the output energy of a DFDL by using a simple model. The calculations showed that the fluctuation in the exciting pulse in time and the fluctuation in the visibility can explain the measured fluctuation. However, the fluctuation in the spatial distribution of the exciting intensity does not cause a significant fluctuation, at least for a non–saturable loss value $\rho = 1$ cm$^{-1}$.

## *References*

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