Suppression of Self-Pulsing Behaviour in Erbium-Doped Fiber Lasers with Resonant Pumping

W. H. Loh

Optoelectronics Research Centre

University of Southampton

Southampton SO17 1BJ

United Kingdom

Tel: +44 01703 594523

Fax: +44 01703 593142

Email: whl@orc.soton.ac.uk

Abstract

A new approach to improving the stability of erbium-doped fiber lasers is presented. Using a model based on ion pair effects, spiking behaviour is shown to be effectively suppressed by resonant pumping, when the pump wavelength is sufficiently close to the lasing wavelength.

Sustained self-pulsing or spiking behaviour is a common feature in three-level solid-state laser systems[1], and the Er^{3+}-fiber laser is no exception[2,3]. Such behaviour is usually unwelcome, especially where low noise laser operation is desired[4]. For Er^{3+}-fiber lasers, evidence has recently been presented to show that this phenomenon is linked to high ion concentration effects, which cause the formation of ion pairs or clusters acting as saturable absorbers[5,6]. High dopant concentrations are however necessary for the realisation of short-cavity Er^{3+}-fiber DBR and DFB lasers[3,4,7,8] in order to achieve efficient and robust single frequency operation, hence there is an important need to find effective ways to stabilise the laser against self-pulsations. It is the purpose of this Letter to point out that this can be accomplished by resonant pumping directly into the metastable ion state.

Considerable work has been devoted to studying the differences between 980 nm and 1480 nm (resonant) pumping of Er^{3+}-fiber amplifiers[9], but little attention has been spent on investigating the choice of pump wavelength on Er^{3+}-doped fiber lasers. We now show, via a theoretical model, that resonant pumping can significantly alter the dynamics of the laser. In particular, by choosing a pump wavelength sufficiently close to the lasing wavelength, self-pulsations can be eliminated.

The model of the self-pulsing laser to be analysed is an extension of that by Sanchez et al[5,6], which has shown good agreement with observed behaviour. In their model, the self-pulsations are due to ion pairs having a different absorption cross-section/lifetime from the isolated ions, thus acting as saturable absorbers. However, the case of resonant pumping was not considered. To incorporate this feature into the model and demonstrate its effectiveness in suppressing self-pulsations, we consider a simple configuration, shown in Fig. 1, where the ground state is split into just 2 Stark levels. Thermalisation is rapid, thus the Stark level populations are determined by the Boltzmann distribution,

$$\frac{N_{12}}{N_{11}} = k = e^{-\frac{\Delta E}{k_B T}} \qquad (1)$$

where ΔE is the energy separation between the 2 Stark levels, and $N_{11} + N_{12} = N_1$ is the ion population in the ground state. We note that $0<k<1$, with k approaching unity for the pump wavelength λ_p close to the laser wavelength λ_l.

Combining the resonant pumping scheme with the self-pulsing laser model of ref. 5, it is not difficult to show that the resulting equations for the new model are

$$\frac{dn_d}{dt} = -i_p \frac{k+n_d(2+k)}{1+k} - i_l \frac{1+n_d(1+2k)}{1+k} - a_2(1+n_d) \qquad (2a)$$

$$\frac{di_l}{dt} = (1-2x)Ai_l \frac{1+(1+2k)n_d}{2(1-k)} - i_l + xAyi_l n_- \qquad (2b)$$

$$\frac{dn_+}{dt} = a_{12}(1-n_-) - \frac{a_{22}}{2}(n_+ - n_-) + y(i_l+i_p)(2-3n_+) \qquad (2c)$$

$$\frac{dn_-}{dt} = -a_{12}(1-n_+) - \frac{a_{22}}{2}(n_+ + n_-) - y(i_l+i_p)n_- \qquad (2d)$$

where $n_d = (N_2 - N_1)/(1-2x)N_0$ is the population difference, N_0 is the erbium concentration, i_p, i_l are the normalised pump and laser intensities, x is the fraction of ion pairs, $a_2 = \tau_l/\tau_2$ is the normalised level 2 relaxation rate, τ_l is the photon lifetime, $A = \sigma N_0 \tau_l$, σ is the absorption cross section for the isolated ion, $y = \sigma'/\sigma$ is the ratio of the ion pair cross-section to that of the isolated ion, n_+, n_- describe the ion pair populations[5] and a_{12}, a_{22} the relevant relaxation rates.

In the above equations, time is normalised to the photon lifetime τ_l. We have also assumed for simplicity that the effect of the ion pair is the same for both wavelengths[6]. In the calculations, the values used for the various parameters are: τ_2 = 10 ms, τ_l = 10 ns, N_0 = 5×10^{18} cm^{-3}, σ = 1.6×10^{-10} cm^3 s^{-1}, y = 0.2, a_{22} = 5×10^{-3}, a_{12} = 10^{-6}. We consider a relatively high ion pair concentration x = 0.15, which has been shown to induce strong spiking behaviour[5].

The lasing characteristics calculated from the above model (by setting the derivatives to zero and solving the steady state equations) are shown in Fig. 2. It is seen that for larger values of k, i.e. as the pumping wavelength approaches the lasing wavelength, the threshold increases, as expected (in the limit where the wavelengths coincide, the threshold will obviously be infinite). In return, however, a significant improvement in the dynamics of the laser can be achieved. To see this, we conduct a linear stability analysis[1], assuming small perturbations about the steady state and linearising the equations (2a)-(2d), to obtain the system matrix

$$M = \begin{bmatrix} 0 & A(1-2x)\bar{i}_l\frac{1+2k}{2(1+k)} & 0 & xAy\bar{i}_l \\ -\frac{1+\bar{n}_d(1-2k)}{1+k} & -a_2-\frac{(2+k)i_p+(1+2k)\bar{i}_l}{1+k} & 0 & 0 \\ y(2-3\bar{n}_-) & 0 & -a_{12}-\frac{a_{22}}{2}-3y(\bar{i}_l+i_p) & -\frac{a_{22}}{2} \\ -y\bar{n}_- & 0 & a_{12}-\frac{a_{22}}{2} & -\frac{a_{22}}{2}-y(\bar{i}_l+i_p) \end{bmatrix} \quad (3)$$

Information about the stability of the system is obtained by solving for the eigenvalues of M; the system will be unstable, or self-pulsing, if any of the eigenvalues have a positive real part. Of the four eigenvalues of the matrix M, two are found to be always real and negative. The remaining two are complex conjugates of each other, and can have a positive real part. It is these two eigenvalues which are of interest here. Fig. 3 shows the evolution of these eigenvalues as a function of the normalised pump parameter $r = i_p/i_{p,th}$. For $k = 0.1$, the eigenvalues assume a positive real part, and the system is unstable over a wide range of pump powers, up to 15 times threshold. For $k \geq 0.2$, however, the real part of the eigenvalues assume negative values for all pump powers, and stability is clearly enhanced. In particular, for $k = 0.3$, the system is well-damped and self-pulsing should be eliminated.

To verify the conclusions of the above small-signal analysis, full numerical solutions to the equations (2a-(2d) were computed, assuming an initial large step in the pump power. To model the self-pulsing solutions properly, a small spontaneous emission term $\beta(1+n_d)$ was added to eqn (2b), with $\beta=10^{-11}$ (corresponding to a spontaneous emission coefficient of 4×10^{-6}). Figs. 4 and 5 show the behaviour of the system for various k and two pump powers, $r = 5$ and 8. It is seen that for $k = 0.1$, the system exhibits sustained self-pulsations at both pump powers, however, it becomes stable for $k = 0.3$. For $k = 0.2$, the system responds to the large-signal pump step by developing into a sinusoidal state for $r = 5$, but this damps out for $r = 8$. The numerical solutions are thus in line with the conclusions drawn from the stability analysis of Fig. 3.

The physical basis for the improvement in stability is believed to be relatively simple. When k is sufficiently large (or λ_p close to λ_l), the pump will also serve as a gain limiter, thus effectively damping out the large oscillations in the inversion that accompanies, indeed contributes to, self-pulsating behaviour. It may be useful to note that in the 1.55 μm region, $k = 0.3$ would correspond to a separation between the pump and lasing wavelength of ~ 60 nm. Thus 1550 nm Er^{3+}-fiber lasers which are self-pulsing when pumped at 980 nm could well become stable when pumped at 1490 nm or longer. However, due to the simplicity of the 2-level Stark model used, any quantitative conclusions should only be taken as a rough guide; in addition, the wavelength separation required to achieve stability would clearly depend on x, with less restriction on the pump wavelength for lower ion pair concentrations.

In conclusion, we have shown that resonant pumping sufficiently close to the lasing wavelength can significantly improve the stability of Er^{3+}-fiber lasers and eliminate the problem of spiking behaviour, yielding quieter laser operation with low-noise output.

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References

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Figure Captions

Fig. 1 Resonant pumping scheme with two Stark levels in the ground state.

Fig. 2 Calculated lasing characteristics for different k values.

Fig. 3 Evolution of eigenvalues with pump parameter for various values of k. $Im(\lambda)$ and $Re(\lambda)$ represent the relaxation oscillation frequencies and damping rates of the system.

Fig. 4 Numerical solution of system for $r = 5$. (a) $k=0.1$, (b) $k=0.2$, (c) $k = 0.3$.

Fig. 5 Numerical solutions of system for $r = 8$. (a) $k = 0.1$, (b) $k=0.2$, (c) $k=0.3$.

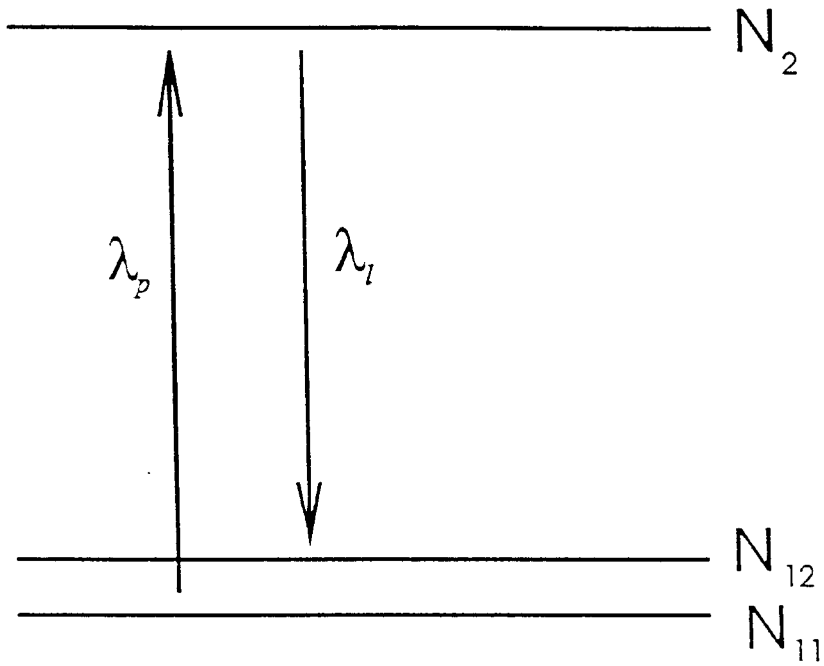
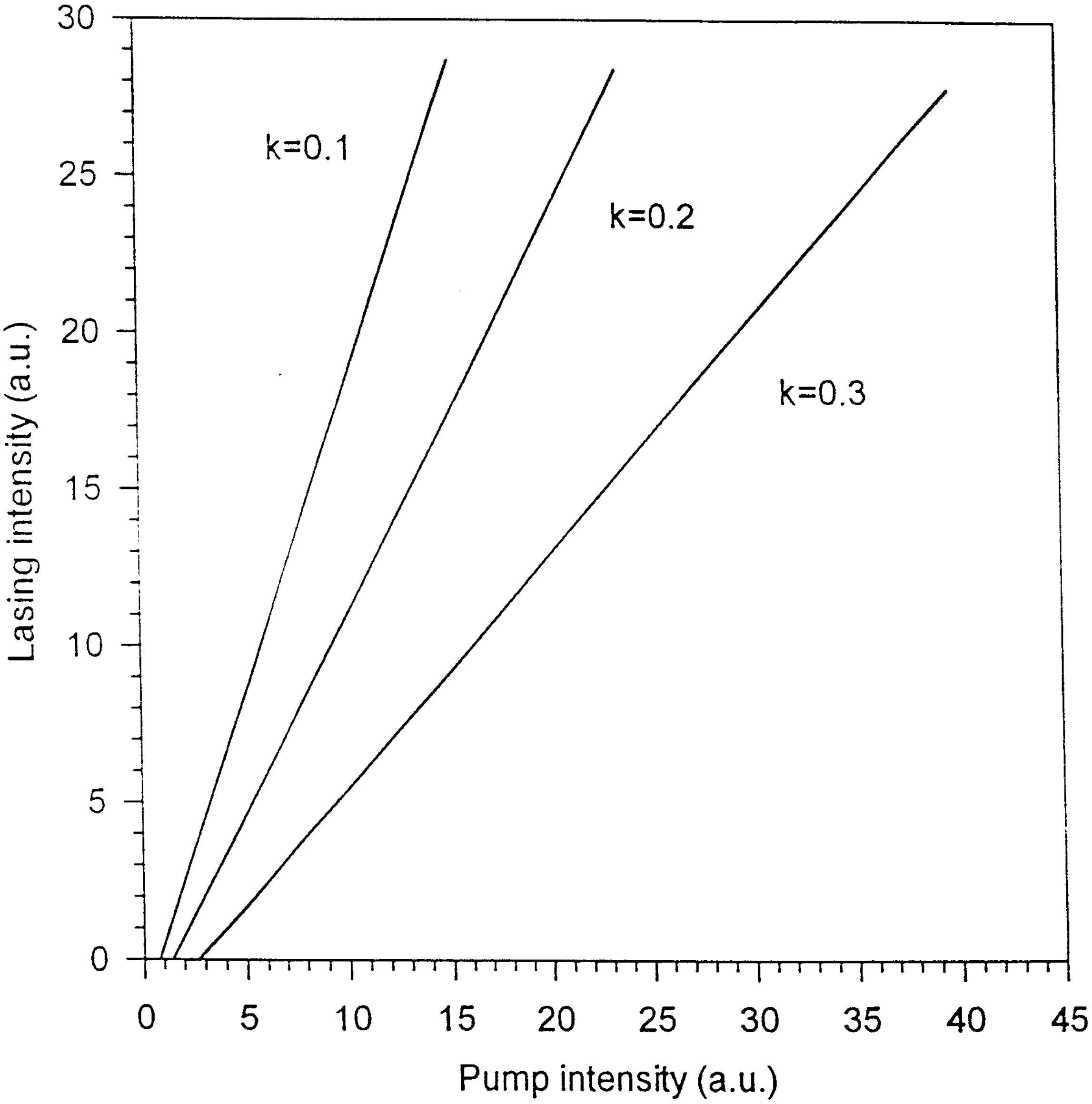


Fig 1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k=0.2
k=0.3
Lasing intensity (a.u.)
Pump intensity (a.u.)
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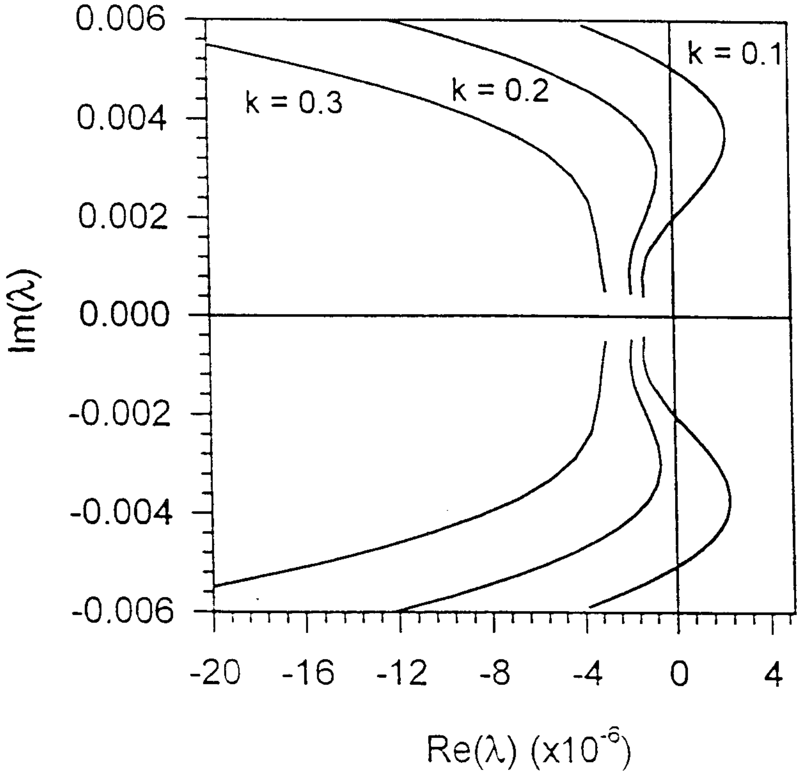
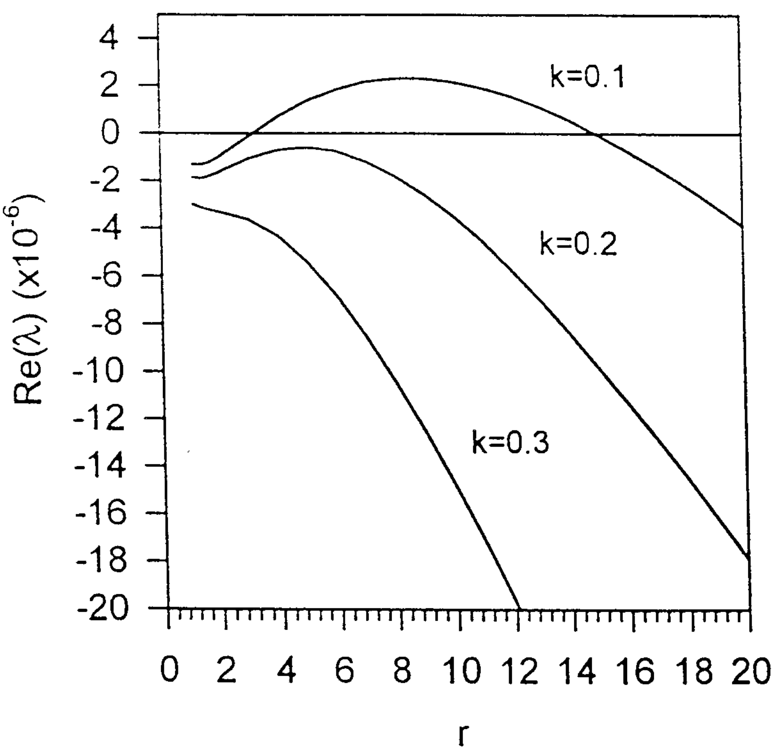
5
10
15
20
25
30
35
40
45

Fig 2



0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
Im(λ)
-20
-16
-12
-8
-4
0
4
Re(λ) (x10^-6)
k = 0.1
k = 0.2
k = 0.3

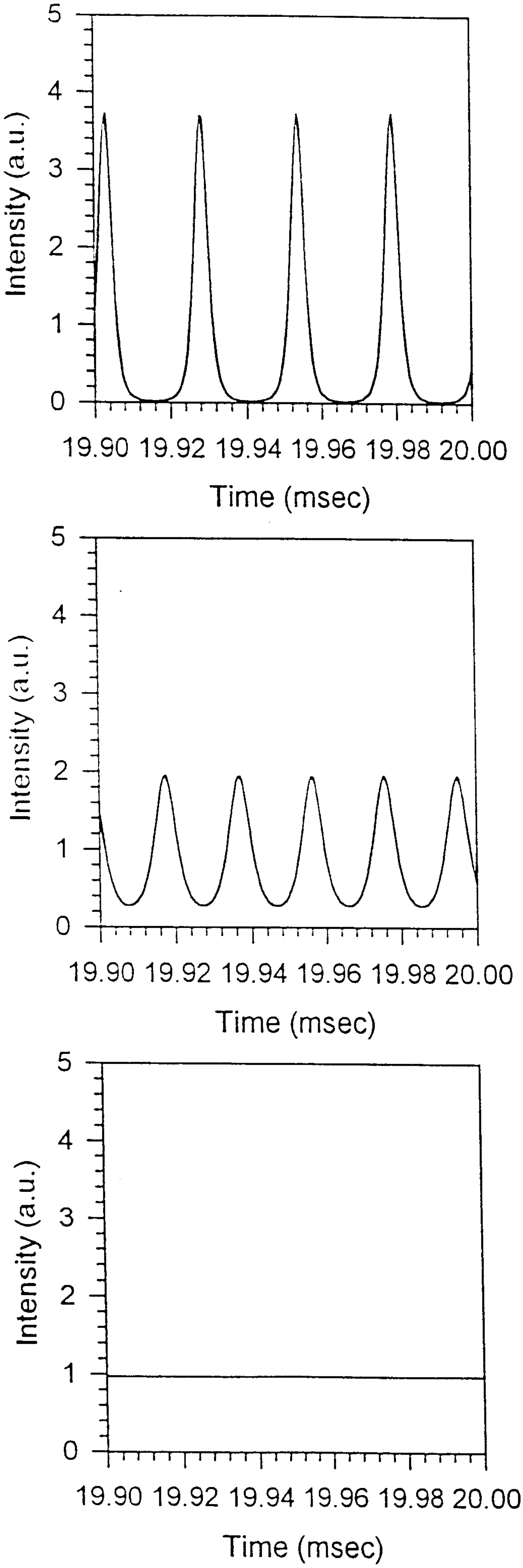
(a)



4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
Re(λ) (x10^-6)
0
2
4
6
8
10
12
14
16
18
20
r
k=0.1
k=0.2
k=0.3

(b)

fig 3

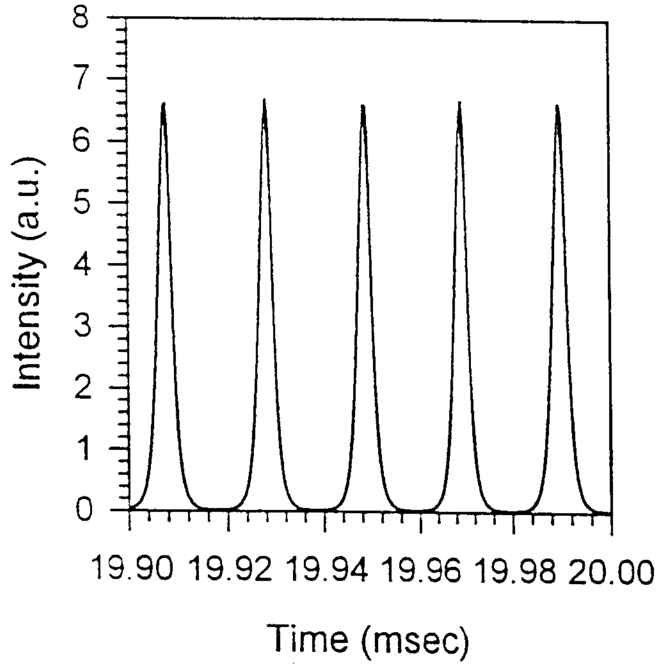


(a)

(b)

(c)

fig. 4


8
7
6
5
4
3
2
1
0
Intensity (a.u.)
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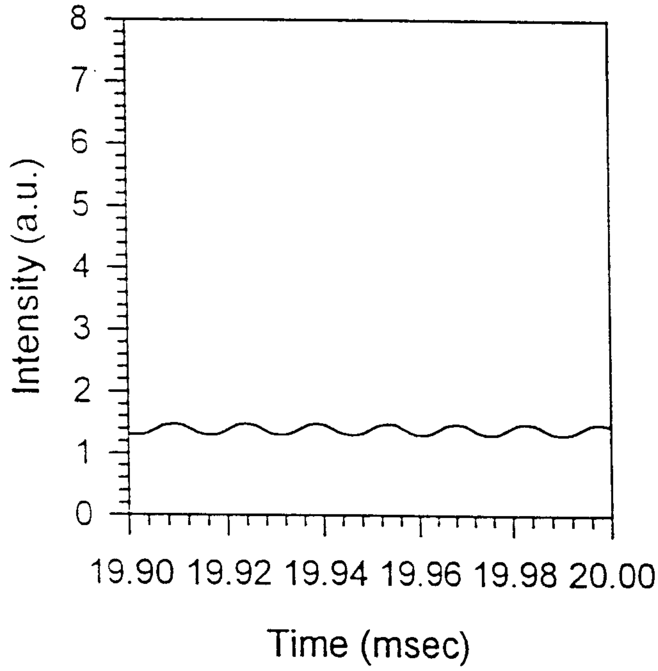
Time (msec)

(a)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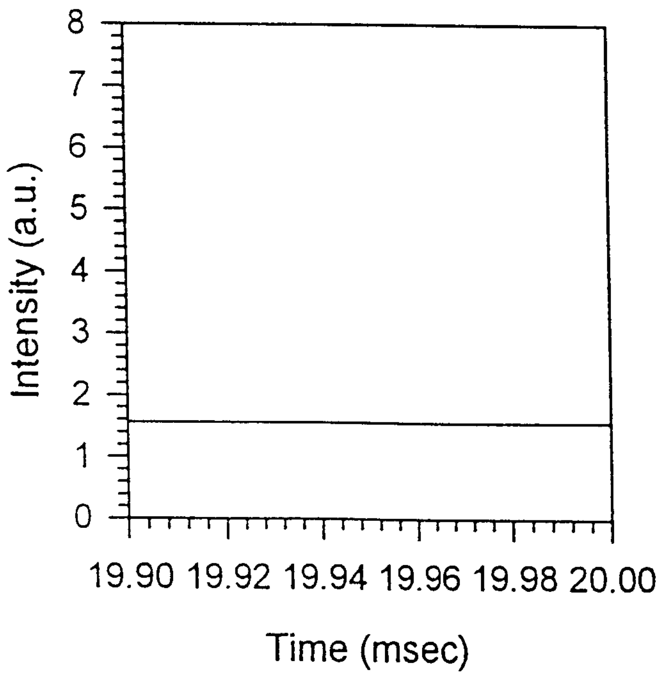
(b)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4
3
2
1
0
Intensity (a.u.)
19.90 19.92 19.94 19.96 19.98 20.00
Time (msec)

(c)

Fig 5