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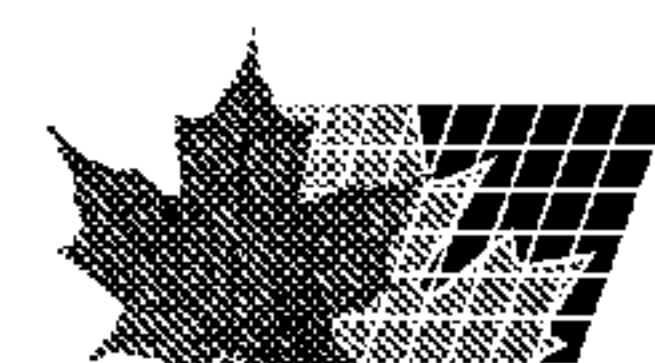
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(72) **Inventeur/Inventor:**
Sasaki, Keiji, JP
(73) **Propriétaire/Owner:**
Research Development Corporation of Japan, JP
(74) **Agent:** SWABEY OGILVY RENAULT

(54) **Titre : DISPOSITIF D'ANALYSE DE FORMES D'ONDE TRANSITOIRES**
(54) **Title: DEVICE FOR ANALYZING A TRANSIENT WAVEFORM**

(57) **Abrégé/Abstract:**

A device for analyzing a transient waveform of the present invention is provided with a computation unit which analyzes the observed transient response waveform as an input adaptive type autoregressive model consisting of a linear function of regressive coefficients dependent upon material parameters or upon material parameters and material spectra. It can perform a rapid and accurate analysis of the transient response waveform observed through the incidence of pulse laser beams, promoting searches into the prime process of material changes.



A B S T R A C T

A device for analyzing a transient waveform of the present invention is provided with a computation unit which analyzes the observed transient response waveform as an input adaptive type autoregressive model consisting of a linear function of regressive coefficients dependent upon material parameters or upon material parameters and material spectra. It can perform a rapid and accurate analysis of the transient response waveform observed through the incidence of pulse laser beams, promoting searches into the prime process of material changes.

A DEVICE FOR ANALYZING A TRANSIENT WAVEFORM

[FIELD OF THE INVENTION]

The present invention relates to a device for analyzing a transient waveform. More particularly, it relates to a device for analyzing a transient waveform with a high speed and a high accuracy whose computation time is much shorter.

[DESCRIPTION OF THE PRIOR ART]

The importance of understanding a prime process of material changes in light energy relaxation, molecule movements, photochemical reactions and other material phenomena has been recognized, and various approaches have been investigated. This is because the proper understanding of these ultra-micro phenomena will develop the control technology and promote new technological innovations to create materials.

Under such circumstances, the method in which ultrashort pulse laser beams are radiated onto a material and a prime process of material changes is analyzed from the obtained transient response waveform has recently been attracted.

In general, the transient waveform observed experimentally appears in a form in which sum of waveforms of plural exponential functions is convoluted with instrumental response functions such as a laser pulse width

and informations as to light energy relaxation, molecular movements, photochemical reactions and other phenomena are obtained from parameters of the individual exponential function (time constant and intensity).

5 Conventionally, as a method for estimating these parameters, the nonlinear least-square fitting method has been used, and the computing and analyzing devices therefor have been realized up to now.

10 However, an impediment putting this nonlinear least-square fitting method to practical application has been an enormous amount of computation.

15 During recent years, as a solution to this shortcoming, a computing device using an autoregressive model whose performance is higher than that of the nonlinear least-square computing device, has been attracted as a high-speed and highly accurate analyzing device for multi-component exponential functions.

20 However, this method and device using an autoregressive model has not actually been accomplished as the method and device for analyzing a transient waveform. The major reason for this is that a complicated deconvolution computation is required for the analyses of a transient waveform since a delta function is assumed as an instrumental function.

25 The present invention has an object to provide a device for analyzing a transient waveform with a high speed and a high accuracy, which requires no computation with an exorbitant amount nor complicated deconvolution computation.

30 According to a broad aspect of the present invention, there is provided a device for analyzing a transient waveform signal and outputting an estimation of the transient waveform signal. The device comprises a computation unit for analyzing the transient response

waveform signal appearing as a convolution of a sum waveform of a material parameter exponential function

$x(t) = \sum_{i=1}^N A_i \exp(-t/\tau_i)$ with an instrumental response function

signal and obtaining the estimation of the transient waveform signal. The computation unit comprises means for analyzing the observed waveform using an input adaptive type autoregressive model consisting of a linear function of regressive coefficients dependent upon material parameters and represented by:

$$X(j\Delta t) = C_1 \cdot X((j-1)\Delta t) + C_2 \cdot X((j-2)\Delta t) + \dots + C_N \cdot X((j-N)\Delta t) + D_1 \cdot Y(j\Delta t) + D_2 \cdot Y((j-1)\Delta t) + \dots + D_N \cdot Y((j-N+1)\Delta t)$$

where $X(t)$ is the observed transient response waveform signal, $Y(t)$ is the instrumental response function signal and C_i and D_i are the regressive coefficients dependent upon the material parameters A_i and τ_i wherein the relationships between the material parameters A_i and τ_i and the coefficients C_i and D_i are given by the equations:

$$\tau_i = -\frac{\Delta t}{\ln Z_i} (i=1, \dots, N) \quad \text{and} \quad D_i = \sum_{j=1}^N (A_j \cdot Z_j^i - \sum_{k=0}^{i-1} C_{i-k} \cdot A_j \cdot Z_j^k) \quad \text{and} \quad \text{the}$$

solutions of $Z^N - C_1 \cdot Z^{N-1} - C_2 \cdot Z^{N-2} - \dots - C_N = 0$ and obtaining the estimation of the transient waveform signal and means for outputting the estimation of the transient waveform signal obtained from the analysis.

Other objects, features and advantages of the present

invention will become clear through the detailed description with reference to the drawings attached.

[BRIEF DESCRIPTION OF THE DRAWINGS]

Figs. 1(a)(b) and (c) are time-intensity correlation diagrams illustrating the observed waveform, a material response function and an instrumental response function, respectively.

Figs. 2 and 3 are diagrams illustrating number of counts-time correlation, showing the waveforms which are considered in examples 1 and 2, respectively.

[DETAILED DESCRIPTION OF THE EMBODIMENTS]

If pulsed laser beams are radiated onto a material, a unique waveform is obtained as shown in Fig. 1 (a). The transient response waveform $X(t)$ observed at this time is generally represented in the following equation.

$$X(t) = x(t) * Y(t) \quad \dots (1)$$

where the $x(t)$ is a material response function; $Y(t)$ is an instrumental function resulting from pulse width and other parameters; and $*$ indicates a convolution computation. That is, the observed transient response waveform $X(t)$ represented in the equation (1) is determined by the convolution computation of the material response function $x(t)$ and the instrumental response function $Y(t)$.

The material response function $x(t)$ and the instrumental response function $Y(t)$ are indicated, for example, in Figs. 1 (b) and (c).

Furthermore, the material response function $x(t)$ is represented as:

$$x(t) = \sum_{i=1}^N \lambda_i \cdot \exp(-t/\tau_i) \quad \dots (2)$$

where A_i and τ_i show material parameters dependent upon the state of the material.

From the equation (2), the aforementioned equation (1) is expressed as:

$$X(t) = \sum_{i=1}^N \lambda_i \cdot \exp(-t/\tau_i) * Y(t) \quad \dots (3)$$

However, the equation (3) bears a nonlinear relationship to the unknown material parameters A_i and τ_i . Therefore, computation to estimate A_i and τ_i from the equation (3) is extremely complicated and the amount of process becomes enormous.

In the device for analyzing a transient waveform of the present invention, the foregoing observed transient response waveform $X(t)$ is dealt with as a substantially different model.

The model of the device of the present invention is represented in the following equation;

$$\begin{aligned} X(j\Delta t) = & C_1 \cdot X((j-1)\Delta t) + C_2 \cdot X((j-2)\Delta t) + \dots + C_N \cdot X((j-N)\Delta t) \\ & + D_1 \cdot Y(j\Delta t) + D_2 \cdot Y((j-1)\Delta t) + \dots + D_N \cdot Y((j-N+1)\Delta t) \quad \dots (4) \end{aligned}$$

where C_i and D_i are regression coefficients (model parameters) dependent upon the material parameters A_i and τ_i . A_i and τ_i are uniquely given from the solutions of the characteristic equation and input regression formula using these C_i and D_i as coefficients.

In other words, estimation of C_i and D_i is performed, assuming $j=i, \dots$ and then number of sampling points (M), by use of a linear simultaneous equations in the case of $M=2N$, and by use of a linear least-square method in the case of $M>2N$. The relationships between C_i , D_i and A_i , τ_i are derived from the equation (6) and the input regression formula (7) using the solutions of $Z_1, Z_2, \dots, Z_N$ of the formula (5);

$$Z^N - C_1 \cdot Z^{N-1} - C_2 \cdot Z^{N-2} - \dots - C_N = 0 \quad \dots (5)$$

$$\tau_i = - \frac{\Delta t}{\ln Z_i} \quad (i = 1, \dots, N) \quad \dots (6)$$

$$D_i = \sum_{j=1}^N (A_j \cdot Z_j^i - \sum_{k=0}^{i-1} C_{i-k} \cdot A_j \cdot Z_j^k) \quad \dots (7)$$

The computation model of the device of the present invention, that is, the equation (4) can be called an input adaptive type autoregressive model from what has been described above. As is clear from the equation (4), this model bears a linear relation to C_i and D_i . For this reason, the amount of computation is reduced, for example, down to two orders compared with the equation (3). This permits to analyze by adding multi-dimensional information such as space.

This means that computation time of the device of the present invention is by far shorter than that using the nonlinear least-square method, and it may be possible for the device of the present invention to be applied to the

multi-dimensional time-resolution measurement.

Furthermore, this device requires no initial parameters for computation, and the estimated accuracy is equivalent or more than that obtained by the nonlinear least-square method, and this device can be applied to any instrumental function.

Incidentally, for the channel shift between the instrumental response function and the transient waveform of the sample, in the conventional nonlinear least-square method, the instrumental response function is caused to shift a bit by bit, the chi-square is evaluated, determining the amount of shift that can give the least chi-square. By this method, however, computation time became longer in proportion to the number of the shifts (normally 10 to 50 pieces) to be evaluated.

On the other hand, in the present invention, since the input adaptive autoregressive model is linear, the amount of shift itself can be incorporated into the model as an unknown parameter. The amount of shift can be determined as solutions of simultaneous equations. The amount of computation at this time is only less than 1.5 times as much as when no consideration is given to shift. Compared with the conventional nonlinear least-square method, the device of the present invention is able to reduce computation time by one order for shift. This permits the autoregressive model to be applied to any instrumental response function.

Furthermore, since the measured wavelengths are slightly different between the instrumental response

function measured using scattering, etc. and that when the fluorescence of a sample is actually measured, the respective waveform may sometimes be different from each other. Such difference makes a large error in the analysis of components with rapid damping, affecting the accuracy of analysis. As a method to avoid this, the delta function convolution method in which the reference sample of a component of the single exponential function is measured by the fluorescence wavelength as same as in measurement of the sample and the result is used in place of the instrumental response function is known. In this method, since the measured wavelengths are identical, there is no difference in the instrumental response function, but because there is no data for the instrumental response function itself, the analysis becomes complicated.

Hence, in the device of the present invention, the delta function convolution method can be modeled as a combination of plural input adaptive type autoregressive models.

That is, for example, if laser light pulses are radiated to a material, then the observed transient fluorescent waveform $X_1(j\Delta t)$ is expressed in the following equation (8) as same as the equation (4) described above:

$$X_1(j\Delta t) = \sum C_i X_1((j-i)\Delta t) + \sum D_i Y((j-i)\Delta t) \quad \dots (8)$$

where $Y(j\Delta t)$ is an instrumental response function.

The transient spectroscopic waveform of the second sample, $X_2(j\Delta t)$ is also given as:

$$X_2(j\Delta t) = \sum C_i' X_2((j-i)\Delta t) + \sum D_i' Y((j-i)\Delta t) \quad \dots (9)$$

When $Y(j\Delta t)$ is eliminated from the equations (8) and (9),

$$X_1(j\Delta t) = \sum C_i'' X_1((j-i)\Delta t) + \sum D_i'' X_2((j-i)\Delta t) \quad \dots (10)$$

Therefore, if the equation (10) is applied to the transient response wavelengths of two samples by a least square fit, it becomes possible to estimate exponential function parameters without using any instrumental response function.

Since the equation (10) becomes a linear equation to C_i'' and D_i'' , the amount of computation required for estimation is extremely small, becoming effective to the analyses of data to which space and other multi-dimensional informations are added.

C_i , D_i and C_i' , D_i' can be determined uniquely from C_i'' and D_i'' , and from linear functions of C_i and D_i to D_i input regression formula can be dealt with in the same manner as the equations (4), (5), (6) and (7) described above.

Furthermore, the device of the present invention also permits the high-speed and highly accurate analyses of the observed transient waveform to which a spectrum information is added.

If a spectrum information is added to transient waveform, the identification of a material or spectroscopic analyses becomes possible. Conventionally, to analyze the transient waveform to which such a spectrum information is added, the method known as global analysis based on the nonlinear least-squares method was employed. However, by this global analysis, the amount of computation became so

exorbitant that computation time extended as long as a day, and hence it was impractical.

In the device of the present invention, when information of wavelength (λ) is added to the $X(t)$ represented in the above-mentioned equation (4), it can be expressed, for example, in the extended input adaptive type autoregressive model as shown in the following equation.

$$\begin{pmatrix} X_1(2) \\ X_1(3) \\ \vdots \\ X_2(2) \\ X_2(3) \\ \vdots \\ X_M(2) \\ X_M(3) \\ \vdots \end{pmatrix} = C_1 \begin{pmatrix} X_1(1) \\ X_1(2) \\ \vdots \\ X_2(1) \\ X_2(2) \\ \vdots \\ X_M(1) \\ X_M(2) \\ \vdots \end{pmatrix} + C_2 \begin{pmatrix} X_1(0) \\ X_1(1) \\ \vdots \\ X_2(0) \\ X_2(1) \\ \vdots \\ X_M(0) \\ X_M(1) \\ \vdots \end{pmatrix} + D_{11} \begin{pmatrix} Y(2) \\ Y(1) \\ \vdots \\ 0 \\ \vdots \\ 0 \end{pmatrix} + D_{12} \begin{pmatrix} Y(1) \\ Y(2) \\ \vdots \\ 0 \\ \vdots \\ 0 \end{pmatrix} + D_{21} \begin{pmatrix} 0 \\ \vdots \\ 0 \\ Y(2) \\ Y(1) \\ \vdots \\ 0 \\ \vdots \\ 0 \end{pmatrix} + \dots$$

.....(11)

where $X_i(j)$ represents the No. j data on i wavelength, $j (j \Delta t)$.

From this equation (11), it can be understood that since the material parameter is not dependent on wavelength, the coefficient C_i is common for all the wavelengths, but that since the material spectrum varies from wavelength to wavelength, the coefficient D_i becomes the linear function of the wavelength. For this reason, computation time required for the estimation of a material parameter and a material spectrum is remarkably reduced.

If equation (11) is fit to the observed time-resolution spectrum data, a material parameter and a material spectrum

can be obtained from the relationships among the foregoing equations (5), (6) and (7). Computation time is extremely shorter than that with the global analysis based on the conventional nonlinear least-square method, for instance, by as much as 3 orders.

The equation (11) is expressed for the two-component system, but it can, of course, be extended to the multi-component system.

The device of the present invention will be described in more details as follows:

Example 1

For the observed transient response waveform as indicated in Fig. 2, a comparison was made as to the performance of analysis between the device of the present invention and the conventional nonlinear least-square method.

In the one-component system ($N=1$), the following settings were made.

$$\Lambda_1 = 1.0$$

$$\tau_1 = 80.0\text{ps}$$

$$\text{Device function FWHM} = 20.0\text{ps}$$

Pseudo-Poisson noise

Maximum count number : 10000

Number of sampling points : 256

A comparison of the estimated results is shown in Table 1.

The device of the present invention can compute data in a time period of less than $1/16$ compared with the

computing device operating on the nonlinear least-square method, while it retains the same level of accuracy.

Table 2 indicates a comparison of the estimation results of the two-component system. It shows well how the device of the present invention permits high-speed analyses with a high accuracy.

When the amount of shift is incorporated into a model as an unknown parameter, the amount of computation per shift of the channel shift between the instrumental response function and the transient waveform is less by more than 1 order compared with the nonlinear least-square method. As a whole, computation time can be reduced by more than one hundred times.

Table 1

Estimation result		τ_1 (ps)	A_1	Computation time(msec)
		80.0	1.00	
Input adaptive type autoregressive modeling	Average	80.0	1.00	12
	Standard deviation	0.3	0.01	
Nonlinear least-square method	Average	79.9	1.00	200
	Standard deviation	0.2	0.01	

Table 2

Estimation result		τ_1 (ps) 10.0	τ_2 (ps) 20.0	Λ_1 0.50	Λ_2 0.50	Computation time(msec)
Input adaptive type autoregressive modeling	Average	9.1	19.8	0.47	0.53	15
	Standard deviation	1.8	0.9	0.09	0.09	
Nonlinear least-square method	Average	7.7	18.9	0.40	0.61	610
	Standard deviation	2.8	1.2	0.15	0.15	

Example 2

For the observed transient response waveform as indicated in Fig. 3, a comparison was made as to performance of analysis between the device of the present invention and the analyzing device by the conventional nonlinear least-square method.

Table 3 indicates the measurement conditions, while Table 4 shows the estimation results.

The device of the present invention can compute data in a time period of less than 1/500 compared with the computing device operating on the nonlinear least-square method, while it retains the same or higher level of accuracy.

It shows well how the device of the present invention permits high-speed analysis with a high accuracy.

It is needless to say that this invention is not limited to the above examples. Various other configurations can be applied to specific components of the device of the

present invention.

Table 3

Sample	Excitation wavelength	Observed wavelength
(a) Pinacyanol/ethanol(one component)	585nm	630nm
(b) Pinacyanol/aceton (one component)	585nm	630nm
(c) Instrumental response function (scattered light)	585nm	585nm

Table 4

	Estimated life (a) (b)	Computation time
Input adaptive type autoregressive modeling	$12.7 \pm 1.6\text{ps}$ $4.9 \pm 1.8\text{ps}$	0.11sec
Nonlinear least-square method	$12.3 \pm 1.1\text{ps}$ $4.6 \pm 1.4\text{ps}$	50.34sec

The embodiments of the invention, in which an exclusive property or privilege is claimed are defined as follows:

1. A device for analyzing a transient waveform signal and outputting an estimation of said transient waveform signal, which comprises:

a computation unit for analyzing said transient response waveform signal appearing as a convolution of a sum waveform of a material parameter exponential function

$x(t) = \sum_{i=1}^N A_i \exp(-t/\tau_i)$ with an instrumental response function

signal and obtaining said estimation of said transient waveform signal, said computation unit comprising means for analyzing said observed waveform using an input adaptive type autoregressive model consisting of a linear function of regressive coefficients dependent upon material parameters and represented by:

$$X(j\Delta t) = C_1 \cdot X((j-1)\Delta t) + C_2 \cdot X((j-2)\Delta t) + \dots + C_N \cdot X((j-N)\Delta t) + D_1 \cdot Y(j\Delta t) + D_2 \cdot Y((j-1)\Delta t) + \dots + D_N \cdot Y((j-N+1)\Delta t)$$

where $X(t)$ is said observed transient response waveform signal, $Y(t)$ is said instrumental response function signal and C_i and D_i are said regressive coefficients dependent upon said material parameters A_i and τ_i wherein the relationships between said material parameters A_i and τ_i and said coefficients C_i and D_i are given by the equations:

$$\tau_i = -\frac{\Delta t}{\ln Z_i} (i=1, \dots, N) \quad \text{and} \quad D_i = \sum_{j=1}^N (A_j \cdot Z_j^i - \sum_{k=0}^{i-1} C_{i-k} \cdot A_j \cdot Z_j^k) \quad \text{and} \quad \text{the}$$

solutions of $Z^N - C_1 \cdot Z^{N-1} - C_2 \cdot Z^{N-2} - \dots - C_N = 0$ and obtaining said estimation of said transient waveform signal; and

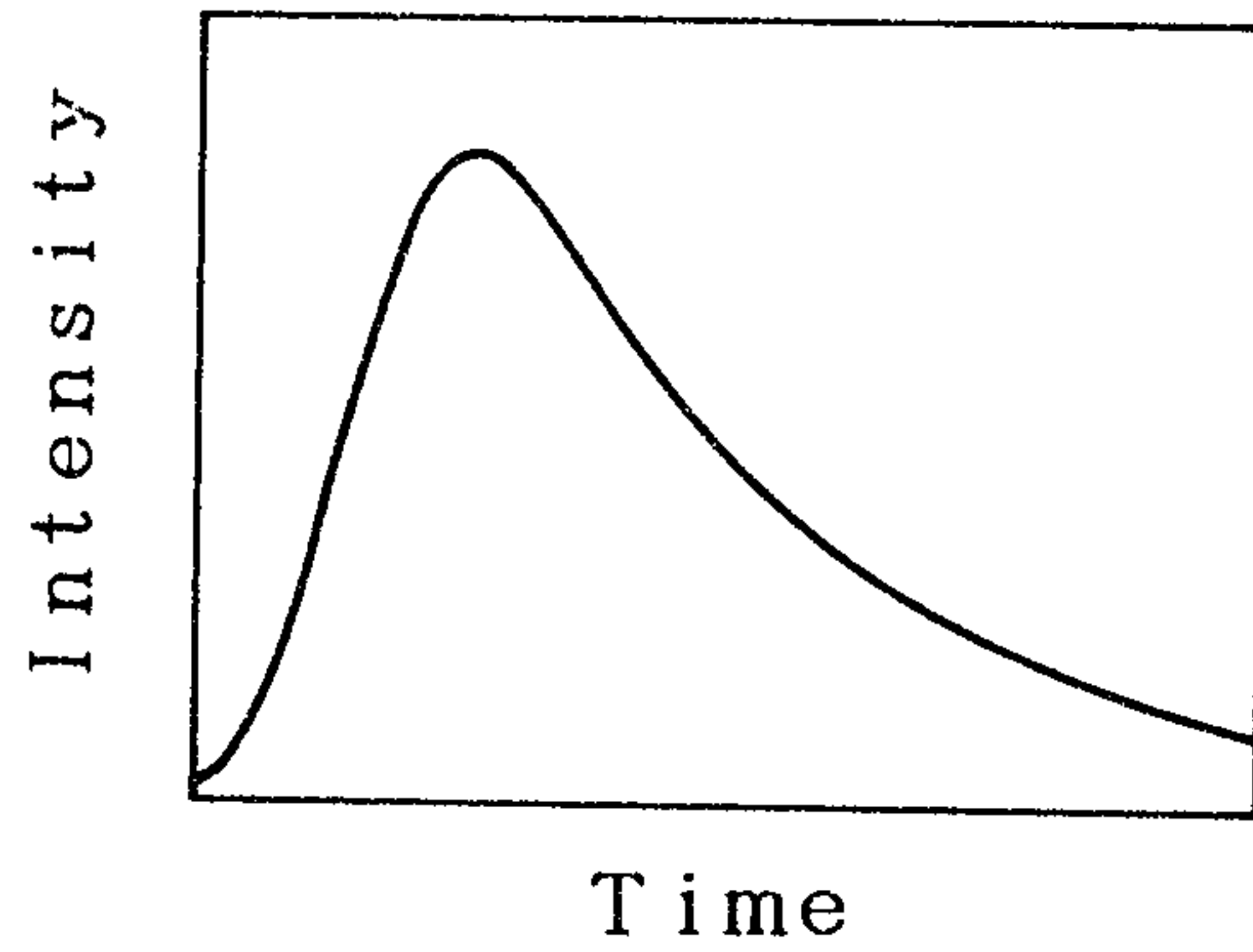
means for outputting said estimation of said transient waveform signal obtained from said analysis.

2. A device for analyzing a transient waveform signal as claimed in claim 1, wherein said means for analyzing further comprise means for incorporating an amount of channel shift between said instrumental response function signal and the transient waveform signal of a sample as an unknown parameter into the input adaptive type autoregressive model, and means for determining the amount of shift as solutions of simultaneous equations representing said autoregressive model.

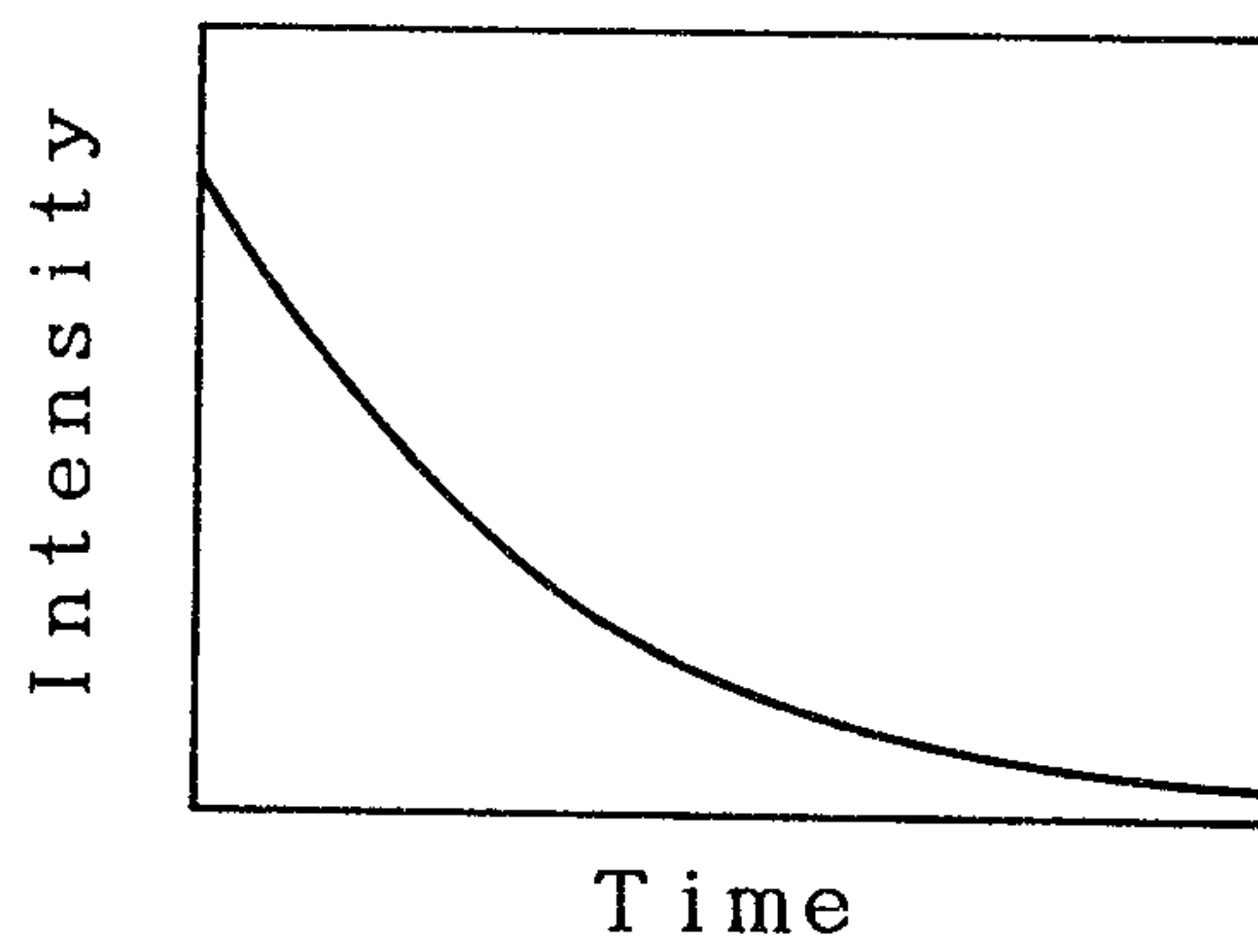
3. A device for analyzing a transient waveform signal as claimed in claim 1 or 2, further comprising means for inputting more than one transient response waveform from a plurality of samples, and wherein said computation unit analyzes a convolution of the observed transient response waveforms of plural samples.

4. A device for analyzing a transient waveform signal as claimed in any one of claims 1, 2 and 3, wherein the transient waveform signal appears not only as a convolution of a sum waveform of a material parameter exponential function with an instrumental response function signal, but also as a function of wavelength, and said means for analyzing analyzes said waveform as an extended input adaptive type autoregressive model consisting of a linear function of regressive coefficients dependent upon material parameters and material spectra.

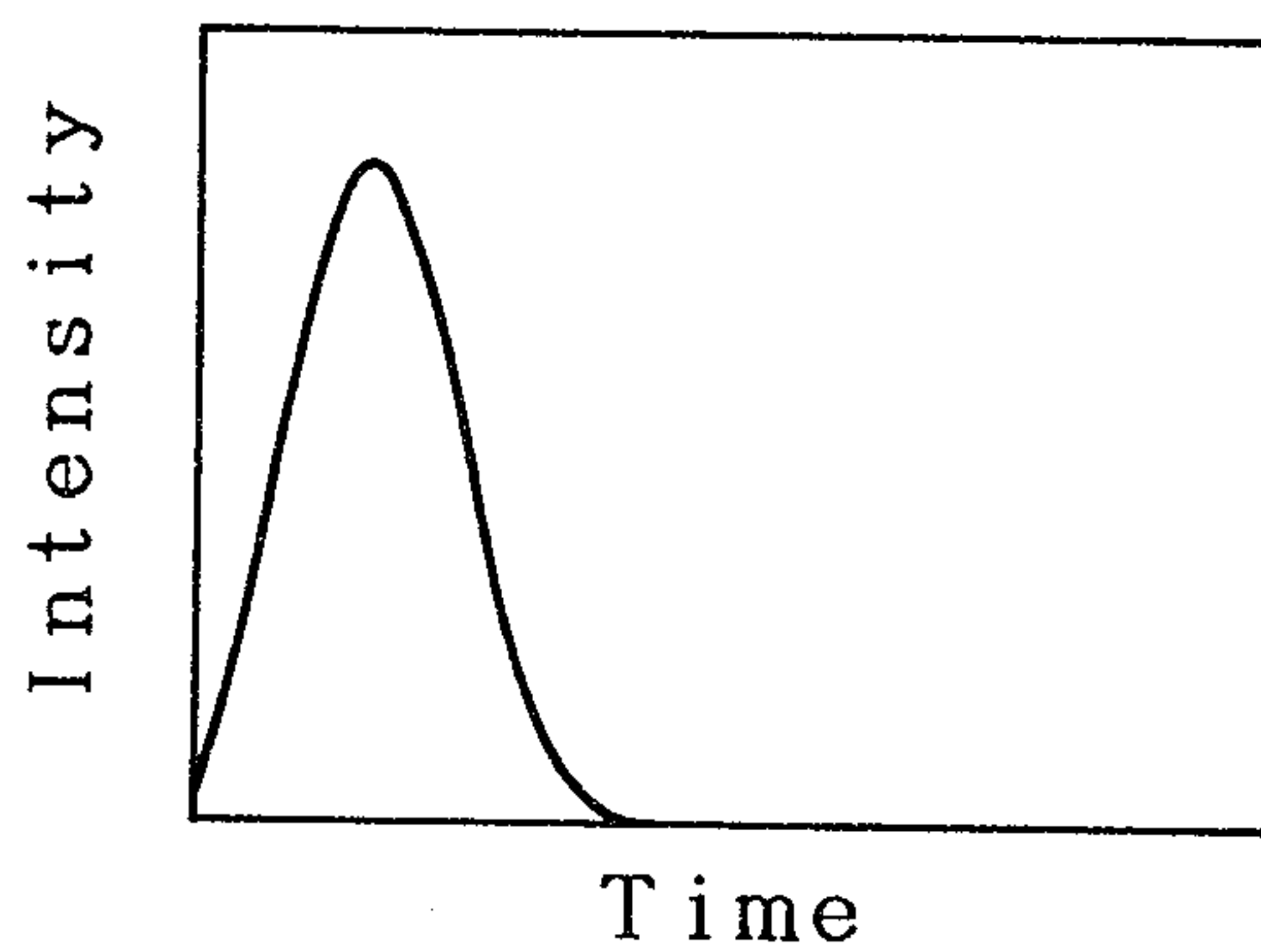
F i g . 1 (a)



F i g . 1 (b)



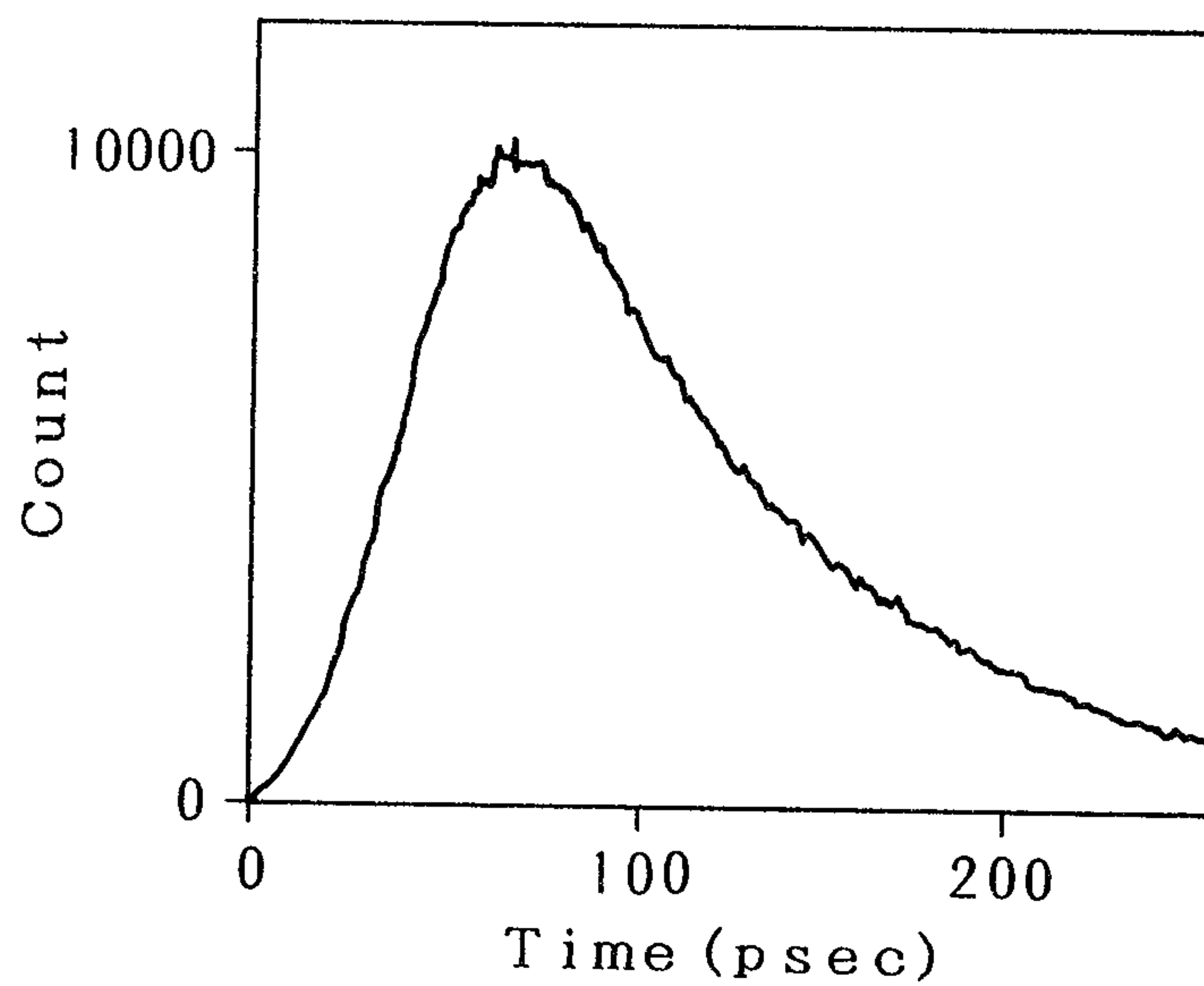
F i g . 1 (c)



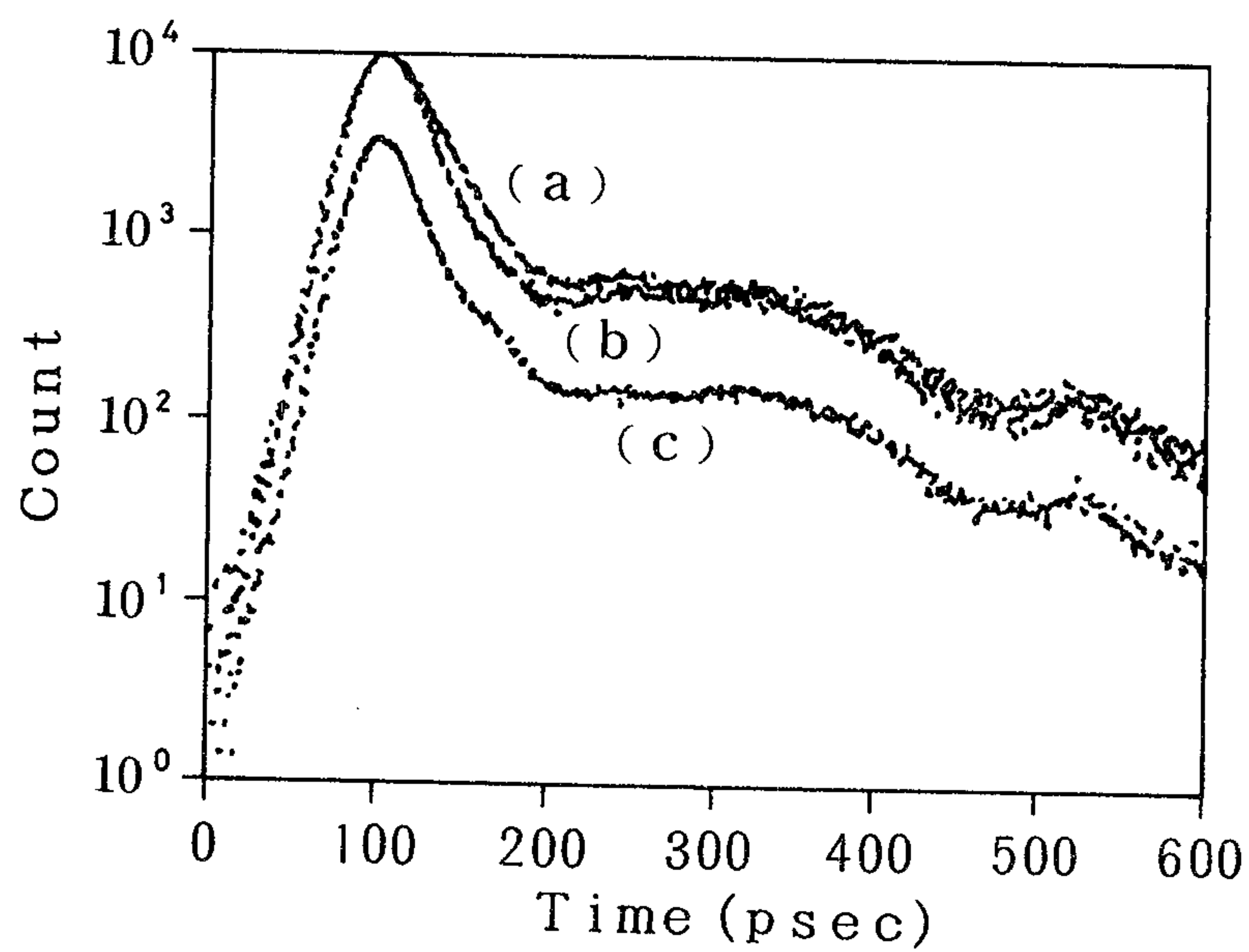
PATENT AGENTS

Rwabeey Ogilvy Renault

F i g . 2



F i g . 3



PATENT AGENTS

Swaney Ogilvy Renault