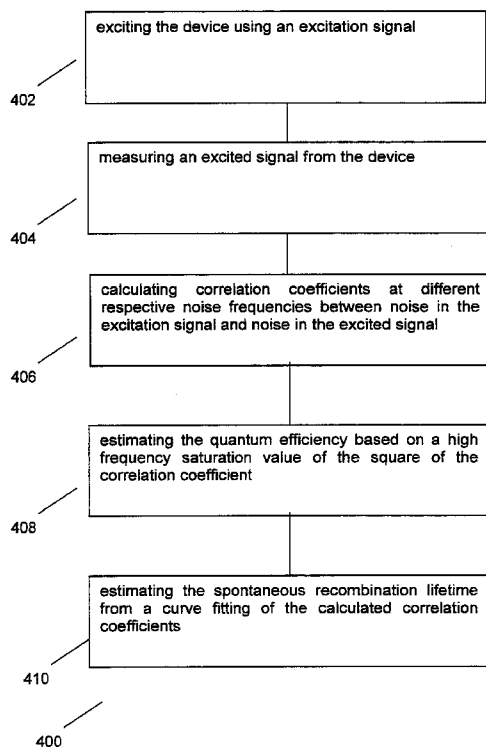




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[Continued on next page]

(54) Title: SYSTEM AND METHOD FOR ESTIMATING QUANTUM EFFICIENCY AND SPONTANEOUS RECOMBINATION LIFETIME



(57) Abstract: A method and system for estimating a quantum efficiency and a spontaneous recombination lifetime of a photonic or photovoltaic device. The method comprises the steps of exciting the device using an excitation signal; measuring an excited signal from the device; calculating correlation coefficients at different respective noise frequencies between noise in the excitation signal and noise in the excited signal; estimating the quantum efficiency based on a high frequency saturation value of the square of the correlation coefficient; and estimating the spontaneous recombination lifetime from a curve fitting of the calculated correlation coefficients.



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SYSTEM AND METHOD FOR ESTIMATING QUANTUM EFFICIENCY AND SPONTANEOUS RECOMBINATION LIFETIME

5 FIELD OF INVENTION

The present invention relates broadly to a system and method for estimating quantum efficiency and spontaneous recombination lifetime of a photonic or photovoltaic device.

10

BACKGROUND

In for example an ideal light-emitting photonic device, each excited electron emits photons as it falls spontaneously to its relaxation state and the quantum efficiency η is close to 1. In real devices, not all excited electrons emit a photon and some will recombine with traps and acceptors non-radiatively in the process known as Auger recombination. This non-radiative recombination results in imperfect quantum efficiency and also in a non-correlation between the electrical and optical fluctuation in the photonic devices.

20

As the quantum efficiency is closely associated with the photon to electron conversion in a light emitting photonic device (or vice-versa in a photovoltaic device), it is a figure of merit for describing the device performance. It is, therefore, of great interest to the photonic and photovoltaic industry to be able to acquire the quantum efficiency accurately. Conventional methods offer to derive the quantum efficiency based on the luminescence *intensity* of the device subjected to electrical or optical excitation. As the measurement on the luminescence is usually performed outside the device, it encompasses the photon loss due to various factors other than the *internal* loss at the active region. Quantum efficiency derived from the conventional methods is deemed as the *external* quantum efficiency which provides less than an accurate picture of the photon to electron conversion (or vice versa) efficiency within the active region, aka the internal quantum efficiency.

30

It is also of great interest to be able to resolve the spontaneous recombination lifetime of an electron into its radiative and non-radiative component in the active region. Radiative lifetime is the average time for an electron in the conduction band to recombine with a hole, accompanied by the emission of a photon. On the other hand,
5 non-radiative lifetime is one for an electron to recombine without photon emission. It is useful to know the radiative and non-radiative lifetime as these account for the imperfectness in the internal quantum efficiency. If the non-radiative lifetime is shorter than the radiative lifetime, then an electron is more likely to recombine non-radiatively, leading to low internal quantum efficiency. Conventional methods for spontaneous
10 recombination lifetime measurement make use of the open-circuit voltage decay exhibited by devices subjected to electrical pulse excitation, but these provide lifetime measurement encompassing the radiative and non-radiative components. Other methods make use of the luminescence decay profile of device during the post-excitation stage, but these are influenced by the photon losses external of the active
15 region.

The estimations of internal quantum efficiency and spontaneous recombination lifetime (and its radiative / non-radiative components) are important aspects of photonic and photovoltaic devices' efficiency characterization. Estimation based on luminescence
20 *intensity* measured outside the test device is influenced by photon losses other than the active region.

A need therefore exists to provide a system and method for estimating the internal quantum efficiency and spontaneous recombination lifetime of a photonic or
25 photovoltaic device that seek to address at least one of the above-mentioned problems.

30 SUMMARY

In accordance with a first aspect of the present invention there is provided a method of estimating a quantum efficiency and a spontaneous recombination lifetime of a photonic or photovoltaic device; the method comprising the steps of

exciting the device using an excitation signal; measuring an excited signal from the device; calculating correlation coefficients at different respective noise frequencies between noise in the excitation signal and noise in the excited signal; estimating the quantum efficiency based on a high frequency saturation value of the square of the correlation coefficient; and estimating the spontaneous recombination lifetime from a curve fitting of the calculated correlation coefficients.

Calculating the correlation coefficients at the different respective noise frequencies may comprise calculating respective root-mean-square (RMS) values of fluctuations in the excitation signal and the excited signal.

Calculating the correlation coefficients at the different respective noise frequencies may further comprise deriving respective normalized excitation and excited signals based on the respective RMS values.

Calculating the correlation coefficients at the different respective noise frequencies may further comprise multiplying the normalized excitation and excited signals to obtain a single waveform.

Calculating the correlation coefficients at the different respective noise frequencies may further comprise dividing the single waveform with a period T used for the calculation of the RMS values of the fluctuations in the excitation signal and the excited signal.

The derived quantum efficiency may comprise an internal quantum efficiency based on the high frequency saturation value of the square of the correlation coefficient.

The method may further comprise deriving a radiative carrier lifetime and a non-radiative carrier lifetime from the estimated spontaneous recombination lifetime.

Deriving the radiative carrier lifetime and the non-radiative carrier lifetime may comprise apportioning a ratio thereof in the estimated spontaneous recombination lifetime based on the estimated quantum efficiency.

5 In accordance with a second aspect of the present invention there is provided a system for estimating a quantum efficiency and a spontaneous recombination lifetime of a photonic or photovoltaic device; the system comprising means for exciting the device using an excitation signal; means for measuring an excited signal from the device; means for calculating correlation coefficients at different respective
10 noise frequencies between noise in the excitation signal and noise in the excited signal; means for estimating the quantum efficiency based on a high frequency saturation value of the square of the correlation coefficient; and means for estimating the spontaneous absorption and recombination lifetime from a curve fitting of the calculated correlation coefficients.

15

The means for calculating the correlation coefficients at the different respective noise frequencies may be configured for calculating respective root-mean-square (RMS) values of fluctuations in the excitation signal and the excited signal.

20

The means for calculating the correlation coefficients at the different respective noise frequencies may further be configured for deriving respective normalized excitation and excited signals based on the respective RMS values.

25

The means for calculating the correlation coefficients at the different respective noise frequencies may further be configured for multiplying the normalized excitation and excited signals to obtain a single waveform.

30

The means for calculating the correlation coefficients at the different respective noise frequencies may further be configured for dividing the single waveform with a period T used for the calculation of the RMS values of the fluctuations in the excitation signal and the excited signal.

The derived quantum efficiency may comprise an internal quantum efficiency based on the high frequency saturation value of the square of the correlation coefficient.

5 The system may further comprise means for deriving a radiative carrier lifetime and a non-radiative carrier lifetime from the estimated spontaneous recombination lifetime.

10 The means for deriving the radiative carrier lifetime and the non-radiative carrier lifetime may be configured for apportioning a ratio thereof in the estimated spontaneous recombination lifetime based on the estimated quantum efficiency.

15 In accordance with a third aspect of the present invention there is provided a data storage medium having stored thereon computer code means for instructing a computing device to execute a method as defined in the first aspect.

BRIEF DESCRIPTION OF THE DRAWINGS

20 Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

25 Figures 1(a) and (b) show schematic drawings illustrating respective systems for estimating a quantum efficiency and a spontaneous recombination lifetime for light emitting photonic devices such as Light Emitting Diode (LED), according to an example embodiment.

 Figures 1(c) and (d) show schematic drawing illustrating respective systems for estimating a quantum efficiency and spontaneous recombination lifetime for photovoltaic devices such as solar cell, according to an example embodiment.

30 Figure 2 shows a flow chart illustrating a method of correlation of the optical and electrical signals, according to an example embodiment.

 Figure 3 shows a graph of the square of the electrical-optical correlation coefficient versus noise frequency, according to an example embodiment.

Figure 4 shows a flow chart illustrating a method of estimating a quantum efficiency and a spontaneous recombination lifetime, according to an example embodiment.

Figure 5 shows a schematic drawings illustrating a computer system for implementing a method and system according to an example embodiment.

DETAILED DESCRIPTION

There are studies to model the correlation coefficient ($C_{\phi,v}$) between the optical and electrical noises in a photonic device as a function of the quantum efficiency and charge carrier lifetime. A model of the noise correlation coefficient ($C_{\phi,v}$) is exemplified in Kim and Yamamoto's theory of noise in the p-n junction of a light-emitting diode (LED):

$$|C_{\phi,v}|^2 \rightarrow \frac{\Omega^2 (\tau_{sp} + \tau_{te})^2}{(1/\eta)[1 + \Omega^2 (\tau_{sp} + \tau_{te})^2] - 1} \dots\dots\dots(1)$$

where,

Ω : frequency of noise,

τ_{sp} : spontaneous recombination lifetime,

τ_{te} : thermionic emission time,

η : quantum efficiency.

The carrier lifetime comprises of the τ_{sp} and τ_{te} , and where τ_{sp} is further comprised of radiative τ_{rad} and non-radiative τ_{nr} recombination times. In Kim and Yamamoto's theory of noise, the model is established to explain the relationship between photon flux and junction voltage fluctuation.

The example embodiments described exploit the model in Kim and Yamamoto's theory to estimate the quantum efficiency and spontaneous recombination lifetime of a device, based on the correlation coefficient between the electrical and optical noise, $C_{\phi,v}$. The quantum efficiency and spontaneous recombination lifetime are of great interest to

the photonic industry as they largely determine the efficiency of photonic and photovoltaic devices.

Some portions of the description which follows are explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

Unless specifically stated otherwise, and as apparent from the following, it will be appreciated that throughout the present specification, discussions utilizing terms such as "scanning", "calculating", "determining", "replacing", "generating", "initializing", "outputting", or the like, refer to the action and processes of a computer system, or similar electronic device, that manipulates and transforms data represented as physical quantities within the computer system into other data similarly represented as physical quantities within the computer system or other information storage, transmission or display devices.

The present specification also discloses apparatus for performing the operations of the methods. Such apparatus may be specially constructed for the required purposes, or may comprise a general purpose computer or other device selectively activated or reconfigured by a computer program stored in the computer. The algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various general purpose machines may be used with programs in accordance with the teachings herein. Alternatively, the construction of more specialized apparatus to perform the required method steps may be appropriate. The structure of a conventional general purpose computer will appear from the description below.

In addition, the present specification also implicitly discloses a computer program, in that it would be apparent to the person skilled in the art that the individual

steps of the method described herein may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language and implementation thereof. It will be appreciated that a variety of programming languages and coding thereof may be used to implement the teachings of the disclosure contained herein. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the spirit or scope of the invention.

Furthermore, one or more of the steps of the computer program may be performed in parallel rather than sequentially. Such a computer program may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a general purpose computer. The computer readable medium may also include a hard-wired medium such as exemplified in the Internet system, or wireless medium such as exemplified in the GSM mobile telephone system. The computer program when loaded and executed on such a general-purpose computer effectively results in an apparatus that implements the steps of the preferred method.

The invention may also be implemented as hardware modules. More particular, in the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). Numerous other possibilities exist. Those skilled in the art will appreciate that the system can also be implemented as a combination of hardware and software modules.

The inventors have recognised that the square of the correlation coefficient, $|C_{\phi,v}|^2$, saturates and approaches the value of η as the noise frequency, Ω , increases, (compare e.g. equation (1) above). Therefore, the quantum efficiency, η , can advantageously be deduced from graphs of $|C_{\phi,v}|^2$ vs Ω by inferring the saturation value of $|C_{\phi,v}|^2$ at the high frequency noise region.

The example embodiments exploit the recognition that the quantum efficiency η so deduced preferably equates to the internal quantum efficiency which is the ratio of the electron number to the photon number at the active (or luminescence) region. It is further recognised by the inventors that the optical and electrical noises originate largely from the fluctuation of photons and electrons in the active region, and therefore, the correlation coefficient of the two noises is representative of the changing ratio of electrons and photons within the active region.

From the so deduced value of η , the total carrier lifetime τ comprising of both τ_{sp} and τ_{te} can advantageously be deduced by curve-fitting the experimental curve of $|C_{\phi,v}|^2$ vs Ω with equation (1) in one example embodiment. Under forward current operation where the carriers are injected across the potential barrier into the active area via a process known as thermionic emission, the forward injection current far exceeds the backward injection current. It can preferably be assumed that the time constant associated with the forward injection current, τ_{fi} , is considerably smaller than that of the backward injection current, τ_{bi} . As the thermionic emission lifetime, τ_{te} , is known to be related to the spontaneous recombination lifetime, τ_{sp} , by a factor of τ_{fi}/τ_{bi} , the thermionic lifetime, τ_{te} , is rendered negligible and τ_{sp} becomes the dominant component in the total lifetime.

It is noted that this assumption applies to both photonic and photovoltaic devices. In a photonic device, photons are emitted while electrons spontaneously recombine from the high to the low energy state. This process is also known as radiative recombination. The thermionic emission (which refers to the process of electron injection across the potential barrier) is a rapid one when the photonic device is operating in a forward bias condition. Hence, the time constant associated with thermionic emission (i.e. thermionic lifetime) is negligible relative to that of the spontaneous recombination. On the other hand, in a photovoltaic device under photoexcitation, electrons also recombine from the high energy state to the low energy state spontaneously, but non-radiatively. Electrons are injected across the potential barrier out of the active area into the electrode rapidly, and the thermionic lifetime is again considered negligible relative to that of the spontaneous recombination.

The example embodiments further exploit the recognition that the proportion of the radiative carrier lifetime in the spontaneous recombination lifetime is directly related to the quantum efficiency. Hence, the radiative and non-radiative carrier lifetime can advantageously be estimated by apportioning their ratio in the spontaneous recombination lifetime, τ_{sp} in the example embodiment, based on η . In this way, the respective lifetimes can be extracted based on the following equations:

$$\tau_{rad} = \tau_{sp} / \eta \quad \dots\dots\dots (2a)$$

$$\tau_{nr} = \tau_{sp} / (1 - \eta) \quad \dots\dots\dots (2b)$$

$$1/\tau_{sp} = 1/\tau_{rad} + 1/\tau_{nr} \quad \dots\dots\dots (2c)$$

where τ_{rad} and τ_{nr} are the radiative and non-radiative lifetime respectively.

A highly efficient light emitting photonic device preferably produces a small τ_{rad} and large τ_{nr} . Conversely a degraded device shall produce a small τ_{nr} and large τ_{rad} , as will be appreciated by a person skilled in the art.

In one example implementation, the optical and electrical fluctuation of a sample are acquired with minimal induced noise from the external environment; using the voltage or current as the proxy for measuring electrical fluctuation. The experimental setup is shown in Fig. 1(a) and 1(b).

As shown in Figure 1(a), the acquisition system/process flow in one set-up involves exciting a photonic device 100 such as an LED with a low-noise voltage source 102 at low power. The electrical fluctuation in the test device 100 is then amplified with a low-noise current amplifier 104 (preferably operated with batteries, such as an SR570 amplifier in one non-limiting example). A voltage output from the current amplifier 104 is applied to a coupling capacitor 105, and analyzed with a Dynamic Signal Analyzer (DSA) 106 coupled to a computer system 107 to extract the electrical noise in the time-domain. A low noise voltage amplifier 109 (such as an SR560 amplifier in one non-limiting example) may optionally be used. During excitation, the test device 100 emits light which is measured with a low noise photo-diode 108. The output of the photodiode 108 is

provided to a coupling capacitor 110 and amplified using a low noise voltage amplifier 112, and then analyzed with a Dynamic Signal Analyzer 114 coupled to the computer system 107 for extraction of the optical fluctuation in the time domain. Both the test device 100 and photodiode 108 are housed in a shielded metallic enclosure 116 in the example embodiment to minimize EMI interference from the surroundings.

As shown in Figure 1(b), the acquisition system/process flow in another set-up involves exciting a photonic device 150 such as an LED with a low-noise current source 152 at low power. The electrical fluctuation in the test device 150 is amplified with a low-noise voltage amplifier 154 (preferably operated with batteries, such as an SR560 in one non-limiting example). The output from the voltage amplifier 154 is applied to a coupling capacitor 155, and analyzed with a Dynamic Signal Analyzer (DSA) 156 coupled to a computer system 157 to extract the electrical noise in the time-domain. An additional low noise voltage amplifier 159 may optionally be used. During excitation, the test device 150 emits light which is measured with a low noise photo-diode 158. The output of the photodiode 158 is provided to a coupling capacitor 160 and amplified using a low noise voltage amplifier 162, and then analyzed with a Dynamic Signal Analyzer 164 coupled to the computer system 157 for extraction of the optical fluctuation in the time domain. Both the test device 150 and photodiode 158 are housed in a shielded metallic enclosure 166 in the example embodiment to minimize EMI interference from the surroundings.

As shown in Figure 1(c), the acquisition system/process flow in another set-up involves exciting a photovoltaic device 200 such as a solar cell with a low-noise light source 202. The electrical output in the test device 200 is then amplified with a low-noise current amplifier 204 (preferably operated with batteries, such as an SR570 amplifier in one non-limiting example). A voltage output from the current amplifier 204 is applied to a coupling capacitor 205, and analyzed with a Dynamic Signal Analyzer (DSA) 206 coupled to a computer system 207 to extract the electrical noise in the time-domain. A low noise voltage amplifier 209 (such as an SR560 amplifier in one non-limiting example) may optionally be used. The optical excitation signal is also provided to a photodiode 208 using a beam splitter 211. The output from the photodiode 208 is in turn provided to a coupling capacitor 210 and amplified using a low noise voltage amplifier 212, and then analyzed with a Dynamic Signal Analyzer 214 coupled to the computer system 207 for extraction of the optical fluctuation in the time domain. Both the test

device 200 and photodiode 208 are housed in a shielded metallic enclosure 216 in the example embodiment to minimize EMI interference from the surroundings.

As shown in Figure 1(d), the acquisition system/process flow in another set-up involves exciting a photovoltaic device 250 such as a solar cell with a low-noise light source 252. The electrical fluctuation in the test device 250 is amplified with a low-noise voltage amplifier 254 (preferably operated with batteries, such as an SR560 in one non-limiting example). The output from the voltage amplifier 254 is applied to a coupling capacitor 255, and analyzed with a Dynamic Signal Analyzer (DSA) 256 coupled to a computer system 257 to extract the electrical noise in the time-domain. An additional low noise voltage amplifier 259 may optionally be used. The excitation signal is also provided to a photodiode 258 using a beam splitter 261. The output from the photodiode 258 is in turn provided to a coupling capacitor 260 and amplified using a low noise voltage amplifier 262, and then analyzed with a Dynamic Signal Analyzer 264 coupled to the computer system 257 for extraction of the optical fluctuation in the time domain. Both the test device 250 and photodiode 258 are housed in a shielded metallic enclosure 266 in the example embodiment to minimize EMI interference from the surroundings.

With reference to Figure 2, the correlation of the optical and electrical signals in an example embodiment can be computed by calculating the root-mean-square [RMS] value for each signal at step 282. The original optical and electrical signals are then normalized with their respective RMS values at step 284. The two normalized signals are then multiplied together to form a new waveform at step 286. The area bounded by the new waveform in a predefined period is then computed at step 288. The correlation coefficient γ' is obtained by dividing the computed area by the period at step 290. This correlation coefficient γ' ranges from -1 to 1. The correlation coefficient can be further adjusted at step 292 so that it ranges from 0 to 1:

$$\gamma = (\gamma' + 1) / 2 \quad \dots\dots\dots (3)$$

In order to extract the correlation coefficient for each frequency, the raw electrical and optical signals are first processed with a Band-Pass Filter algorithm in the example embodiment which can be found in data processing software such as Origin. The filtered signals are then used in the calculation of the correlation coefficients for different noise

frequencies using the steps described above with reference to Figure 2. The algorithms for the computation of correlation coefficient in one example embodiment can be described in the following equations:

- 5 • Computing the root-means-square for voltage fluctuations.

The average voltage, V_a , over a defined period, T , is first computed from the band-passed filtered data, V_i :

10
$$V_a = \sum_{i=1}^n V_i / T \dots\dots\dots (4a)$$

The fluctuation for each sample data, F_i , is computed by taking V_a as the reference base-line:

15
$$F_i = V_i - V_a \dots\dots\dots (4b)$$

The area bounded by F_i^2 is then computed by:

20
$$A = \left(F_1^2 + \sum_{i=2}^{n-1} 2F_i^2 + F_n^2 \right) * t / 2 \dots\dots\dots (4c)$$

where t is the sampling interval.

The RMS of the fluctuation is then computed by:

25
$$V_{rms} = A / T \dots\dots\dots (4d)$$

- Deriving normalized signals

The normalized signal, NV_i , is obtained by:

30
$$NV_i = F_i / V_{rms} \dots\dots\dots (4e)$$

The above algorithms in equations (4a) to (4e) can similarly be applied on the optical fluctuation to obtain the normalized values, denoted as NL_i .

- Computing the area bounded by the new waveform comprising of the multiplication of normalized electrical and optical fluctuation.

The normalized electrical and optical noise are then multiplied together to obtain a single waveform of $NV_i * NL_i$, and the area bounded by the new waveform is computed by:

$$A_{VL} = NV_1 * NL_1 + \sum_{i=2}^{n-1} 2(NV_i * NL_i) + NV_n * NL_n \dots\dots(4f)$$

- Deriving correlation coefficients

The correlation coefficient γ' is computed by dividing the area A_{VL} with the period T . This correlation coefficient ranges from -1 to 1.

$$\gamma' = A_{VL} / T \dots\dots\dots(4g)$$

The correlation coefficient is then adjusted to confine it to range of 0 – 1.

$$\gamma = [(A_{VL} / T) + 1] / 2 \dots\dots\dots(4h)$$

An example embodiment of the invention was applied on an OLED sample operating at low current (100 μ A), and the optical and electrical noises were acquired.

The correlation coefficients between the optical and electrical noises at various frequencies were computed in accordance with the above algorithms in equations (4a) to (4h), and plotted as shown in Figure 3.

As the experimental curve 300 saturates at the correlation coefficient of 0.8 , it can be deduced that the quantum efficiency η approximates this value. With $\eta = 0.8$, the experimental curve can be fitted with equation (1) to establish the value of the total lifetime τ , comprising of τ_{sp} and τ_{te} . In this example, the total lifetime τ is 3 ms.

Assuming that the thermionic emission lifetime is much smaller than the spontaneous recombination lifetime, the radiative recombination lifetime, τ_{rad} , can be estimated with equation 2(a):

5

$$\begin{aligned}\tau_{\text{rad}} &= 3 / 0.8 \text{ ms} \\ &= 3.75 \text{ ms}\end{aligned}$$

On the other hand, the non-radiative recombination lifetime is estimated by:

10

$$\begin{aligned}\tau_{\text{nr}} &= 3 / (1-0.8)\text{ms} \\ &= 15 \text{ ms}\end{aligned}$$

Embodiments of the present invention aim to estimate the quantum efficiency and charge carrier lifetime using optical and electrical noise correlations. The example embodiments exploit the electrical/optical noise correlation model for estimating quantum efficiency and charge carrier lifetimes, and advantageously make appropriate adjustment to resolve the charge carrier lifetime into radiative and non-radiative components. The example embodiments also provide a system setup to acquire the electrical and optical noise, and algorithms for computing the electrical/optical noise correlation coefficient. Example embodiments can also be implemented for measuring quantum efficiency and carrier lifetimes (radiative and non-radiative) of photovoltaic devices such as solar cells. In the case of e.g. a solar cell, the solar cell is excited by an optical source, and the correlation coefficients between the optical noise of the excitation source and electrical noise of the device are used in the analysis.

25

It is noted that an assumption in example embodiments is that the optical fluctuation at the test sample surface is equivalent to that detected by e.g. a photodiode, whether it is in the case of a photonic or a photovoltaic device. The example embodiments seek to correlate the optical fluctuation on the sample surface with the electrical fluctuation, regardless of which is the excitation or the excited signal. In a photonic device, though the excitation source (electrical) appears to co-exist with the excited signal (light) in the same sample, the light is actually detected away from the sample by e.g. the photodiode, and the above assumption is adopted in example

30

embodiments. Likewise, in a photovoltaic device, although the excitation source is physically detached from the sample, the same assumption applies in such embodiments.

5 Figure 4 shows a flow chart 400 illustrating a method of estimating a quantum efficiency and a spontaneous recombination lifetime, according to an example embodiment. At step 402, the device is excited using an excitation signal. At step 404, an excited signal from the device is measured. At step 406, correlation coefficients at different respective noise frequencies between noise in the excitation
10 signal and noise in the excited signal are calculated. At step 408, the quantum efficiency is estimated based on a high frequency saturation value of the square of the correlation coefficient. At step 410, the spontaneous recombination lifetime is estimated from a curve fitting of the calculated correlation coefficients.

15 The method and system of the example embodiment can be implemented on a computer system 500, schematically shown in Figure 5. It may be implemented as software, such as a computer program being executed within the computer system 500, and instructing the computer system 500 to conduct the method of the example embodiment.

20

The computer system 500 comprises a computer module 502, input modules such as a keyboard 504 and mouse 506 and a plurality of output devices such as a display 508, and printer 510.

25 The computer module 502 is connected to a computer network 512 via a suitable transceiver device 514, to enable access to e.g. the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN).

30 The computer module 502 in the example includes a processor 518, a Random Access Memory (RAM) 520 and a Read Only Memory (ROM) 522. The computer module 502 also includes a number of Input/Output (I/O) interfaces, for example I/O interface 524 to the display 508, and I/O interface 526 to the keyboard 504.

The components of the computer module 502 typically communicate via an interconnected bus 528 and in a manner known to the person skilled in the relevant art.

5 The application program is typically supplied to the user of the computer system 500 encoded on a data storage medium such as a CD-ROM or flash memory carrier and read utilising a corresponding data storage medium drive of a data storage device 530. The application program is read and controlled in its execution by the processor 518. Intermediate storage of program data maybe
10 accomplished using RAM 520.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly
15 described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. A method of estimating a quantum efficiency and a spontaneous recombination lifetime of a photonic or photovoltaic device; the method comprising the steps of:

- 5 exciting the device using an excitation signal;
 measuring an excited signal from the device;
 calculating correlation coefficients at different respective noise frequencies between noise in the excitation signal and noise in the excited signal;
 estimating the quantum efficiency based on a high frequency saturation value
10 of the square of the correlation coefficient; and
 estimating the spontaneous recombination lifetime from a curve fitting of the calculated correlation coefficients.

2. The method as claimed in claim 1, wherein calculating the correlation
15 coefficients at the different respective noise frequencies comprises calculating respective root-mean-square (RMS) values of fluctuations in the excitation signal and the excited signal.

3. The method as claimed in claim 2, wherein calculating the correlation
20 coefficients at the different respective noise frequencies further comprises deriving respective normalized excitation and excited signals based on the respective RMS values.

4. The method as claimed in claim 3, wherein calculating the correlation
25 coefficients at the different respective noise frequencies further comprises multiplying the normalized excitation and excited signals to obtain a single waveform.

5. The method as claimed in claim 4, wherein calculating the correlation
30 coefficients at the different respective noise frequencies further comprises dividing the single waveform with a period T used for the calculation of the RMS values of the fluctuations in the excitation signal and the excited signal.

6. The method as claimed in claim 1, wherein the derived quantum efficiency comprises an internal quantum efficiency based on the high frequency saturation value of the square of the correlation coefficient.

5 7. The method as claimed in any one of the preceding claims, further comprising deriving a radiative carrier lifetime and a non-radiative carrier lifetime from the estimated spontaneous recombination lifetime.

10 8. The method as claimed in claim 7, wherein deriving the radiative carrier lifetime and the non-radiative carrier lifetime comprises apportioning a ratio thereof in the estimated spontaneous recombination lifetime based on the estimated quantum efficiency.

15 9. A system for estimating a quantum efficiency and a spontaneous recombination lifetime of a photonic or photovoltaic device; the system comprising:
means for exciting the device using an excitation signal;
means for measuring an excited signal from the device;
means for calculating correlation coefficients at different respective noise frequencies between noise in the excitation signal and noise in the excited signal;
20 means for estimating the quantum efficiency based on a high frequency saturation value of the square of the correlation coefficient; and
means for estimating the spontaneous absorption and recombination lifetime from a curve fitting of the calculated correlation coefficients.

25 10. The system as claimed in claim 9, wherein the means for calculating the correlation coefficients at the different respective noise frequencies is configured for calculating respective root-mean-square (RMS) values of fluctuations in the excitation signal and the excited signal.

30 11. The system as claimed in claim 10, wherein the means for calculating the correlation coefficients at the different respective noise frequencies is further configured for deriving respective normalized excitation and excited signals based on the respective RMS values.

12. The system as claimed in claim 11, wherein the means for calculating the correlation coefficients at the different respective noise frequencies is further configured for multiplying the normalized excitation and excited signals to obtain a single waveform.

5

13. The system as claimed in claim 12, wherein the means for calculating the correlation coefficients at the different respective noise frequencies is further configured for dividing the single waveform with a period T used for the calculation of the RMS values of the fluctuations in the excitation signal and the excited signal.

10

14 The system as claimed in claim 9, wherein the derived quantum efficiency comprises an internal quantum efficiency based on the high frequency saturation value of the square of the correlation coefficient.

15

15. The system as claimed in any one of claims 9 to 14, further comprising means for deriving a radiative carrier lifetime and a non-radiative carrier lifetime from the estimated spontaneous recombination lifetime.

20

16. The system as claimed in claim 15, wherein the means for deriving the radiative carrier lifetime and the non-radiative carrier lifetime is configured for apportioning a ratio thereof in the estimated spontaneous recombination lifetime based on the estimated quantum efficiency.

25

17 A data storage medium having stored thereon computer code means for instructing a computing device to execute a method as claimed in any one of claims 1 to 7.

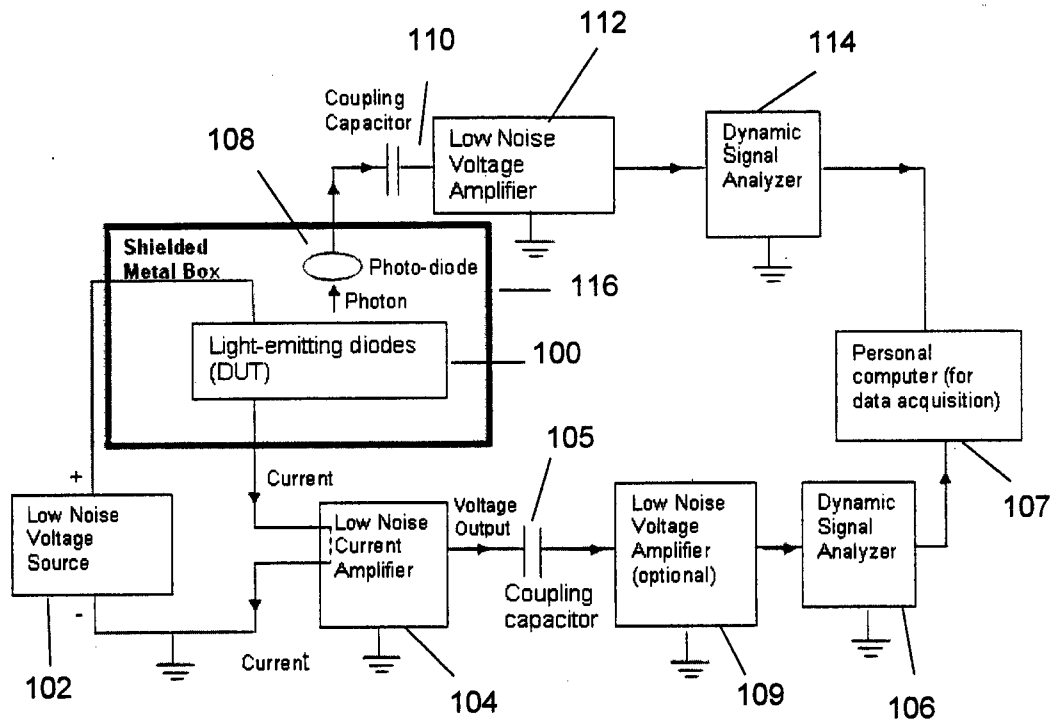


Figure 1(a)

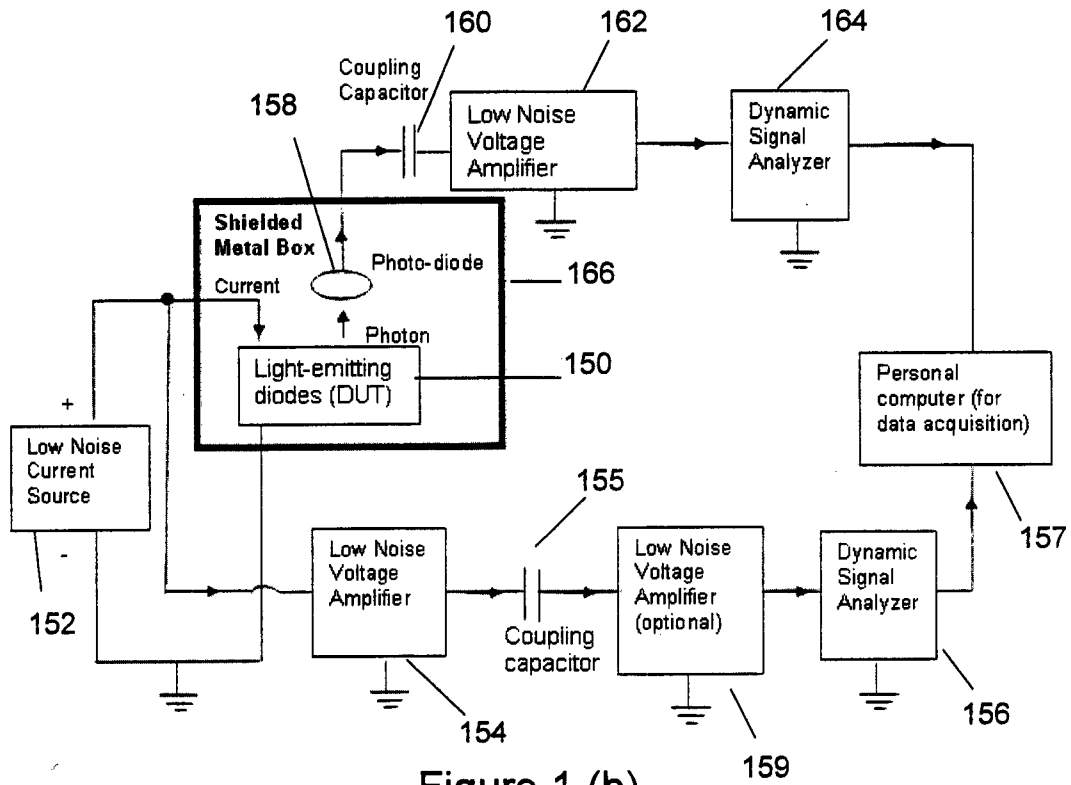
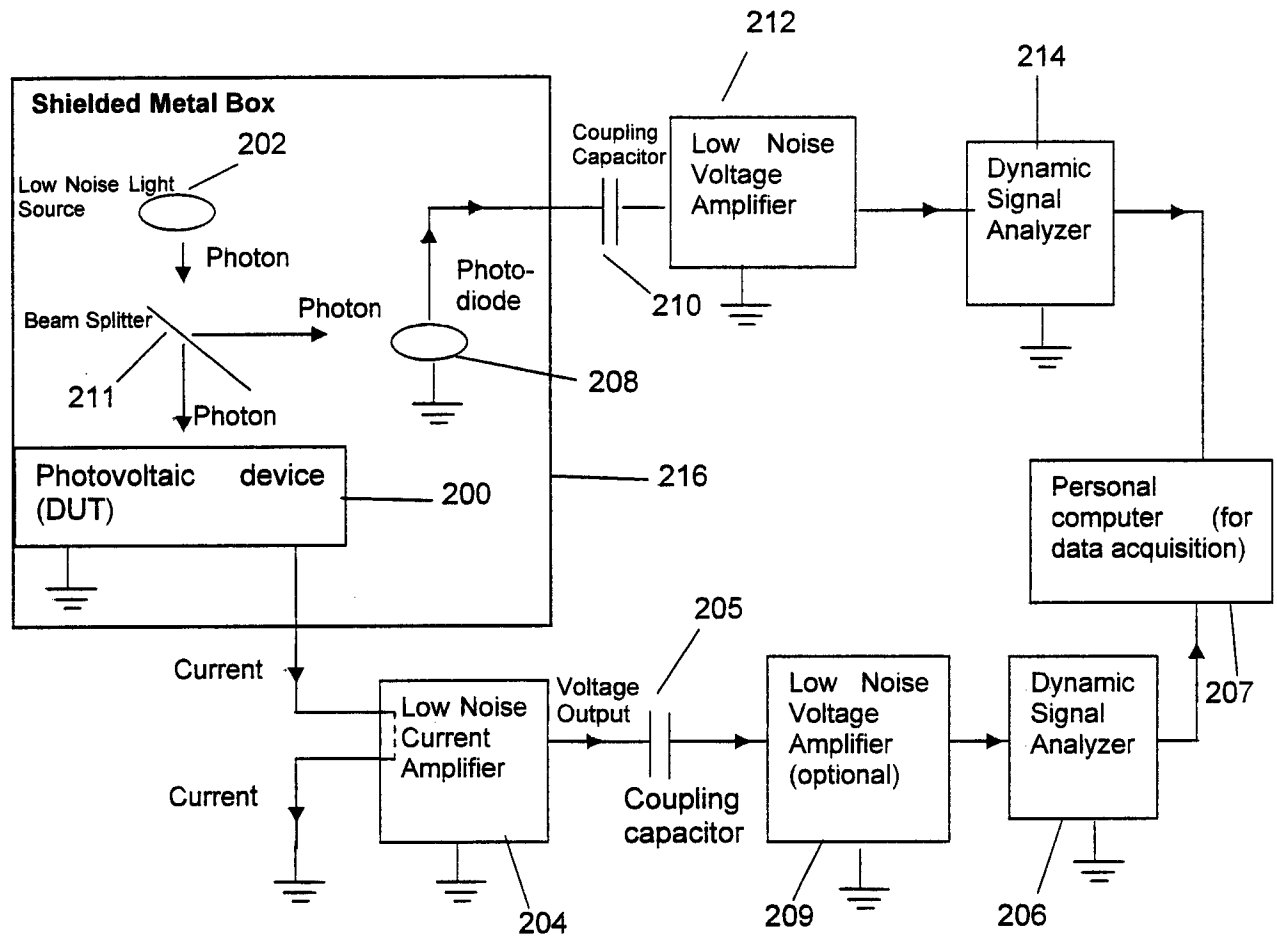
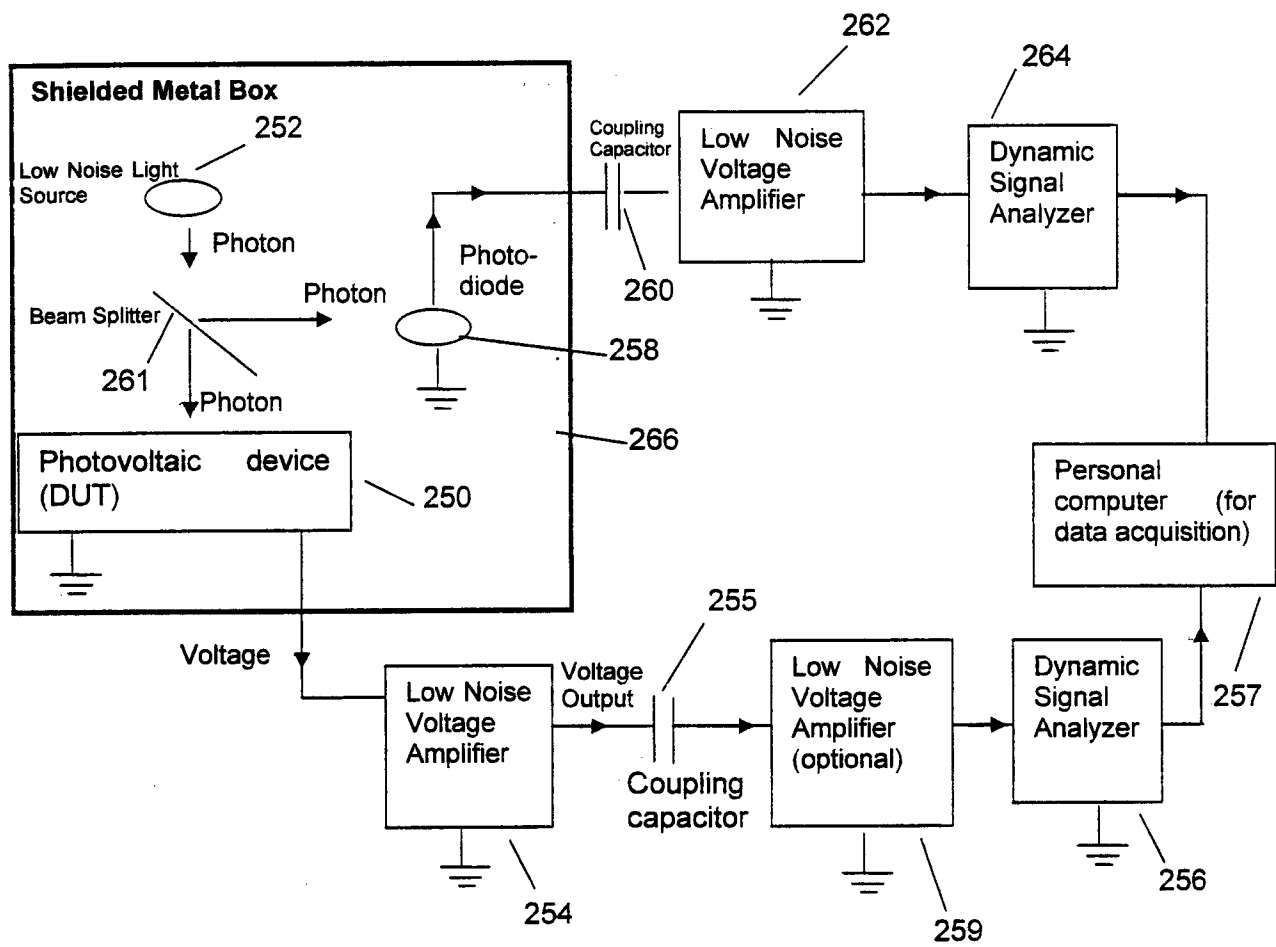
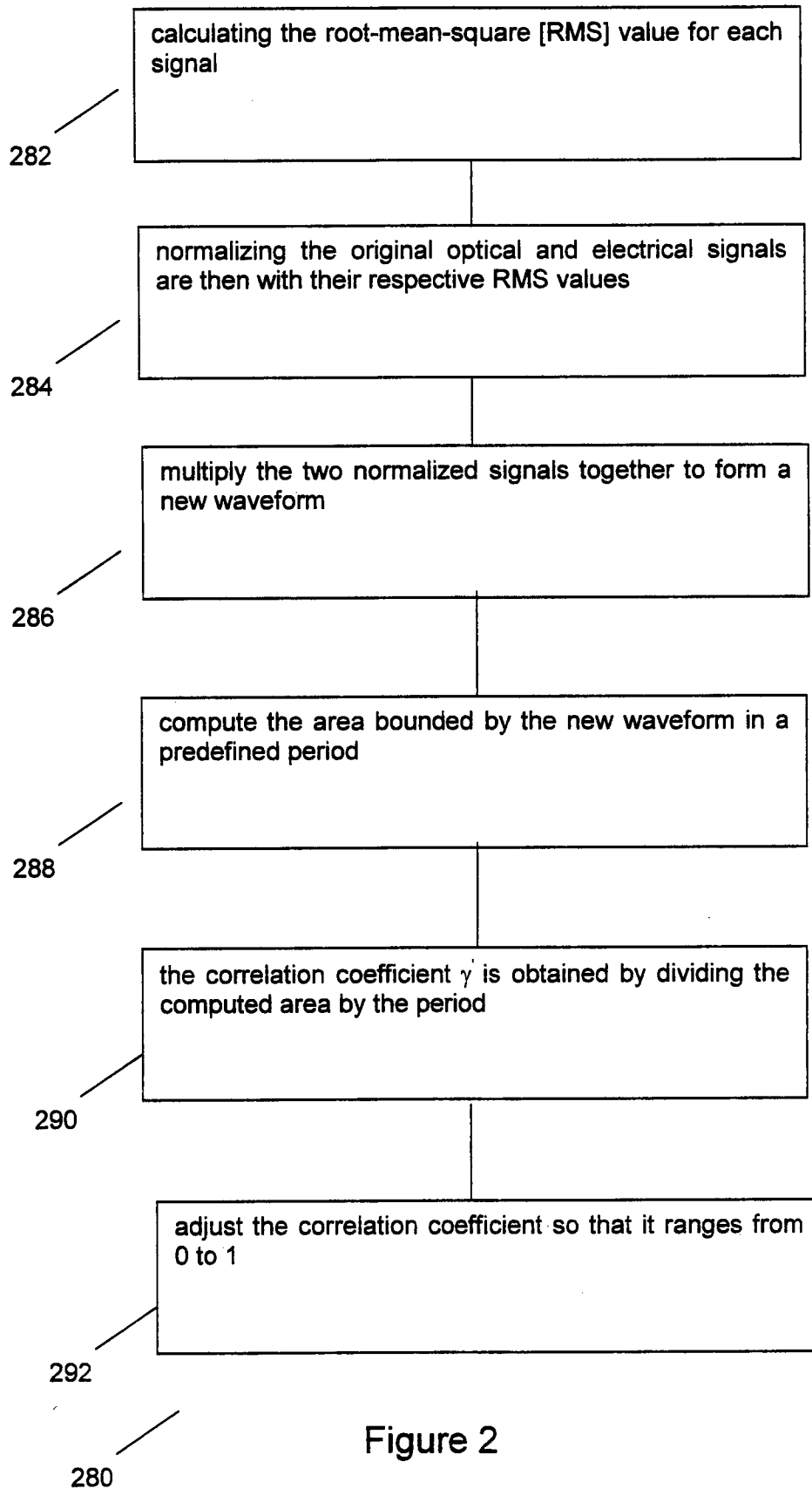


Figure 1 (b)

**Figure 1 (c)**

**Figure 1 (d)**



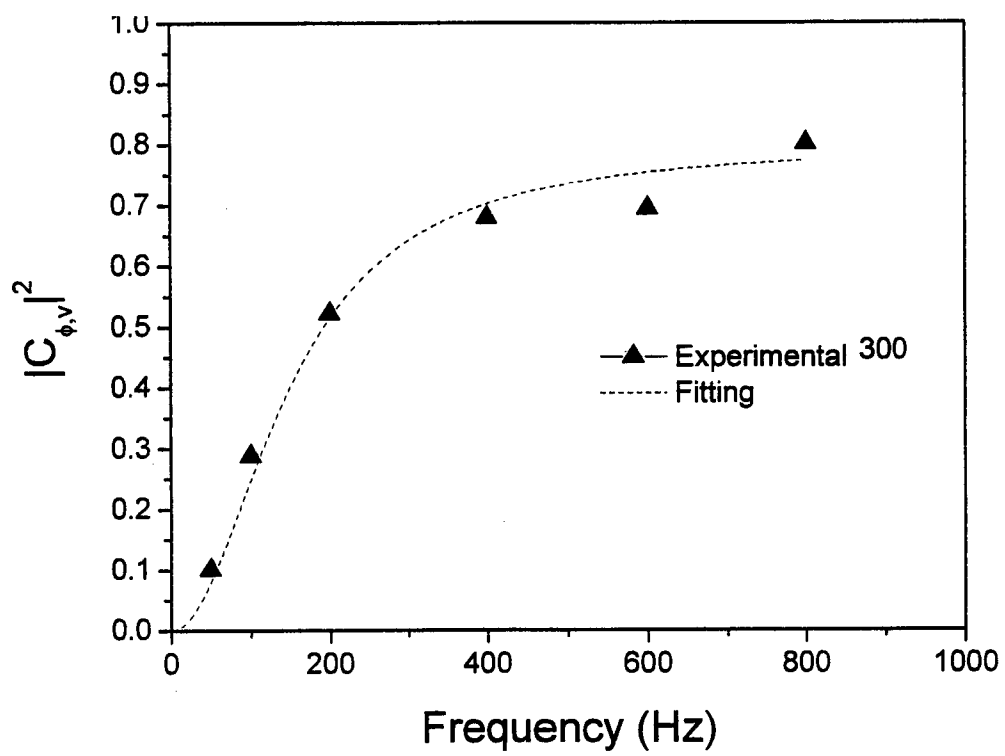


Figure 3

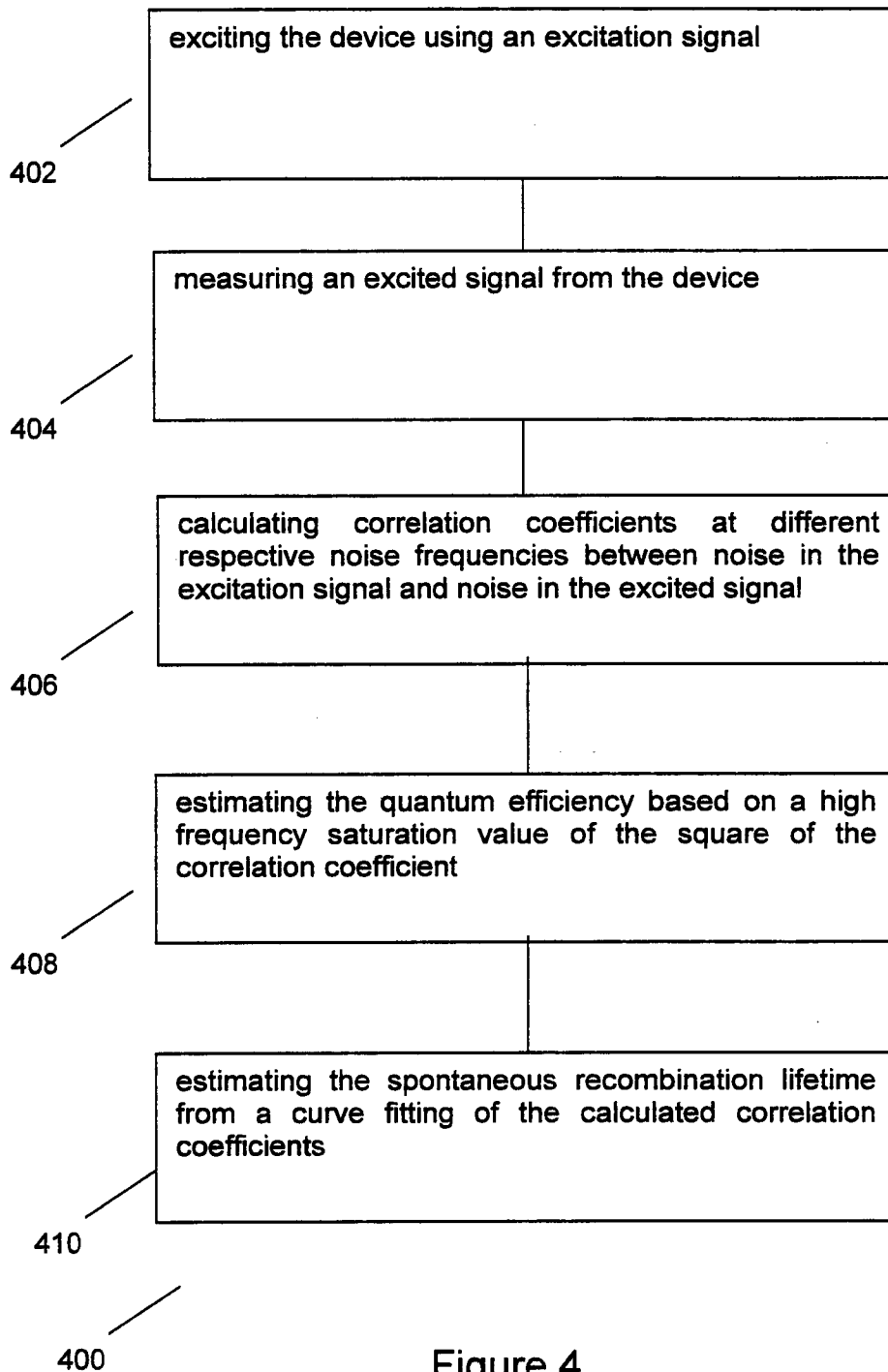


Figure 4

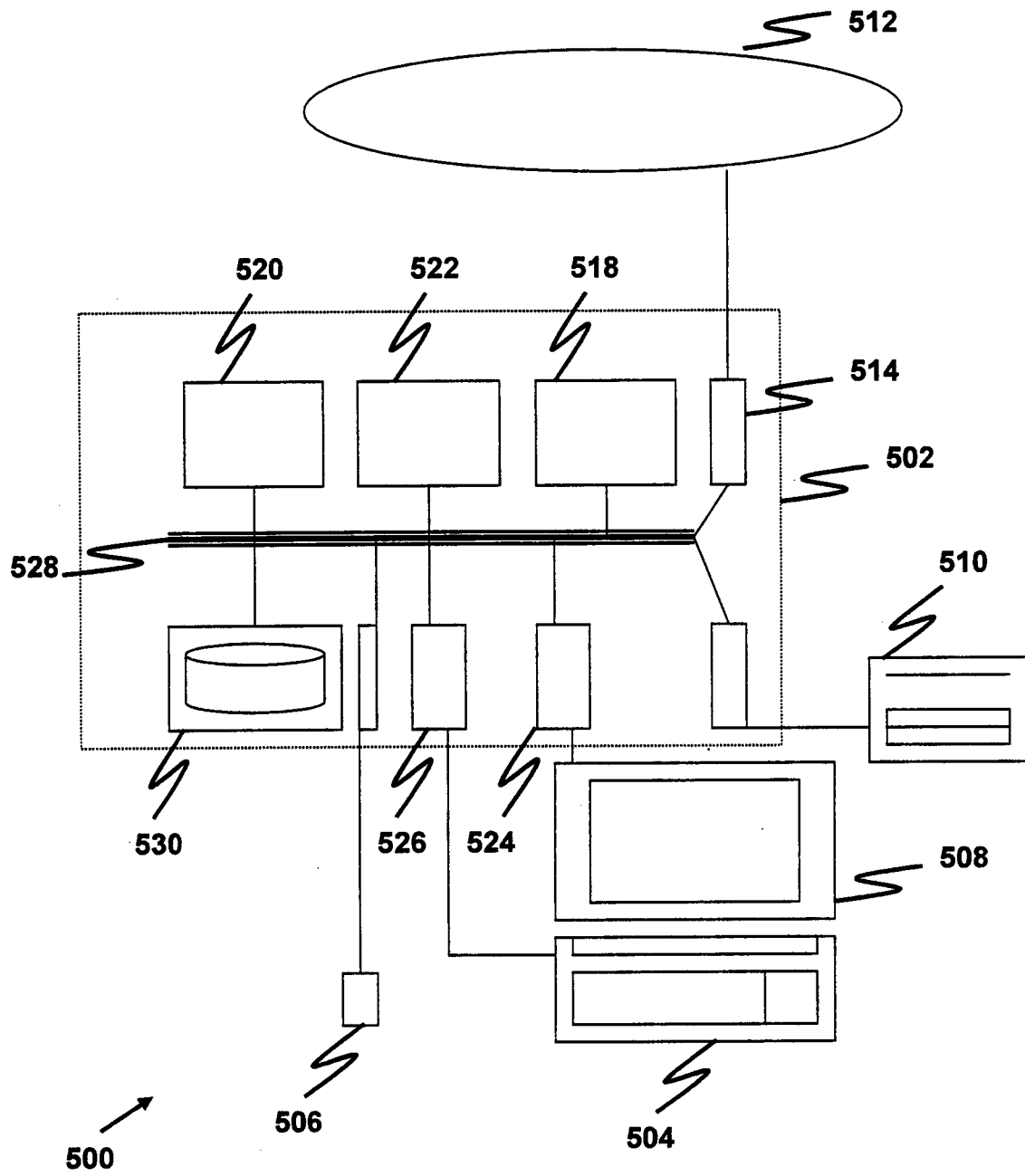


Figure 5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2011/000224

A. CLASSIFICATION OF SUBJECT MATTER												
Int. Cl.												
<i>H01L 21/66</i> (2006.01) <i>G01R 29/26</i> (2006.01)												
According to International Patent Classification (IPC) or to both national classification and IPC												
B. FIELDS SEARCHED												
Minimum documentation searched (classification system followed by classification symbols)												
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched												
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) WPI/EPODOC/INSPEC & keywords (quantum, efficiency, spontaneous, recombination, noise, frequency and similar terms); Espacenet and keywords ("agency for science", quantum, efficiency); GOOGLE/GOOGLE PATENTS/GOOGLE SCHOLAR & keywords (quantum, efficiency, noise, frequencies, spontaneous, recombination, lifetime)												
C. DOCUMENTS CONSIDERED TO BE RELEVANT												
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.										
X	Lin, K. et al, "Correlation analysis of electrical and optical low frequency fluctuation in organic device degradation", Journal of Applied Physics, 105, pp 064504-1 to 064504-7, pub on-line 19 March 2009 See whole document	1-17										
A	Vandamme, L.K.J., "Noise as a diagnostic tool for quality and reliability of electronic devices", IEEE Transactions on Electron Devices, Vol. 41, No. 11, pp 2176-2187, November 1994 See p2178 section D											
A	Rumyantsev, S.L., et al., "Current and optical low-frequency noise of GaInN/GaN green light emitting diodes", Proc. of SPIE, Vol. 6600, pp 660001-1 to 660001-9, 2007 See abstract											
☐ Further documents are listed in the continuation of Box C ☐ See patent family annex												
* Special categories of cited documents: <table border="0"> <tr> <td>"A" document defining the general state of the art which is not considered to be of particular relevance</td> <td>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</td> </tr> <tr> <td>"E" earlier application or patent but published on or after the international filing date</td> <td>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</td> </tr> <tr> <td>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</td> <td>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</td> </tr> <tr> <td>"O" document referring to an oral disclosure, use, exhibition or other means</td> <td>"&" document member of the same patent family</td> </tr> <tr> <td>"P" document published prior to the international filing date but later than the priority date claimed</td> <td></td> </tr> </table>			"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention	"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone	"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art	"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family	"P" document published prior to the international filing date but later than the priority date claimed	
"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention											
"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone											
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art											
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"P" document published prior to the international filing date but later than the priority date claimed												
Date of the actual completion of the international search 09 August 2011		Date of mailing of the international search report 12.08.2011										
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustalia.gov.au Facsimile No. +61 2 6283 7999		Authorized officer STEPHEN CLARK AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6283 2781										