Low frequency noise of light emitting diodes

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ABSTRACT

Light emitting diodes (LEDs) are excellent candidates for the applications requiring low noise light sources with wavelengths ranging from 200 nm to 900 nm. These applications include the detection of fluorescence from protein molecules excited with the ultraviolet (UV) light (200-300nm) for identifying miniscule amounts of hazardous biological pathogens. The detection system including the light source must exhibit low noise and high stability over tens of minutes. In comparison with xenon, tungsten halogen lamps, lasers, and other conventional UV sources, UV LEDs are more stable, have lower noise, are smaller, cheaper, and easier to use. We report on the low frequency fluctuations of the current and light intensity of LEDs (fabricated by SET, Inc.) with wavelengths ranging from 265nm to 340nm. The results are compared with the noise properties of the halogen lamps and other commercially available LEDs with the wavelengths of 375nm, 505nm and 740nm. We show that the LEDs fabricated by Sensor Electronic technology, Inc. are suitable for studying steady state and time-varying UV fluorescence of biological materials. The correlation coefficient between the current and light intensity fluctuations varies with the LED current and load resistance. This dependence is explained in terms of the contributions to the 1/f noise from the active region and from the LED series resistance. The noise level could be reduced by operating the LEDs at a certain optimum current level and by using a large external series resistance (in the current source driving mode).

Keywords: light emitting diode, LED, low frequency noise, 1/f noise, GaN, gallium nitride, ultraviolet light, UV

I. INTRODUCTION

Low noise light sources with wavelengths ranging from 200 nm to 900 nm are required for many biological experiments. For example, voltage-sensitive dyes have found wide application as molecular probes for monitoring electrical activity in cells and tissues, because the absorbance and/or fluorescence of these dyes vary with the cell potential. Therefore they may be used to monitor action potentials, synaptic potentials, or other changes in membrane voltage from a large number of sites at once. However, these optical signals are relatively small, so very low noise light sources are required for detecting these potentials.

The protein molecules that contribute to the structure of microorganisms strongly absorb in the deep ultraviolet (200-300nm) range and exhibit fluorescence at longer wavelengths. Detection of fluorescence from these molecules is an effective method for identifying miniscule amounts of hazardous biological pathogens. Mercury and xenon lamps, solid state or gas lasers, and even stable tungsten-halogen lamps used in such detection systems are large, costly, heavy, and difficult to use. Since a very small amount of pathogen protein has to be detected, the detection system must exhibit high sensitivity; i.e. the smallest amount of the biological agent should give a reproducible and stable response above the system noise. The task becomes even more difficult when longer observation times needed to track biomolecular changes. These experiments require not only a very low noise, but also a very high stability over tens of seconds.

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The first study of the intensity fluctuations in GaAs-based LEDs was published by Brophy in 1967\(^\text{10}\). Both \(1/f\) noise and generation-recombination noise were found, and the correlation between the fluctuations in light intensity and the diode current noise was established.

Several papers on laser diodes (LDs) noise properties reported on noise both below and above the lasing threshold (see\(^\text{11-14}\) and references therein). As shown in\(^\text{11,12}\), the relative intensity noise (RIN) of the low frequency light intensity fluctuations in LDs depends non-monotonically on the diode current. At low currents, RIN decreases with the current increase, reaches a minimum, and then increases when the current approaches the lasing threshold.

Shot noise is dominant in LEDs at high frequencies. This noise can be partially suppressed by driving the diode via a constant-current source\(^\text{15,16}\). Several publications dealing with current fluctuations in LEDs have shown that the low frequency current noise can be used to study degradation phenomena in semiconductor and organic LEDs\(^\text{17-19}\).

In our recent publications\(^\text{20,21}\), we analyzed the time- and frequency-domain behavior of non-coherent light sources, including high power LED’s, UV LEDs, and the quartz tungsten halogen lamps commonly used in microscopy. We also proposed a noise figure-of-merit for LED’s\(^\text{20}\). We observed that LED’s exhibit low-frequency noise characteristics that are superior to those of other non-coherent light sources including quartz tungsten-halogen lamps. The extreme stability over tens of seconds, combined with readily selectable wavelengths, makes LED’s to be potentially optimal light sources for recording of slow optical changes from cells and tissues.

In this paper, we review our recent results and report on new experiments studying noise properties of LEDs with the wavelength ranging from 265 to 740nm.

2. EXPERIMENTAL DETAILS.

The UV LED structures fabricated by Sensor Electronic Technology, Inc. (SET, Inc.) were grown in a custom-designed vertical Metalorganic Chemical Vapor Deposition (MOCVD) system, with trimethyl aluminum (TMA), trimethyl gallium (TMG), silane, Cp2-Mg, and NH\(_3\) as precursors and basal plane sapphire as substrates. The AlN buffer and superlattices for strain management were grown by the Migration Enhanced MOCVD (MEMOCVD\(^\text{TM}\)). The active region consisted of 5 periods Si-doped Al\(_{0.5}\)Ga\(_{0.5}\)N/Al\(_{0.4}\)Ga\(_{0.6}\)N quantum wells with the barrier and well thickness to be approximately 70 Å and 35 Å, respectively. Commercially available LEDs from Nichia and Roithner Lasertechnik were also studied for the comparison.

Table I summarizes the electrical and optical parameters of the LEDs under investigation. First generation SET UVTOP\(^\text{®}\) LEDs are devices studied in ref.\(^\text{21}\). Second generation LEDs represent recent development of SET, Inc, which are characterized by higher power, efficiency, and spectral purity. Specific details on LED parameters and design are presented in ref.\(^\text{22,23}\). Fig.1 and Fig.2 show the example of electroluminescence spectrum and current dependence of the wall-plug-efficiency for second generation of the SET UVTOP\(^\text{®}\) 280nm LED. The spectral line half-width does exceed 11 nm and wall-plug-efficiency for the best devices approaches 1% for the DC current \(I=20\) mA.

The LED light intensity fluctuations were measured by the UV enhanced Si photodiode UV-100L from UDT Sensors, Inc. The photodiode was biased by a low noise battery using a load resistor, \(R_{\text{phd}}\), varying from 1 to 10 kΩ. The LEDs were biased by a low noise battery with a load resistor, \(R_{\text{LED}}\), varying from 10 to 1000 Ω. The halogen lamps were powered using a high capacity 12V car battery. The voltage fluctuations across the resistors \(R_{\text{phd}}\) and \(R_{\text{LED}}\) were amplified by a Signal Recovery low noise amplifier (model 5184) and analyzed using a SR 770 Network Analyzer or “Photon” portable dynamic signal analyzer that allows measuring cross spectra of signals.
Table 1. Electrical and optical parameters of the light sources under investigation

<table>
<thead>
<tr>
<th>Light source</th>
<th>Peak wavelength</th>
<th>Forward current</th>
<th>Forward voltage</th>
<th>Typical radiant flux (W), or Luminous intensity (mcd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SET UVTOP® (second generation)</td>
<td>265nm</td>
<td>20mA</td>
<td>5.5-7.5V</td>
<td>0.2mW</td>
</tr>
<tr>
<td>SET UVTOP® (second generation)</td>
<td>270nm</td>
<td>20mA</td>
<td>5.5-7.5V</td>
<td>0.5mW</td>
</tr>
<tr>
<td>SET UVTOP® (second generation)</td>
<td>280nm</td>
<td>20mA</td>
<td>5.5-7.5V</td>
<td>1mW</td>
</tr>
<tr>
<td>SET UVTOP® (first generation)</td>
<td>280nm</td>
<td>50mA</td>
<td>5-7V</td>
<td>0.1mW</td>
</tr>
<tr>
<td>SET UVTOP® (second generation)</td>
<td>295nm</td>
<td>20mA</td>
<td>5.5-7.5V</td>
<td>0.7mW</td>
</tr>
<tr>
<td>SET UVTOP® (second generation)</td>
<td>305nm</td>
<td>20mA</td>
<td>5.5-7.5V</td>
<td>0.5mW</td>
</tr>
<tr>
<td>SET UVTOP® (first generation)</td>
<td>340nm</td>
<td>50mA</td>
<td>5-6.5V</td>
<td>0.5mW</td>
</tr>
<tr>
<td>NICHIA NSHU550A</td>
<td>375nm</td>
<td>25mA</td>
<td>3.5-4V</td>
<td>2mW</td>
</tr>
<tr>
<td>NICHIA NSPE510S</td>
<td>505nm</td>
<td>30mA</td>
<td>3.5-4V</td>
<td>3200 mcd</td>
</tr>
<tr>
<td>Roithner Lasertechnik,</td>
<td>740nm</td>
<td>750mA</td>
<td>&gt;9V</td>
<td>&gt;1W</td>
</tr>
<tr>
<td>LED740-66-60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig.1. Electroluminescence spectrum of the SET UVTOP® 280nm (second generation) at $I_{LED}=20$ mA.

Fig.2. Wall-plug-efficiency as a function of the current for the SET UVTOP® 280nm LED (second generation).

3. RESULTS AND DISCUSSIONS

3.1 Noise spectra

Figure 3 shows the noise spectra of the photodiode current fluctuations, $S_{phd}^{phd}$, obtained after the subtraction of the background noise measured in the dark (also shown in the figure). The LED bias current was the maximum current specified by the manufacturer (see Table 1). Since the photodetector responsivity and the LED powers are different for different wavelengths, the photodetector current varied from one LED to another. However, in each case, the 1/f^-like noise was always proportional to the square of the photodiode current $S_{phd}^{phd} \propto I_{phd}^2$ varied by varying the amount of light reaching the photodiode. Therefore, the noise spectra shown for these LEDs in Fig.1 were normalized to the equivalent photodiode current of $I_{phd}=250\mu$A for all LED assuming $S_{phd}^{phd} \propto I_{phd}^2$. As seen, at low frequencies, the 1/f^-
noise with $\gamma=1-2$ was dominant for all LEDs. At higher frequencies (where $1/f^\gamma$ noise was small), the shot noise was or the thermal noise of load resistor $R_{phd}$ were dominant.

As seen from Fig. 3, the second generation SET UVTOP® LEDs exhibit the noise level of the same order of magnitude as visible and UV LEDs produced by NICHIA and much smaller than the noise of the first generation SET UVTOP® LEDs with the same wavelength.

![Graph](image_url)

**Fig. 3.** Noise spectra of light intensity fluctuations for different LEDs. The background noise measured in darkness, the levels of the shot noise $S_I=2qI_{phd}$ and thermal noise $S_T=4k_B T/R_{phd}$ are also shown ($I_{phd}=250\mu A$, $R_{phd}=1k\Omega$).

In comparison, the halogen lamps demonstrated unstable behavior. The noise amplitude varied from measurement to measurement by about one order of magnitude at low frequency (one measurement session took approximately 5 min). In Fig. 4, the hatched areas show the range of this variation for the two halogen lamps under study. The noise spectra for the LED740-66-60, SET UVTOP® LED 280nm, the background noise, and the shot noise $S_I=2qI_{phd}$ are also shown in Fig. 4. The noise spectra of the halogen lamps were close to a $1/f^4$ law. This rather unusual shape for the spectra is probably a signature of the non-stationary behavior of the halogen lamps. As seen, at low frequencies, the noise level of deep UV SET UVTOP® LEDs is smaller than for the halogen lamps.

![Graph](image_url)

**Fig. 4.** Noise spectra of the light intensity fluctuations for two Halogen lamps (hatched areas), LED740-66-60, SET UVTOP® 280nm. Background noise, and shot noise are shown for comparison. $I_{phd}=250\mu A$. 

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3.2 Noise characteristics

Figure 5 shows $S_{i}^{phd} / I_{phd}^2$ at frequency $f=10$ Hz as a function of the LED current for several LEDs under study. As seen, the relative spectral noise density of the light intensity fluctuations decreases with the increase of the LED current. The short wavelength SET UVTOP® LEDs demonstrate the noise level of the same order of magnitude or smaller as the longer wavelength LEDs (NICHIA NSHU550A and NICHIA NSPE510S.)

In ref. 3, we introduced the LED noise quality factor:

$$\beta = \frac{S_I}{I_{phd}^2} \frac{fn\tau}{q} I_{LED}. \quad (1)$$

where $f$ is the frequency, $n$ is the number of chips connected in series, $\tau$ is the radiation life-time, $q$ is the electronic charge, and $I_{LED}$ is the LED current. The lower the value of $\beta$, the better is the LED noise quality. This parameter is similar to the Hooge parameter used as a figure of merit for the $1/f$ noise for semiconductor materials and devices. The product $(n\tau q)I_{LED}$ plays the same role as the total number of carriers, $N$, in the expression for the Hooge parameter:

$$\alpha = \frac{S_I}{I_{phd}^2} fN. \quad (2)$$

Fig. 6 shows the $\beta$ as a function on the wavelength for different LEDs for $I_{LED} = 20$ mA. For a crude estimate, we assumed $\tau q \sim 10^{10}$ A^{-1} for all devices. As seen, short wavelength SET UVTOP® LEDs demonstrate the quality factor $\beta$ of the same order of magnitude as the 375nm and 505nm LEDs produced by Nichia.

![Graph showing noise characteristics](image_url)
3.3 Correlation coefficient between the optical and current noise

In ref.\textsuperscript{21}, we investigated the correlation coefficient between the optical and current noise

$$\gamma = \frac{S_{\text{phdLED}}}{\sqrt{S_{\text{phd}} \text{ } S_{\text{LED}}}}$$

as a function of the LED current for SET UVTOP\textsuperscript{®} 340nm for two values of the load resistor, $R_{\text{LED}}$ (see Fig. 7). Here $S_{\text{phd}}$ and $S_{\text{LED}}$ are the LED and photodiode current noise spectra and $S_{\text{phdLED}}$ is the cross spectrum of the LED and photodiode current fluctuations. Note that $S_{\text{phd}}$ and $S_{\text{LED}}$ are not short circuit but actual current fluctuations. As seen, from Fig.7, the correlation coefficient changes from ~0.3 to ~0.9 for $R_{\text{LED}}=10 \, \Omega$ when LED current increases from 5mA to 50mA. For $R_{\text{LED}}=100 \, \Omega$, the correlation coefficient is smaller.
To explain the observed $\gamma$ versus $I_{LED}$ dependence, we considered the simplified LED equivalent circuit consisted of the diode barrier resistance, $r$, the internal LED series resistance $R_c$ (which is the sum of the base and contact resistances), and the external resistance $R_{LED}$. Since, at high LED currents, resistance $R_c$ dominates the total diode resistance, we could assume that the fluctuations $\delta R_c$ of this resistance is the main source of the LED current fluctuations. For simplicity, in the model developed in [21], we assumed that these current fluctuations are dominant even when barrier resistance $r$ is comparable with $R_c$ at relatively low currents. We also assumed that there are additional fluctuations of the light intensity $\delta \Phi$, which are not related to the fluctuations of the resistance $R_c$. Fluctuations $\delta \Phi$ might relate, for example, to the fluctuations of the radiative recombination process, fluctuations of the substrate transparency, or fluctuations of the electron-hole pair concentration, $\delta n$, in the light emitting region. At high LED currents, the resistance of the light emitting region is small compared to the base and series resistance, and, therefore, fluctuations $\delta n$ are not expected to contribute much to the total LED resistance. The dependence of the photodiode current on the LED current was always linear for all LEDs studied ($\eta = I_{phd}/I_{LED} = 4 \times 10^{-4}$) within the studied current ranges. Hence, the LED and photodetector current fluctuations are given by:

$$\delta I_{LED} = I_{LED} \frac{\delta R_c}{(R_{LED} + R_c + r)}$$

$$\delta I_{phd} = \eta I_{LED} \frac{\delta R_c}{(R_{LED} + R_c + r)} + \eta I_{LED} \frac{\delta \Phi}{\Phi}$$

If $\delta R_c$ and $\delta \Phi$ are uncorrelated, the correlation coefficient is given by:

$$\gamma = \frac{S_{R_c}}{(R_{LED} + R_c + r)^2}$$

$$\sqrt{\frac{S_{R_c}^2}{(R_{LED} + R_c + r)^4} + \frac{S_{\Phi}^2}{\Phi^4} \frac{S_{R_c}}{(R_{LED} + R_c + r)^2}}$$

where $S_{R_c}$ is the spectral noise density of the resistance $R_c$ fluctuations given by

$$S_{R_c} = \frac{S_{I_{LED}}^{LED}}{I_{LED}^2} (R_c + r)^2.$$  

Here $S_{I_{LED}}^{LED}$ is the relative spectral noise density of the short circuit LED current fluctuations.

Spectral noise density $(S_{\Phi}/\Phi)$ can be evaluated as

$$S_{\Phi} = \frac{S_{I_{phd}}^{phd}}{I_{phd}^2} - \frac{S_{I_{phd}}^{LED}}{I_{LED}^2} \frac{(R_c + r)^2}{(R_{LED} + R_c + r)^2}$$

We found that the spectral noise density $(S_{\Phi}/\Phi)$ decreases with the increase of the LED current as $(S_{\Phi}/\Phi)^{-1} I_{LED}^2$. Solid lines in Fig.7 show the results of the calculation using Eq. (6) with the parameters extracted from the experimental data. As seen, the agreement with the measured dependences is quite good.

### 3.4 Signal to noise ratio

For many applications, the “signal to noise” ratio in certain frequency bandwidth $\Delta f= f_2-f_1$ is an important parameter. Here the “signal” is the power $P_{opt} = (\eta I_{LED})^2 R_{phd}$ dissipated by the resistor $R_{phd}$. The “noise” is the power, $P_{noise}$, of the thermal, shot and $1/f$ noise dissipated by the same resistor. Therefore, the signal to noise ratios for different noise sources are:
\[
\frac{P_{\text{opt}}}{P_{\text{noise/thermal}}} = \frac{(\eta I_{\text{LED}})^2 R_{\text{phd}}}{4kT\Delta f},
\]
\[
\frac{P_{\text{opt}}}{P_{\text{noise/shot}}} = \frac{(\eta I_{\text{LED}})^2}{2q(\eta I_{\text{LED}} + I_{\text{dark}})\Delta f},
\]
\[
\frac{P_{\text{opt}}}{P_{\text{noise/1/f}}} = \frac{I_{\text{LED}}n}{\beta \ln(f_2/f_1)} \frac{\tau}{q},
\]

where the 1/f noise power is taking as \(P_{\text{noise}} = \int_{f_1}^{f_2} \frac{\beta \eta^2 I_{\text{LED}} R_{\text{phd}} q}{\tau} \frac{df}{f} \) and \(I_{\text{dark}}\) is the dark current of photodetector. The coefficient \(\eta\) in the Eq.(9) is a function of the LED wall-plug-efficiency, photodetector responsivity, amount of light collected by photodetector, and number of chips connected in series (\(\eta \propto n\)). Therefore, in order to achieve a high “signal to noise ratio”, one needs photodetectors with the maximum responsivity for a given wavelength and efficient LEDs. Using several LEDs or a single LED of a larger area also improves the “signal to noise” ratio. Note that for the 1/f noise, the signal to noise ratio does not depend on \(\eta\). As shown above, there are at least two main sources of the 1/f noise in LEDs. The noise related to the internal series resistance can be partially suppressed by using a large external series resistance. The noise originating from the light emitting region could be decreased by optimizing the design of the light generating layer.

Figures 8, shows the dependencies of the signal to noise ratio on the LED current for two different LEDs for the frequency bandwidth from 1Hz to 1kHz (the actual dependence of the quality factor \(\beta\) on the LED current is taken into account). As seen, the “signal to noise ratio” can be limited by either shot, thermal or 1/f noise of LED, depending on the operating regime.

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Fig.8. Signal to noise ratios for two different LEDs as function of the LED current for the frequency bandwidth \(\Delta f\) from 1Hz to 1 kHz \(^{21}\).
3.5 Long term stability and example of optical measurements in neuroscience

Fig. 9 (from Reference 7) shows a series of measurements of the changes in transmitted light intensity (light scattering) from a mouse neurohypophysis in response to seven stimuli delivered at 16 Hz at time $t=10s$. Figures 9a and 9c correspond to the measurements performed with high power LED740-66-60, while figures 2b and 3c correspond to the measurements with the halogen lamp.

As discussed in 7, there is little difference in the optical noise from the two light sources over a 1.2 second recording period (Figures 9c, 9d). The individual scattering changes ($1.3 \times 10^{-4}$) are well resolved in both instances. This result is agreement with the low noise level for both halogen lamp and LED at frequency $f>50Hz$. However, when the full 50 second optical recordings are examined, it is very clear that the low frequency noise in the tungsten halogen traces is ~6-20 times larger than in the LED recordings. This result is also consistent with the high noise level of halogen lamp at low frequencies (see Fig.4). For monitoring short term intrinsic optical changes from the peptidergic nerve terminals of the neurohypophysis, the tungsten halogen light source is evidently adequate. However, for following slow changes in the optical properties of this tissue, the high power LED source is transparently superior.

![Fig. 9. Optical noise in the transmitted light intensity through a different unstained mouse neurointermediate lobe (neurohypophysis plus pars intermedia), during and after seven action potentials stimulated at 16 Hz. A and C depict records using LED740-66-60. B and C depict records using quartz tungsten halogen lamp.](image)

4. CONCLUSIONS

At low frequencies $f<(10^2-10^4)$ Hz, the noise spectra of UV LEDs depend on frequency as $1/f^\gamma$ with $\gamma = 1-2$. This $1/f$-like noise dependence on current is different for different LED types. UV LEDs exhibit a noise level and quality factor $\beta$ of the same order of magnitude as visible wavelength LEDs. Our results show that UVTOP® LEDs are suitable for studying steady state and time-varying UV fluorescence of biological materials.

The correlation coefficient between fluctuations of LED current and light intensity depends on the LED current and LED load resistance: the higher is the LED current and the smaller is the load resistance, the higher is the correlation coefficient. This result is explained by the contribution to the $1/f$ noise of two uncorrelated processes: fluctuations of the internal series resistance and fluctuations of light caused, most probably, by concentration fluctuations in the light emitting region. The light intensity fluctuations can be partially suppressed by a large external series resistance. The “signal to noise” ratio is limited by either thermal, shot or $1/f$ noise and is a function of the of the LED wall-plug efficiency, photodetector responsivity, the amount of light collected by the photodetector, LED current, the total LED area, and by the amplitude of the LED $1/f$ noise.
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