Corrections to *A Guide to Experiments in Quantum Optics*

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The following are corrections to errata within the Second Edition of *A Guide to Experiments in Quantum Optics*.

Chapter 2 - Classical models of light

§2.1.4

Page 17

The second line of Equation 2.1.13 should read $X2(\mathbf{r},t) = -i[\alpha(\mathbf{r},t) - \alpha^*(\mathbf{r},t)]$**.**

Chapter 4 - Quantum models of light

§4.1.2

Page 61

In the third line, "ad" should read as.

§4.3.3

Page 76

In the caption of Figure 4.6, "two" should read three.

§4.4.1

Page 78

In the caption and title of Table 4.1 "Properties of quantum noise" should be replaced by Properties of coherent states.

Chapter 5 - Basic optical components

§5.1.1

Page 100

In Figure 5.1, all E should be replaced by α.

Page 106

In Figure 5.3, the 2 labels $|2>_r\ |0>_t$ and $|0>_r\ |2>_t$ should be removed and replaced by the single label $|2>_r\ |0>_t - |0>_r\ |2>_t$ placed in the bottom right corner.

§5.1.5

Page 109

In the section *Transfer function for a beam splitter*, $\delta\tilde{\mathbf{X}}2 = i(\delta\tilde{\mathbf{a}} - \tilde{\delta})a^\dagger$ should be $\delta\tilde{\mathbf{X}}2 = i(\delta\tilde{\mathbf{a}} - \delta\tilde{\mathbf{a}}^\dagger)$.

§5.2.1

Page 114

In equation 5.2.5, $\frac{\sqrt{I_{II}I_I}}{I_{II}+I_I}$ should be $\frac{2\sqrt{I_{II}I_I}}{I_{II}+I_I}$.

§5.3.5

Page 133

In Figure 5.14, the labels A_{out1} and A_{out2} should be swapped.

§5.3.1

Page 125

New citation to a note in the chapter 5 references should be inserted at the end of the first paragraph on page 125. The note should read: Note that the definition of *under coupled* and *over coupled* used here is the opposite of the conventional definition used for example in the book *Lasers* by A. Siegman

Chapter 7 - Photodetection techniques

§7.4.1

Page 186

The paragraph after equation 7.4.5 should read: One of the largest contributions is normally the thermal noise. Consider the following example: for a DC current of 1 [mA], equivalent to 1 [mW] of power at $\lambda = 1000$ [nm], the thermal noise at room temperature for an impedance of 50 [Ohm] and a detection bandwidth of 100 [kHz] is $\Delta i(t)^2_{\text{thermal}}/\bar{i}^2 = 4k_B TB/R\bar{i}^2 = 4 * 1.38\,10^{-23} * 300 * 10^5/(50 * 10^{-6}) = 3.3\,10^{-11}$. The relative noise which corresponds to the shot noise for this bandwidth and average power is $\Delta i(t)^2/\bar{i}^2 = 2\,e\,B\,/\bar{i} = 2 * 1.6\,10^{-19} * 10^5/10^{-3} = 3.2\,10^{-11}$. This means that for the given conditions both quantum noise and electrical noise produce comparable relative fluctuation $\Delta i(t)$ of about $5\,10^{-6}$.

Chapter 8 - Quantum noise: Basic measurements and techniques

§8.3.1

Page 213

In the last line of the first paragraph of §8.3.1 the a **should be deleted.**

In the fourth line of the second paragraph, $\delta\tilde{\mathbf{A}}_e$ **should read** $\delta\tilde{\mathbf{A}}_{el}$**.**

Page 214

In Equation 8.3.1, $\delta\tilde{\mathbf{A}}_{il} = \delta\tilde{\mathbf{A}}_{\text{las}} + h(\Omega)\delta\tilde{\mathbf{A}}_{\text{las}}$ **should read** $\delta\tilde{\mathbf{A}}_{il} = \delta\tilde{\mathbf{A}}_{\text{las}} + h(\Omega)\delta\tilde{\mathbf{A}}_{\text{el}}$**, and** $\delta\tilde{\mathbf{A}}_{il} = \delta\tilde{\mathbf{A}}_{\text{f}} = \delta\tilde{\mathbf{A}}_{\text{e}}$ **should read** $\delta\tilde{\mathbf{A}}_{il} = \delta\tilde{\mathbf{A}}_{\text{f}} = \delta\tilde{\mathbf{A}}_{\text{el}}$**.**

In Equation 8.3.3, $\delta\tilde{\mathbf{A}}_{il} = \frac{\delta\tilde{\mathbf{A}}_{\text{las}}}{|1-h(\Omega)|^2}$ **should read** $\delta\tilde{\mathbf{A}}_{il} = \frac{\delta\tilde{\mathbf{A}}_{\text{las}}}{|1-h(\Omega)|}$**.**

§8.3.2

Page 217

In Equation 8.3.6, $g\sqrt{\epsilon\mu}(\Omega)$ **should read** $\sqrt{g(\Omega}$**.**

The first line of paragraph two should read: which describes the action of the intensity modulator which combines...

The reference to Appendix K **above Equation 8.3.8 should read** Appendix D**.**

After Equation 8.3.9, $h(\Omega) = \eta\epsilon\, g(\Omega)$ **should read** $h(\Omega) = \sqrt{\eta\epsilon\, g(\Omega)}$**.**

§8.5

Page 229

The caption of Figure 8.18, "A normalized noise transfer spectrum of an injection locked laser.." should read "A normalized noise spectrum of a free-running Nd:YAG laser..."

And the last paragraph should be replaced by the following text: "The outcome of these models and of experiments [Har96] is that the characteristic of the laser intensity noise varies with the detection frequency. There are clearly distinguishable regions of frequencies that show different properties. A practical example is the locking of two Nd:YAG lasers. One region is centered roughly around the relaxation oscillation frequency of the slave laser (see Fig. 8.18). Here, the slave laser operates effectively like an amplifier for the noise of the master laser. Note that if the master laser is quantum noise limited this means output is considerably noisier than a QNL laser with the same power as the slave laser. At very high frequencies the output can reach the quantum limit, it maintains the properties of the slave laser. At very low frequencies the dominant source of noise is the pump source of the slave laser. Different strategies have to be followed to optimize the system at the different frequencies."

Chapter 9 - Squeezing experiments

§9.5

Page 265

The following should be appended to the caption of Figure 9.27: and for a finite quantum efficiency $\eta \leq 1$.

Appendix D - Calculation of the quantum properties of a feedback loop

The following is the entire corrected version of Appendix D:

An electronic intensity control system, or electronic noise eater, as discussed in Section 8.3.2, is described by the following set of equations.

$$\begin{aligned}
\delta\tilde{\mathbf{A}}_{il} &= \delta\tilde{\mathbf{A}}_{\text{las}} + \sqrt{g(\Omega)}\,\delta\tilde{\mathbf{A}}_{\text{el}} \\
\delta\tilde{\mathbf{A}}_{f} &= \sqrt{\epsilon}\,\delta\tilde{\mathbf{A}}_{il} + \sqrt{1-\epsilon}\,\delta\tilde{\mathbf{A}}_{\text{vac1}} \\
\delta\tilde{\mathbf{A}}_{\text{el}} &= \sqrt{\eta}\,\delta\tilde{\mathbf{A}}_{f} - \sqrt{1-\eta}\,\delta\tilde{\mathbf{A}}_{\text{vac2}} \\
\delta\tilde{\mathbf{A}}_{o} &= \sqrt{1-\epsilon}\,\delta\tilde{\mathbf{A}}_{il} - \sqrt{\epsilon}\,\delta\tilde{\mathbf{A}}_{\text{vac1}} \\
\delta\tilde{\mathbf{A}}_{\text{out}} &= \sqrt{\eta}\,\delta\tilde{\mathbf{A}}_{o} - \sqrt{1-\eta}\,\delta\tilde{\mathbf{A}}_{\text{vac3}}
\end{aligned} \tag{1}$$

Here we are explicitly solving these equations to derive the transfer functions for the photocurrents inside the system (*il*, *f* and *el*)) and for the output beam (*out*). Combining the different parts of Eq. (1) we obtain

$$\begin{aligned}
\delta\tilde{\mathbf{A}}_{\text{el}} &= \sqrt{\eta}\,\delta\tilde{\mathbf{A}}_f - \sqrt{1-\eta}\,\delta\tilde{\mathbf{A}}_{\text{vac2}} \\
&= \sqrt{\eta\epsilon}\,\delta\tilde{\mathbf{A}}_{il} + \sqrt{\eta(1-\epsilon)}\,\delta\tilde{\mathbf{A}}_{\text{vac1}} - \sqrt{1-\eta}\,\delta\tilde{\mathbf{A}}_{\text{vac2}} \\
&= \sqrt{\eta\epsilon}\delta\tilde{\mathbf{A}}_{\text{las}} + \sqrt{\eta\epsilon\, g(\Omega)}\,\delta\tilde{\mathbf{A}}_{\text{el}} + \sqrt{\eta(1-\epsilon)}\,\delta\tilde{\mathbf{A}}_{\text{vac1}} - \sqrt{1-\eta}\,\delta\tilde{\mathbf{A}}_{\text{vac2}}
\end{aligned}$$

which leads to the equations for the quadrature

$$\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{el}} = \sqrt{\eta\epsilon}\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{las}} + \sqrt{\eta\epsilon\, g(\Omega)}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{el}} + \sqrt{\eta(1-\epsilon)}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{vac1}} - \sqrt{1-\eta}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{vac2}}$$

$$\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{el}} = \frac{\sqrt{\eta\epsilon}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{las}} + \sqrt{\eta(1-\epsilon)}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{vac1}} - \sqrt{1-\eta}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{vac2}}}{1 - \sqrt{\eta\epsilon\, g(\Omega)}} \tag{2}$$

and we can now define the open loop gain $h(\Omega) = \sqrt{\eta\epsilon\, g(\Omega)}$ where we keep the frequency dependence explicitly as a reminder of the specific properties of the feedback system. The operators for the quadratures always contain the frequency dependence of the field. We can now derive the spectrum for the in-loop electric current as:

$$\begin{aligned}
V1_{\text{el}}(\Omega) &= \frac{\eta\epsilon V1_{\text{las}}(\Omega) + \eta(1-\epsilon) + (1-\eta)}{|1 - \sqrt{\eta\epsilon g(\Omega)}|^2} \\
&= \frac{\eta\epsilon(V1_{\text{las}}(\Omega) - 1) + 1}{|1 - h(\Omega)|^2}
\end{aligned} \tag{3}$$

In a similar way we derive the spectrum of the photocurrent at the output of the apparatus. We start with the field amplitude

$$\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{out}} = \sqrt{\eta(1-\epsilon)}\left(\sqrt{g(\Omega)}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{el}} + \delta\tilde{\mathbf{X}}\mathbf{1}_{\text{las}}\right) - \sqrt{\eta\epsilon}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{vac1}} - \sqrt{1-\eta}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{vac3}} \tag{4}$$

The spectrum of the outcoming laser beam can be derived by substituting Equation (2) into Equation (4) resulting in

$$\begin{aligned}
\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{out}} &= \frac{\sqrt{\eta(1-\epsilon)}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{las}} + (\eta\sqrt{g(\Omega)} - \sqrt{\eta\epsilon})\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{vac1}}}{1 - h(\Omega)} \\
&\quad - \frac{\sqrt{\eta(1-\epsilon)(1-\eta)g(\Omega)}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{vac2}} + (1 - h(\Omega))\sqrt{1-\eta}\,\delta\tilde{\mathbf{X}}\mathbf{1}_{\text{vac3}}}{1 - h(\Omega)}
\end{aligned}$$

which leads to

$$
\begin{aligned}
V1_{\text{out}}(\Omega) &= \frac{\eta(1-\epsilon)V1_{\text{las}}(\Omega) + |\eta\sqrt{g\,(\Omega)} - \sqrt{\eta\epsilon}|^2}{|1-h(\Omega)|^2} \\
&+ \frac{\eta(1-\eta)(1-\epsilon)\,g(\Omega) + |1-h(\Omega)|^2(1-\eta)}{|1-h(\Omega)|^2} \\
&= 1 + \frac{1-\epsilon}{\epsilon}\;\frac{\eta\epsilon(V1_{\text{las}}(\Omega)-1) + |h(\Omega)|^2}{|1-h(\Omega)|^2}
\end{aligned} \tag{5}
$$

This spectrum is obviously, in most situations, above the QNL, never below. This result shows the effect of the feedback loop adding vacuum noise which is entering the system through the unused port of the beamsplitter and at the detectors. This is quite different from the predictions of a classical theory. The classical equations apply in the limit of large noise or modulations, that is $V1_{\text{las}} >> 1$.