Electrical source of pseudothermal light

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(Dated: August 21, 2018)

Abstract

We describe a simple and compact electrical version of the pseudothermal light source. The source is based on electrical white noise whose spectral properties are tailored by analog filters. This signal is used to drive a light-emitting diode. The type of the second-order coherence of the output light can be either Gaussian or Lorentzian, and the intensity distribution can be either Gaussian or non-Gaussian. The output light field is similar in all viewing angles and thus there is no need for a small aperture or optical fiber in temporal coherence analysis.

I. INTRODUCTION

Characterization of whether a light source emits classical or quantum light is a common task in quantum optics experiments. In practice, this task can be performed by measuring the second-order temporal coherence $g^{(2)}(\tau)$. By analyzing $g^{(2)}(\tau)$ as a function of the delay time τ we can classify thermal, coherent-laser, and single-photon light. Measurement of $g^{(2)}$ for natural thermal light is not possible in student laboratories and is very challenging in a research laboratory. This challenge is the result of the very short coherence time of these sources, which is typically only a few femtoseconds. Martienssen and Spiller introduced the construction of a *pseudothermal* source with a coherence time that is several orders of magnitude longer.[1] In this source, a laser beam is focused on the rotating ground glass and the resulting scattered light creates moving or evolving speckle patterns that imitate the intensity variability of thermal light. This method of producing a pseudothermal source has been implemented in many fundamental studies of photon statistics, including the first demonstrations of photon bunching phenomenon,[2,3] and has also been used in several student laboratory experiments.[4–6] From a pedagogical point of view, such a pseudothermal source has the following significant benefit: the formation of the light field, i.e., the speckle patterns, is concrete and visible. Thus the rotating ground disk acts as an excellent physical simulator of the thermal light emitted by a collection of atoms.

However, the actual function of the rotating ground disk source is quite complex and the coherence time depends on many factors, including the divergence of the laser beam, focal length of the focusing lens, and distance of the laser waist and measuring point from the ground disk.[7–9] In practice, it is difficult to adjust the coherence time over a large range and simultaneously maintain the Gaussian intensity distribution. Since the light field has strong spatial coherence, light should be collected through a very small aperture or with a optical fiber when measuring the second-order temporal coherence either directly from the intensity time series or via coincidence analysis of the beamsplitter outputs.

Here, we describe a purely electrical source of pseudothermal light whose second-order coherence function can be changed. The main idea of this source is as follows: generate wide-band electrical noise and then change the frequency distribution of this noise by simple analog filtering in order to create the required second-order coherence function with a Gaussian intensity distribution. The tailored electrical signal is converted to light by using a light-emitting diode (LED). It should be mentioned that this device cannot create any speckle patterns, thus it cannot display all aspects of thermal light; only the temporal coherence of thermal light can be demonstrated.

Our device has some similarities with the experimental setup that created a Poissonian and sub-Poissonian source of light using an LED.[10] In the Poissonian case, the LED was driven by a noisy current source consisting of the a halogen lamp and photodiodes. In the limit of very low efficiency, this drive current and the output light intensity has Poissonian statistics.

II. THERMAL LIGHT AND SECOND-ORDER COHERENCE

If the intensity of the light field is measured at one point in space, the second-order *temporal* coherence is

$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}, \tag{1}$$

where we assume that the statistical properties of the intensity do not change in time. When the fluctuation of the intensity is measured as a time series, $g^{(2)}(\tau)$ is simply the normalized autocorrelation function of the intensity and it can be easily computed. For classical light fields, $1 \leq g^{(2)}(0)$ and $g^{(2)}(\tau) \leq g^{(2)}(0)$.[11,12] The actual functional form of $g^{(2)}$ for real thermal sources depends on the details of the generation process. There are two important cases. First, if the electric field consists of a single frequency component, but the phase changes abruptly and randomly in time, we obtain

$$g_L^{(2)}(\tau) = 1 + \exp\{-2|\tau|/\tau_c\}, \tag{2}$$

where τ_c is the coherence time. The corresponding normalized frequency spectrum of the intensity time series has a *Lorenzian* form

$$F_L(\omega) = \frac{\gamma/\pi}{(\omega_0 - \omega)^2 + \gamma^2}, \tag{3}$$

where $\gamma = 1/\tau_c$ and ω_0 is the center angular frequency.[11,12] Second, if the electric field has many different frequency components with a Gaussian distribution, and each component has constant but randomly distributed phase, we have

$$g_G^{(2)}(\tau) = 1 + \exp\{-\pi(\tau/\tau_c)^2\} \tag{4}$$

and the corresponding frequency spectrum has a *Gaussian* form

$$F_G(\omega) = \exp\{-(\omega_0 - \omega)^2/(2\Delta^2)\}/\sqrt{2\pi\Delta^2} \tag{5}$$

where $\Delta = \sqrt{\pi}/\tau_c$.[11,12]

The aim of the design of our electrical pseudothermal source is to produce white noise and then approximate the frequency spectra of Eqs. (3) and (5) by suitable analog filtering. If this is possible, then we can realize the second-order coherences given by Eqs. (2) and (4).

III. EXPERIMENTAL SETUP

The pseudothermal light source is an LED (any type can be used) driven by a filtered noise voltage source. The voltage source, shown in Fig. 1, is based on the avalanche breakdown of the base-emitter junction of the transistor. In order to achieve the breakdown, the supply voltage should be at least 12 V. The spectrum of the generated noise extends up to tens of MHz and, in the frequency range from ∼0 to tens of kHz, it can be regarded as white noise. The noise voltage of a few millivolts is amplified by the operational amplifier U1. The amplitude of the noise should be maximized by adjusting the potentiometer P1. The noise signal is filtered by one or four identical Sallen-Key type of low-pass filters shown in Fig. 2. The operational amplifier U2 is used to drive the LED. With the potentiometer P2, a small offset voltage is added to the output in order to shift the bipolar noise voltage to a unipolar current for the LED.

The frequency response of the low-pass filter is

$$|H(f)| = \frac{1}{\sqrt{[-(f/f_c)^2 + 1]^2 + (2f/f_c)^2}}, \tag{6}$$

where the cutoff frequency $f_c = 1/(2\pi RC)$.[13] In the limit of high frequencies, this relation becomes $|H(f)| \approx 1/(f/f_c)^2$. By setting $\omega_0 = 0$ and taking the limit $\omega = 2\pi f \to \infty$ in Eq. (3), we get exactly the same frequency dependency. In the low-frequency limit, the response given in Eq. (6) deviates from that of Eq. (3), but this is not expected to be a severe limitation. At low frequencies the frequency response (6) is approximately constant (unity) and the spectrum is flat, therefore there is no correlation, i.e., the autocorrelation $\langle I(t)I(t+\tau)\rangle = \langle I(t)\rangle\langle I(t+\tau)\rangle$ and the second-order coherence approaches unity. In conclusion, by filtering white noise with a low-pass filter whose response follows Eq. (6), we can obtain a reasonably good approximation of the Lorentzian second-order coherence given by Eq. (2).

When N low-pass filters are cascaded, the frequency response in the limit of high frequencies is $|H(f)| \approx 1/(f/f_c)^{2N}$. The Gaussian frequency spectrum of Eq. (5) has a decreasing exponential form, but its leading term can be approximated as $F_G(\omega) \approx 1/\omega^M$, where $M \gg 1$. So, if the number of the low-pass filters is high enough, we can at least approximate the Gaussian frequency spectrum in the high-frequency range. In practice, we found that just four filters are needed to produce excellent results.

The natural thermal light source has a Gaussian (exponential) intensity distribution and its second-order coherence has the maximum value of 2 at zero delay time. The intensity distribution of our source can be changed by adjusting the offset voltage in the last amplifier section (via potentiometer P2). We produced an (almost) exponential distribution when the offset is set in such a manner that the noise signal is slightly cut. This approach is possible because the LED acts like a half-wave rectifier and so the output light can be observed only when the driving voltage exceeds the threshold voltage of the LED.

IV. RESULTS

Figure 3 shows the amplitude spectrum of the white noise source and the frequency responses for the Gaussian and Lorentzian cases. Here, $R = 10\,\mathrm{k\Omega}$ and $C = 10\,\mathrm{nF}$, producing a cutoff frequency $f_c = 1592$ Hz. The cutoff frequencies below 100 Hz do not work properly, and the highest frequency is limited by the properties of the operational amplifiers; typically it is tens of kHz. The corresponding light intensities as a function of time are shown in Figs. 4 and 5. All intensities are measured by a fast photodiode (BPX61, Osram) and standard operational amplifier circuit and recorded by a digital oscilloscope (Picoscope 2206, using a sampling frequency of 100 kHz). We calculated the intensity autocorrelation of the data using homemade data-analysis software. The offset voltage was repeatedly adjusted, and the second-order coherence calculated, until the maximum value of 2 was accurately achieved.

The final results of the coherence analysis are shown in Fig. 6. The theoretical coherence functions of Eqs. (2) and (4) were numerically fitted to this experimental data over the delay time range of 0 – 5 ms. As can be seen, the experimental results are quite close to theoretical ones, especially in the range of small delay times where the distinctly different functional form of these two cases is clearly visible. For larger delay times, $g^{(2)}$ does not reach the value of 1 monotonically, but has minor oscillations as expected, since the frequency spectra do not have the exact correct shape.

Finally, we calculated the distribution of the light intensity. The Gaussian case is shown in Fig. 7. This distribution is not exactly exponential, but is reasonably close to it over three orders of frequency. The residual variation away from the ideal intensity distribution is mainly caused by the method of rectifying the noise signal. It should be noted that the intensities can be cut more heavily by changing the offset voltage, and then we can obtain a clearly non-Gaussian intensity distribution when $g^{(2)}(0) > 2$. If the intensities are not cut at all, the intensity distribution has the maximum not at the zero-level, but on some positive value and $g^{(2)}(0) < 2$. Thus, the light more resembles coherent light.

V. CONCLUSION

We describe a simple “solid-state” alternative for a pseudothermal light source. This construction has some benefits over the well-known mechanical version based on a rotating ground glass. First, with this source it is possible to generate both Gaussian and Lorentzian type of light. The coherence time of the source can be easily adjusted between 0.01 – 10 ms, or even more, just by changing the values of R and C in the analog filters. The light field from the LED is similar at all viewing angles. Thus it is not necessary to use a small aperture or optical fiber in collecting the light for coherence analysis, as it must be done with the rotating ground glass. The main drawback of this device is that the pseudothermal light field is not constructed optically but electronically, and the conceptually important physics of speckle pattern generation is missing. This limits the use of this approach when teaching the statistical properties of thermal light. On the other hand, this device can be used in simple experiments on intensity autocorrelation in order to demonstrate relevant mathematical properties of random signals.

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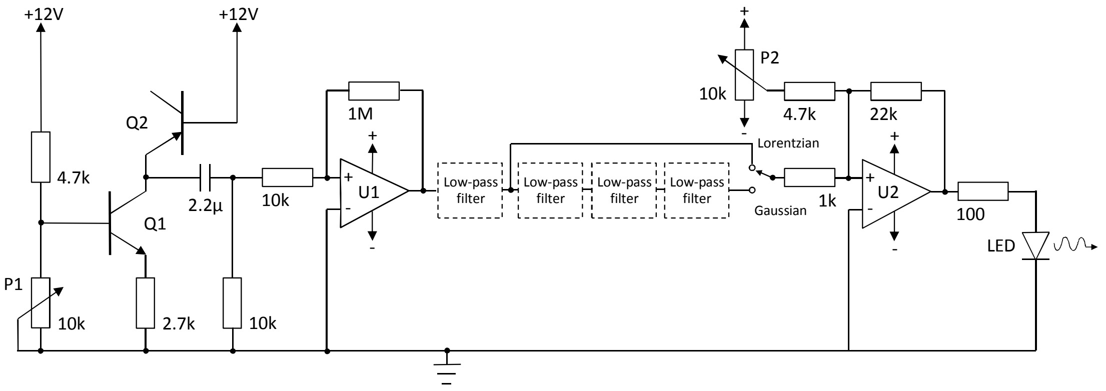

FIG. 1. The source of the pseudothermal light. The transistor Q1 acts as a current source for the reverse-biased emitter-base junction of the transistor Q2. The small noise signal is amplified with the operational amplifier U1 and low-pass filtered by one or four cascaded identical filter stages. The final signal is used to drive the light-emitting diode.

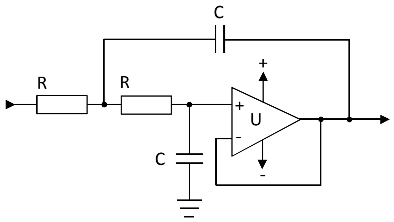

FIG. 2. A second-order low-pass filter based on the Sallen-Key architecture.

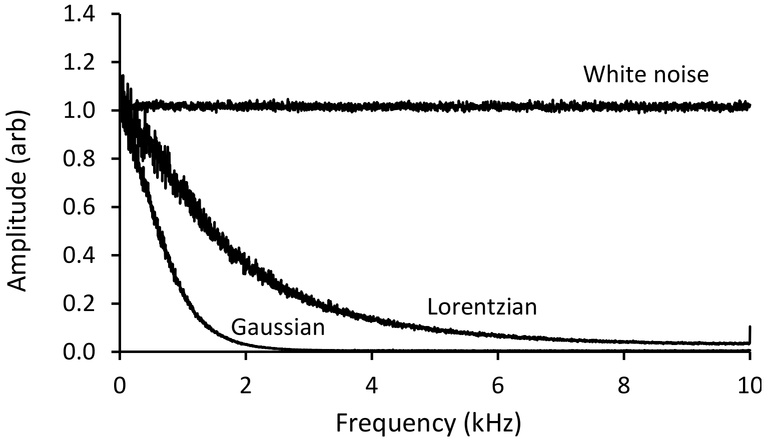

FIG. 3. The normalized amplitude spectrum of the noise source (White noise), and the frequency response of one (Lorentzian) or four cascaded (Gaussian) low-pass filters.

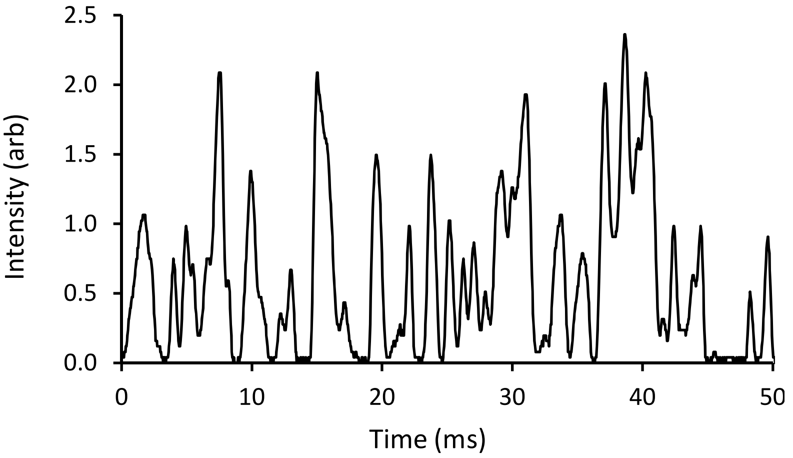

FIG. 4. Light intensity of the Gausssian type of source.

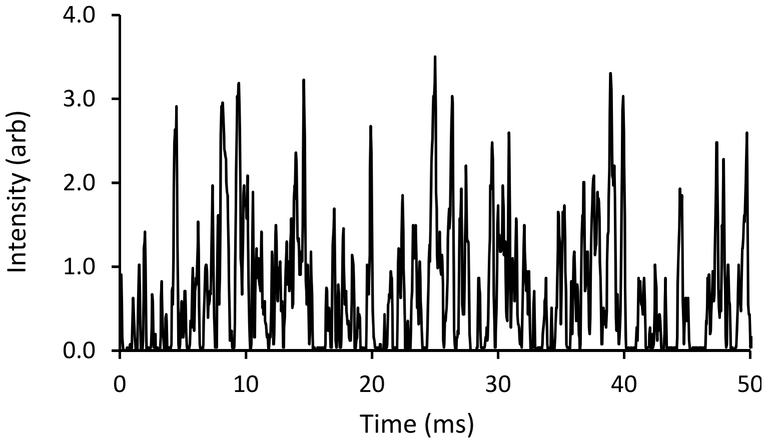

FIG. 5. Light intensity of the Lorentzian type of source.

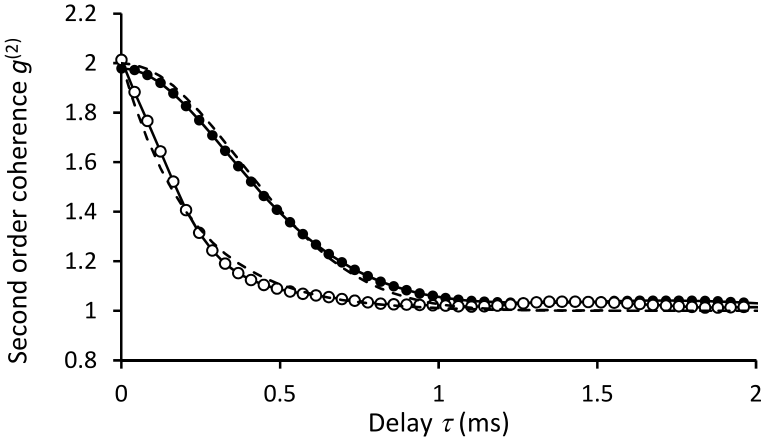

FIG. 6. Second-order coherence as a function of the delay time: Gaussian (solid dots) and Lorentzian light (open dots). Experimental data is fitted by the theoretical function given in Eq. (2) or Eq. (4) (dashed lines).

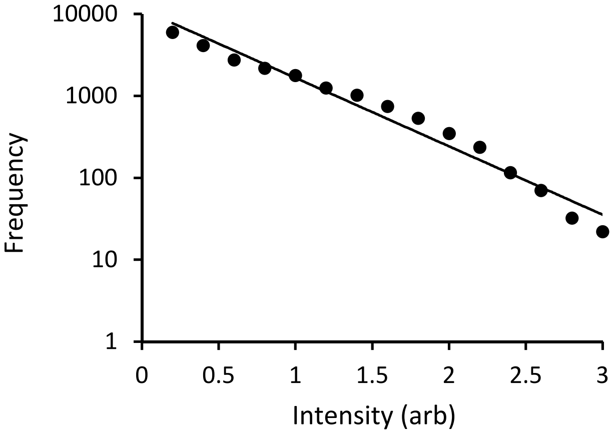

FIG. 7. Distribution of intensity for Gaussian light. The distribution fits quite well to a straight line on this semilog plot.