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A Triple Correlator of Radiation Intensities of a Multimode Semiconductor Laser

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Abstract: In this work, temporal correlations of radiation intensities of a multimode Fabry-Perot (FP) semiconductor laser are studied. Second- and third-order intensity correlation functions are measured both for the multimode FP laser and a pulsed Ti: Sapphire (TiSp) laser. Triple correlators of the latter demonstrate an ordinary product of double correlators (the classic case). The behavior of the multimode laser is more complex and can indicate the quantum nature of optical field correlations. We follow a specific phenomenological formula for calculation of the triple temporal correlator.

Keywords: intensity correlation functions; quantum correlations; triple correlators; multimode semiconductor laser

1. Introduction

Measurements of light field intensity correlations in two different spatial-temporal points are widely used in modern quantum optics. These correlations strongly depend on optical path difference so the effect of an intensity correlation is often termed the intensity interference effect. The first experiments on observations of such correlations for thermal sources of light were carried out by Hanbury Brown and Twiss (HBT) [1]. Connection of the light field state and measurement correlations of its intensities was established in [2–4]. From the outset it was clear that in addition to intensity correlations in two spatial-temporal points the correlations in three, four, or a growing number of such points can be considered. Theoretical formulas were derived for certain correlation functions of the third and higher orders. However, the higher the order of the measurement correlator, the more complex the experimental setup. For HBT correlators, the measurement signal is proportional to the square of average light intensity $\langle I\rangle^2$, while for the triple correlator, it is of the order $\langle I\rangle^3$. Most light sources are not bright enough, so measurements of high-order correlators require long integration times to obtain a reasonable signal. This in turn sets high requirements for long-term light stability as well as internal noises of light detectors. Lasers are the brightest light sources in laboratory settings. The light field state of a single-mode laser working well above the lasing threshold is sufficiently close to a coherent state, as studied by Roy J. Glauber [2]. In a coherent state, an intensity correlator of any order should be equal to 1. Therefore, the study of high order correlators does not provide fundamentally new information in this case. Experimental works have mainly dealt with the studying of laser intensity correlations near a lasing threshold. Correlations of the pseudo-thermal light sources produced by modulation of laser radiation have been otherwise studied. It has appeared that, besides checking on theoretical conceptions, measurements of high-order correlators may be of considerable interest for image transmission. In particular, third-order correlators are used for so called “ghost imaging”, or “correlation imaging” [5,6]. This is a technique that produces images by combining information from several light detectors. The question about the effect of the quantum nature of light on properties of observed correlators continues to attract interest as well [7]. Additionally, multimode laser radiation is still insufficiently studied. So far, relatively little research has been carried out to clarify the character of intermodal correlations. Such correlations may be both classical [8,9] and quantum phenomena [10]. In this context, it was ascertained in our previous studies that different longitudinal modes of a multimode Fabry-Perot (FP) semiconductor laser have unusual statistical properties [11,12]. Herewith, there is a strong correlation between photons detected from different longitudinal modes. The feature of quantum correlations is the effects of measurement on a quantum system. For a quantum object, a probability density of a certain measurement outcome at the present moment can depend on whether a previous measurement was performed just beforehand. In this regard, a comprehensive notion of triple correlators could provide the means for an experiment which tests the Leggett–Garg inequality [13]. This is a mathematical inequality fulfilled by all macrorealistic physical theories. We hope that this work will enable us to progress forward in the understanding of the nature of observed correlations in multimode lasers.

2. Experiments and Methods

In our experiments a standard continuous multimode semiconductor FP laser (model FPL-852+/−2 nm, Nolatech) was used. Laser units of this type are used for a wide range of research tasks (high-precision optical measurements, quantum informatics, nonlinear gain, optical feedback, and many others). The control unit Nolatech was used for laser pumping as well as temperature control so that the laser internal temperature was always kept at 26 °C. The output power of the laser in our experiments was about 30 mW. The spectrum of the laser is shown in Figure 1. It consists of a large number (approximately 35) of longitudinal modes grouped into broad peaks corresponding to different transverse modes. Every transverse mode contains up to 7 longitudinal ones with spacing of about 0.2 meV.

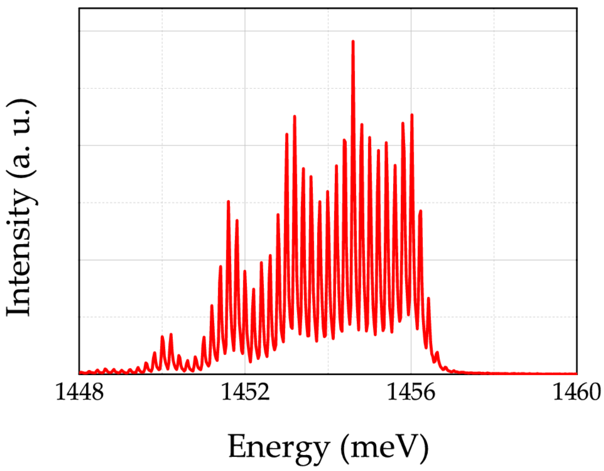

Figure 1. Optical spectrum of the multimode semiconductor Fabry-Perot (FP) laser.

Using a double monochromator one can select a desired spectral range with which to study the intensity correlation function either for a single longitudinal mode or for a chosen number of such modes [11,12]. We have revealed that the intensity correlation function $g^{(2)}$ obtained by an ordinary HBT scheme depends critically on the number of simultaneously selected modes. A detailed description of the measurement procedure and the experimental setup has been reported in [11]. It turned out that decreasing the number of simultaneously detected longitudinal modes leads to a monotonic increase of the visibility (see Figure 2). Thereby, the $g^{(2)}$ functions show oscillations between superbunching and antibunching regimes with a surprisingly high visibility and very long correlation times. The visibility of the second-order correlation function is

$$V = \frac{g^{(2)}_{max} - g^{(2)}_{min}}{g^{(2)}_{max} + g^{(2)}_{min}}, \quad (1)$$

where $g^{(2)}{}_{max}$ and $g^{(2)}{}_{min}$ denote the maximum and minimum of the second-order correlation function.

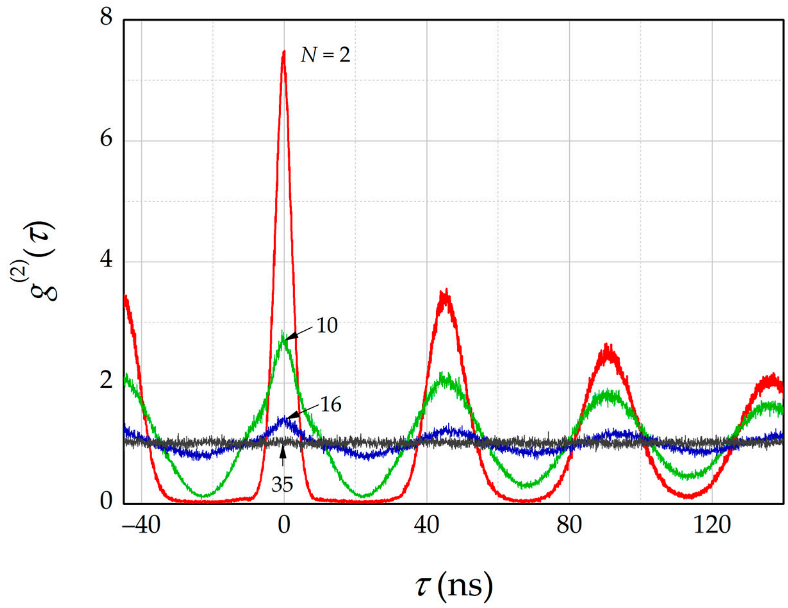

Figure 2. The intensity correlation functions $g^{(2)}$ obtained by an ordinary Hanbury Brown and Twiss (HBT) setup. N is the number of simultaneously detected longitudinal modes shown in Figure 1.

The result shown in Figure 2 for $N = 2$ denotes $V = 98\%$, i.e., there is a significant excess (65%) above a classical value of V (for classical light, V cannot exceed 33% [7]). It seems that a substantial share of quantum correlations occurs when the number of simultaneously detected longitudinal modes noticeably decreases.

Furthermore, we have focused on measurements of third-order intensity correlation functions in the hope that these measurements will provide more information about the nature of the correlations observed. We took note that these measurements exploit similar ideas to the Leggett-Garg temporal inequalities (the combination of three two-time correlations) [13]. To illustrate the effect of a measurement on the quantum state, we refer to an experimental setup for measuring the $g^{(3)}$ correlator which has been published previously [12]. It is shown in Figure 3.

Radiation of the multimode semiconductor laser was attenuated by a neutral filter and was focused into the fiber, after which it was directed onto the entrance slit of a double grating monochromator MDR-6U (1200 lines/mm) with additive dispersion. Entrance and intermediate slits of the monochromator were almost completely closed (width $L = 5$ mkm). This allowed for the extracting of a single longitudinal mode in the optical spectrum at the wavelength $\lambda = 852.2$ nm. The combined effect of the neutral filter and monochromator allowed for the attenuating of the laser radiation to a level acceptable for single photon avalanche diodes, i.e., no more than 2×10^5 counts per second. This combination provides the highest possible spectral-time resolution. The 400 mkm-fiber end face served as an exit slit. Furthermore, the signal was distributed between the three avalanche diodes (D1, D2, and D3) by means of two fiber splitters. Optical paths from the monochromator to each of the avalanche diodes were equalized to accuracy no worse than 50 cm. The discriminator DS1 of the first avalanche diode produced a standard NIM pulse (a fast negative logic signal −800 mV into 50-Ω impedance; pulse width: nominally 5 ns) simultaneously with a gate pulse (a running time of $\delta = 8$ ns) which was sent to the Gate input of a time-to-amplitude converter (TAC). The pulse from discriminator DS2 of the avalanche diode D2 was sent to the Start input of TAC, which was stopped by means of a pulse of the discriminator DS3 (the Stop input). The shortest time resolution of the system was about 300 ps. The characteristic integration time in one experiment was 1.6×10^4 s. The experimental setup registered an event if the three following conditions had been fulfilled: (1) the diode D1 response, (2) the arrival of the D2 pulse within the time window δ = 8 ns, and (3) the diode D3 response. The probability of this event is proportional to the normalized $g^{(3)}$ correlator:

$$g^{(3)} = \frac{\langle I(t_1)I(t_2)I(t_3)\rangle}{\langle I\rangle^3}. \tag{2}$$

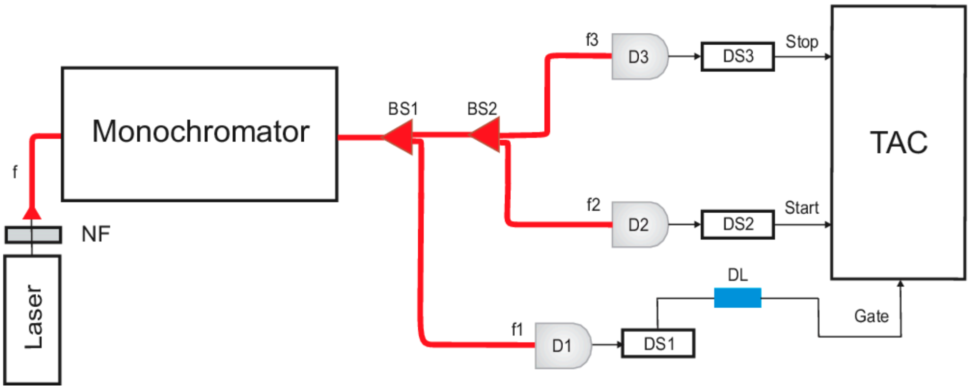

Figure 3. Schematic of the experimental setup. BS1 and BS2 are fiber-Y-splitters. f, f1, f2, and f3 are optical fibers. NF is a neutral density filter. D1, D2, and D3 are single photon detectors (silicon avalanche photodiodes). DS1, DS2, and DS3 are discriminators. DL is a delay line; TAC (ORTEC) is a time-to amplitude converter which measures the time interval between pulses to its Start and Stop inputs and generates an analog output pulse proportional to the measured time.

3. Results

We can see that the probability in Formula (2) is proportional to a product of intensities measured in three different moments in time. It should be noted that the difference between quantum efficiencies of the detectors and the nonideality of the splitting of light flux into three beams does not play an important role for a normalized correlator. The registering of photon counts is a stationary random process. This is evident in the experiments while repeatedly measuring the same correlators and mean intensities as well. Herewith, we can see that values of these variables do not vary with time. We know that the probability of a stationary random process may be dependent only on difference in time or from relative time delays. In our case these are variables Δ and τ, where the first represents the time delay of a gate pulse (the Gate input) relative to the pulse D1 and the second the time delay between the Start and Stop pulses. So, $g^{(3)} = g^{(3)}(\Delta, \tau)$. When Δ significantly exceeds the decaying time of the second-order correlator $g^{(2)}$, one can suggest that the *non-normalized* third-order correlator $G^{(3)}$ should be equal to a product of second-order correlators, i.e.,

$$G^{(3)}(\Delta, \tau) = G^{(2)}(\Delta)G^{(2)}(\tau)G^{(2)}(\tau + \Delta). \tag{3}$$

In order to verify Formula (3), we used a pulsed Ti: Sapphire (TiSp) laser "Millennia" (Spectra-Physics) which produced periodic pulses with the period T_{TiSp} = 125 ns and pulse width τ_{TiSp} = 2 ps (the spectral width 1.2 meV). The energy of the laser quantum was 1.459 eV. In this case, the intensity of light was a periodic function with the period T_{TiSp}. The function $G^{(2)}$ was also a periodic function, i.e.,

$$G^{(2)}\left(\tau + T_{TiSp}\right) = G^{(2)}(\tau). \tag{4}$$

Figure 4 shows that triple correlators are actually an ordinary product of $G^{(2)}$ correlators and the result is in good agreement with Formula (3).

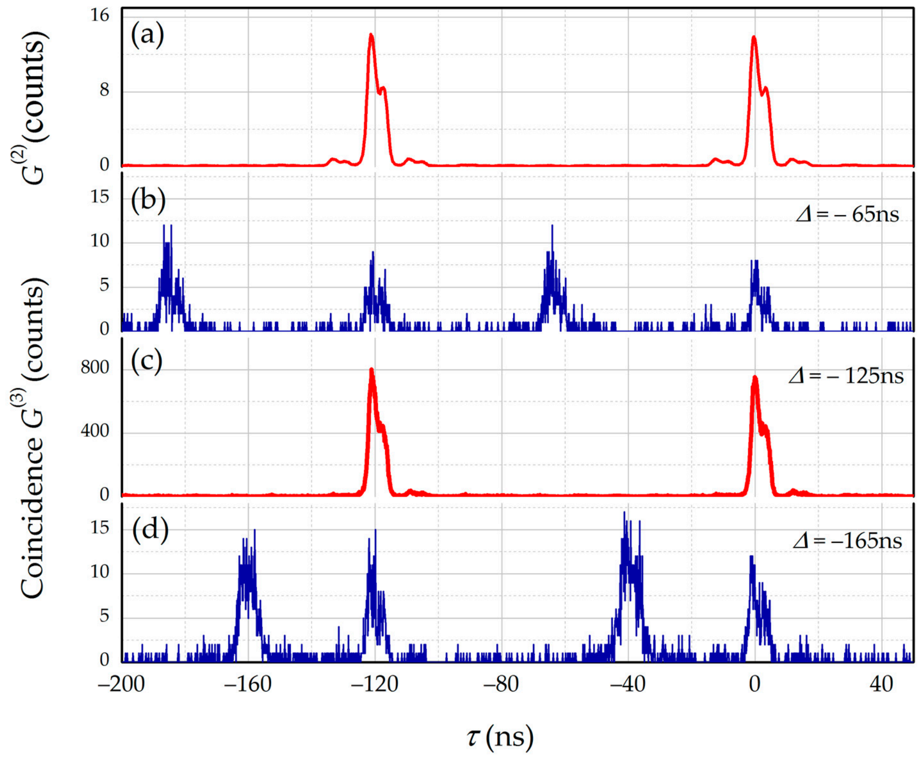

Figure 4. (**a**) The double correlator $G^{(2)}(\tau)$ as a function of delay τ and (**b–d**) the triple correlator $G^{(3)}(\tau)$ at different values of Δ. The double peak shape of the laser line was a result of an apparatus function.

In particular, for $\Delta = T_{\mathrm{TiSp}}$, Formula (3) shows that the function $G^{(3)}$ is simply $G^{(2)}(\tau)$-squared, i.e.,

$$G^{(3)}\left(T_{TiSp}, \tau\right) = G^{(2)}(0)\left[G^{(2)}(\tau)\right]^2, \tag{5}$$

and for τ = 0, the function $G^{(3)}(0, 0) = [G^{(2)}(0)]^3$. In the experiment, the triple correlator actually increases significantly ($G^{(3)} \sim 1000$) under these conditions and compares with $[G^{(2)}(0)]^3$ (see Figure 4c).

However, the experiments with a multimode laser showed that the behavior of the triple correlator is quite different. It has an oscillating character with high visibility as well as the double correlator, but has two main maxima (see Figure 5, [12]).

The fitting of these results by a product of double correlators (Formula (5)) is in bad agreement with experimental data [12]. Here, there is one aspect that we consider important to highlight. Quantum measurement theory implies that each measurement prepares a new state of the quantum system, i.e., it has an impact on the outcome of the subsequent measurement. At the same time, owing to the principle of causality, later measurements cannot affect the earlier outcomes. These circumstances mean that a simple product of double correlators is not working in that particular case and we need a specific empirical formula for calculating the triple correlator that was found (Formula (8) in [12]). The key component of the new formula is the Heaviside step function formula which characterizes the so called "quantum jump" (see the Discussion section). The results of calculations in accordance with such a formula which includes the Θ factor are in good agreement with the experimental data (see Figure 6).

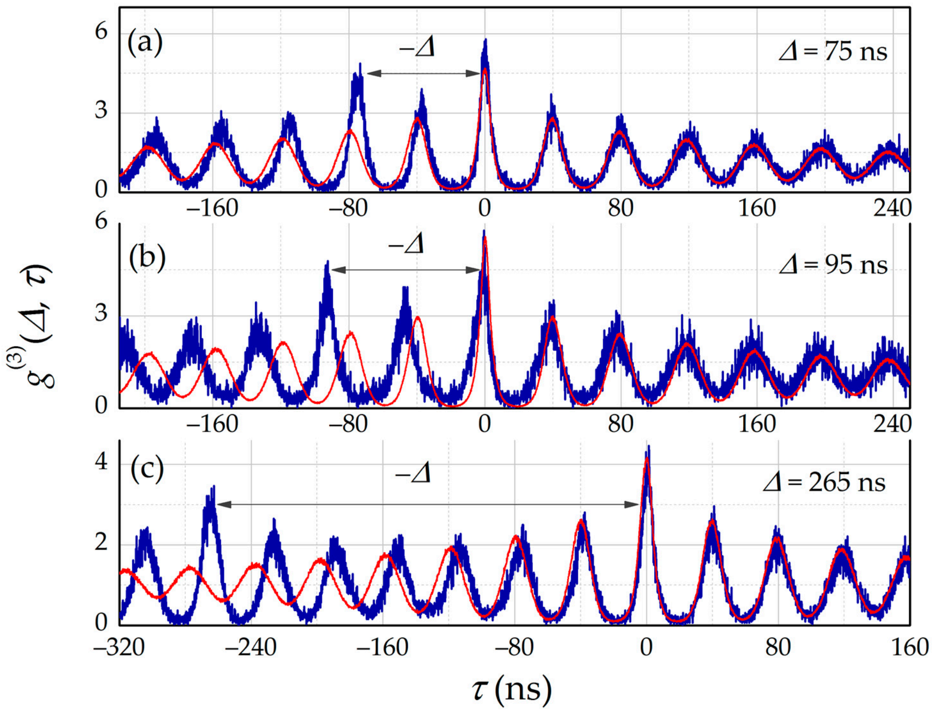

Figure 5. The normalized triple correlator $g^{(3)}$ as a function of delay τ (blue lines) at different time shifts of the gate pulse Δ and the $g^{(2)}(\tau)$ correlator (red lines). (**a**–**c**) correspond to three different values of Δ.

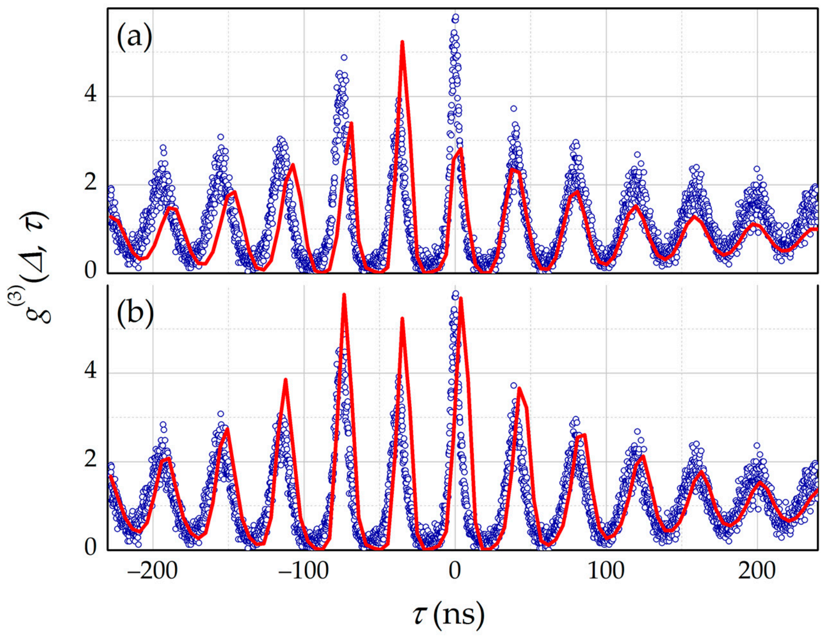

Figure 6. The approximation of a $g^{(3)}$ correlator using the specific phenomenological formula in [12]: (**a**) with no Θ-function and (**b**) including the Θ-function. The blue symbols are the experimental data and the red solid lines are the fittings. The experimental value Δ = 75 ns.

4. Discussion

The fittings presented in Figure 6 include the following points. In the scheme proposed by us, each measurement, i.e., photon registration, is followed by quantum state reduction. The delay between the detection of photons 1 and 2 is rigidly set by the experimental conditions. If photon 3 is detected within the time interval between the detection of photons 1 and 2, then it obviously destroys the free time evolution of an initial quantum state. At that, the triple correlator should be described by the product of correlators 1–3 and 3–2. If photon 3 is detected before photon 1 then it cannot correlate with photon 2, as all correlations are destroyed by quantum state reduction in connection with the detection of photon 1. Analogical reasoning is true for a case when photon 3 comes after photon 2. It therefore follows that there is a strong correlation between photons detected from different laser modes. We used an empirical formula, Formula (8) presented in [12], which includes the Heaviside step function Θ, for calculating the triple correlator of such a system. This function follows up the quantum state reduction which is called a "quantum jump". We have used this term in order to demonstrate that experimental curves are well described using the formula containing the stepwise component. In turn, the results mentioned above could probably be interpreted from the point of view of the theory of quantum jumps [14]. This could consider explicitly giving the quantum jump operator which would predict outcomes of that kind. In addition, the recently developed theory of past quantum states [15,16] provides new possibilities in the analysis of correlations in the system described, which would provide a rigorous theoretical framework for further experiments.

5. Conclusions

Given the above, the measurements of third-order $g^{(3)}$ intensity correlation functions (triple correlators) of a multimode semiconductor Fabry-Perot laser could provide additional and very useful information on states of the optical field in comparison with an ordinary Hanbury Brown and Twiss technique. Comparative measurements of triple correlators were carried out in this work for two cases: that using a multimode FP laser and a pulsed TiSp laser. These experiments have shown that the use of the latter results in a classical picture of correlations: the triple correlators are an ordinary product of double correlators. In the case of the multimode laser, the situation is more complex. There are a number of distinctive features of the $g^{(3)}$ functions, indicating that it is necessary to take into account the dependence of the measurements outcome from a quantum state. The $g^{(3)}$ functions oscillate between superbunching and antibunching regimes with a surprisingly high visibility and very long correlation times as well as $g^{(2)}$ functions. The visibility shows a significant excess above a classical value. It was revealed that $g^{(3)}$ functions are not described by a simple product of double correlators $g^{(2)}$ under such conditions. In that case, we follow a specific phenomenological formula, as given in [12], which includes the Heaviside step function Θ characterizing the quantum state reduction (a "quantum jump"). The results of calculations in accordance with such a formula are in good agreement with the experimental data. Quantum correlations of a multimode semiconductor laser reveal new ways to understand the mechanisms of an intermodal coupling and could provide new opportunities in quantum optics and applications. An intriguing fact is that all these effects were observed at room temperature.

Author Contributions: Conceptualization, M.L.; methodology, M.L.; software, A.D.; validation, M.L., O.M., and A.P.; formal analysis, A.D., A.P., and O.M.; investigation, M.L. and A.D.; resources, M.L.; data curation, M.L. and A.P.; writing—original draft preparation, M.L.; writing—review and editing, M.L. and A.P.; visualization, M.L., A.D., and A.P.; supervision, M.L.; project administration, M.L.; funding acquisition, M.L.

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References

1. Hanbury Brown, R.; Twiss, R. Interferometry of the intensity fluctuations in light. I. Basic theory: The correlation between photons in coherent beams of radiation. *Proc. R. Soc. A* **1957**, *242*, 300–324.
2. Glauber, R.J. Coherent and incoherent states of the radiation field. *Phys. Rev.* **1963**, *151*, 2766–2788. [CrossRef]
3. Mandel, L. Fluctuations of photon beams and their correlations. *Proc. R. Soc.* **1958**, *72*, 1037–1048. [CrossRef]
4. Mandel, L. Intensity fluctuations of partially polarized light. *Proc. R. Soc.* **1963**, *81*, 1104–1114. [CrossRef]
5. Cao, D.-Z.; Xiong, J.; Zhang, S.-H.; Lin, L.-F.; Gao, L.; Wang, K. Enhancing visibility and resolution in nth-order intensity correlation of thermal light. *Appl. Phys. Lett.* **2008**, *92*, 201102. [CrossRef]

6. Li, H.-G.; Zhang, Y.-T.; Cao, D.-Z.; Xiong, J.; Wang, K.-G. Third-order ghost interference with thermal light. *Chin. Phys.* **2008**, *B17*, 4510–4515.
7. Agafonov, I.N.; Iskhakov, T.S.; Penin, A.N.; Chekhova, M.V. Classical visibility limit for three-photon interference. *JETP Lett.* **2007**, *85*, 381–385. [CrossRef]
8. Koryukin, I.V.; Povyshev, V.A. Antiphase dynamics of a multimode quantum well semiconductor laser. *Laser Phys.* **2007**, *17*, 680–683. [CrossRef]
9. Ohtsubo, J. *Semiconductor Lasers: Stability, Instability and Chaos*, 3rd ed.; Springer-Verlag: Berlin, Germany, 2017; pp. 1–626.
10. Kim, Y.-S.; Slattery, O.; Kuo, P.S.; Tang, X. Two-photon interference with continuous-wave multi-mode coherent light. *Optics Express* **2014**, *22*, 3611–3620. [CrossRef] [PubMed]
11. Demenev, A.A.; Domaretskii, D.R.; Parakhonskii, A.L.; Lebedev, M.V. On the origin of nonclassical light generation upon resonant excitation of a GaAs semiconductor microcavity. *JETP Lett.* **2017**, *106*, 549–554. [CrossRef]
12. Lebedev, M.V.; Demenev, A.A.; Parakhonsky, A.L.; Misochko, O.V. Multimode semiconductor laser: Quantum versus classical behavior. *J. Russ. Laser Res.* **2019**, *40*, 64–70. [CrossRef]
13. Leggett, A.J.; Garg, A. Quantum mechanics versus macroscopic realism: Is the flux there when nobody looks? *Phys. Rev. Lett.* **1985**, *54*, 857–860. [CrossRef] [PubMed]
14. Wiseman, H.M.; Milburn, G.J. Interpretation of quantum jump and diffusion processes illustrated on the bloch sphere. *Phys. Rev. A* **1993**, *47*, 1652–1665. [CrossRef] [PubMed]
15. Gammelmark, S.; Julsgaard, B.; Mølmer, K. Past quantum states of a monitored system. *Phys. Rev. Lett.* **2013**, *111*, 160401. [CrossRef] [PubMed]
16. Xu, Q.; Greplova, E.; Julsgaard, B.; Mølmer, K. Correlation functions and conditioned quantum dynamics in photodetection theory. *Phys. Scr.* **2015**, *90*, 128004. [CrossRef]