Quantum Optics of and with Superluminescent Diodes: the Hanbury-Brown & Twiss Experiment in its 61th Anniversary

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ABSTRACT

The talk will start with a historical review appreciating and emphasizing the importance and relevance of the Hanbury-Brown & Twiss (HBT) experiment for nowadays quantum optics. Then, we investigate within a modern and sophisticated version of the HBT experiment the quantum optical properties of optoelectronic quantum dot based superluminescent diodes (SLDs). The demonstrated full incoherence of these Broad-Area SLDs will subsequently be exploited in a classical ghost imaging (GI) scheme, thus demonstrating the applicability of this most compact, ultra-miniaturized light source for GI. Finally, we shall discuss future perspectives and applications.

Keywords: quantum optics and applications, photon statistics, coherence, ghost imaging, semiconductor emitters, superluminescent diodes

1. INTRODUCTION: THE HANBURY-BROWN TWISS EXPERIMENT

The Hanbury-Brown Twiss (HBT) experiment has been conceived by Robert Hanbury Brown and Robert Quentin Twiss in various versions, beginning in 1954 with the radio-astronomical version [1] via the optical one applied to Sirius in 1956 [2]) leading finally to the terrestrial one [3]. The Hanbury-Brown & Twiss experiment has been originally motivated by the request for determining the angular diameter of stars with unprecedented stability by measuring intensity correlations instead of field correlations. We review this experiment with its tremendous outreach into nowadays quantum optics research, an experiment having been fundamental in the spirit of quantum optics at a time even before the 1st laser existed. Within the framework of the terrestrial version in 1956 [3] from nowadays 61 years ago, the discovery of photon bunching, the quantum nature of light emitted by a thermal source has founded modern quantum optics (see e.g. R. Glauber's Nobel lecture [4]), even when originally accompanied by a vivid and at the beginning converse discussion.

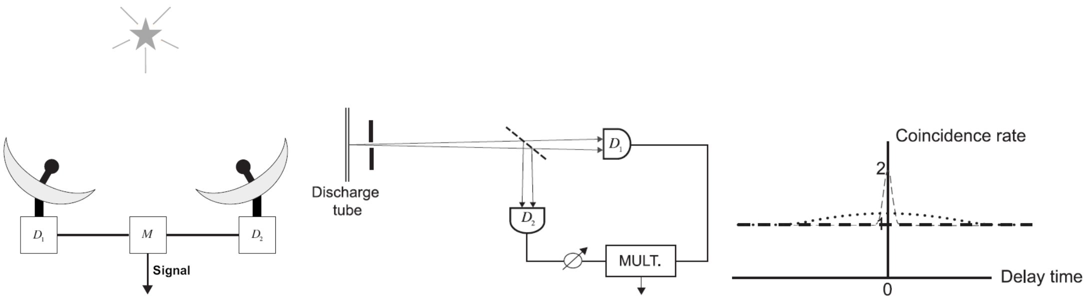

Figure 1. From left to the right: HBT experiment as stellar interferometer, terrestrial version for determining the photon bunching of a thermal Hg discharge lamp, which results are shown at the right with curve 2 for a thermal source and curve 1 for a laser [according to [4]].

HBT nowadays is used to characterize novel light sources as e.g. micro-pillar emitters or Photonic band gap emitters with respect to their laser or single photon finger prints, i.e. their classicality features.

Furthermore, HBT is actually in the realm of Ghost imaging [5], either in the classical version with bunched photons [6,7,8] or in the quantum version with entangled photons [9], a novel fascinating imaging modality based on photon correlations.

2. QUANTUM OPTICS OF SUPERLUMINESCENT DIODES

In the spirit of the HBT experiment, we shall devote comprehensive investigations to the quantum optical properties of a particular thermal source, an optoelectronic, semiconductor-based superluminescent diode emitting directional amplified spontaneous emission. Today, well-developed and highly sophisticated semiconductor laser technology provides compact amplified spontaneous emission (ASE) light sources realized with superluminescent diodes (SLD), which are semiconductor-based opto-electronic emitters generating broadband light. The technological development of these high-performance devices with wide-ranging material structure systems is boosting application areas such as telecommunications, medicine, and industry. When it comes to compact, miniaturized light sources with spectrally broad properties, SLDs are the first choice. The here investigated SLD (see Fig. 2 Left) is based on a quantum dot (QD) active medium consisting of

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15 inhomogeneously broadened InAs/InGaAs QD layers separated by GaAs buffer layers which form a total active layer of 0.620 µm thickness. The 6 mm long waveguide is overall tilted by 7° with respect to the facets which are both AR-coated. The tapered waveguide structure consists of a straight section of 500 µm length and 14 µm width followed by the tapered section of 5500 µm length and a resulting facet width of 110 µm. The processing has been made by photolithographic technique and proton implantation inducing a gain-guided waveguide structure in combination with slight index-guiding. Hence, strong amplification with high output powers as well as broad-area (BA) emission at the tapered output facet is implemented. The BA-SLD is operated at room temperature and the pump current is set to approximately 1.3 A, well above ASE threshold. An optical spectrum is shown in Fig. 2B revealing near-infrared emission at 1250 nm. The full-width-at-half-maximum (FWHM) amounts to 13nm which corresponds to 2.5 THz in terms of frequency.

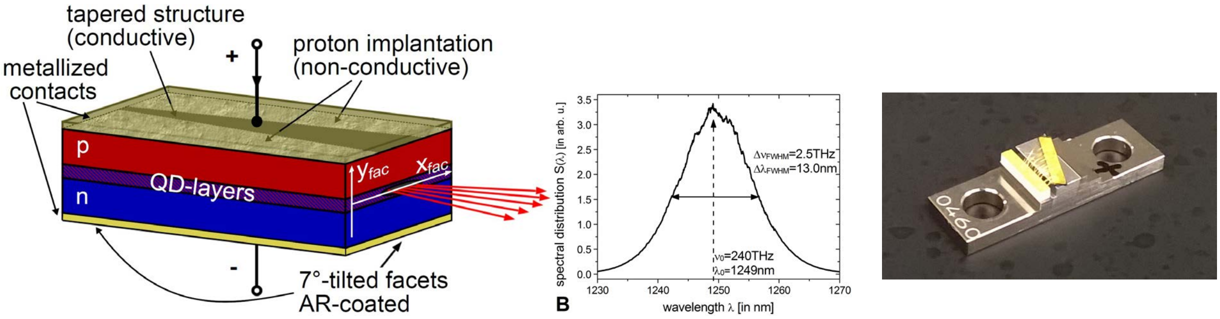

Figure 2: (Left) Schematic of the BA-SLD structure. Note that this drawing does not represent the actual proportions. The substrate (n-doped) of the device with about 200µm thickness is more than 100 times larger than the diode transition. The broad-area facet coordinates are denoted as x_{fac} and y_{fac} perpendicular and along the epitaxial growth direction, respectively. Middle (B): Optical spectrum measured with a commercial optical spectrum analyzer with indications of the spectral distribution center and the FWHM both in terms of frequency and wavelength and (Right) photograph of a mounted SLD.

We found in comprehensive investigations of the second order coherence properties (measured with a HBT like set-up as depicted in Fig. 3) of amplified spontaneous emission light generated by these semiconductor-based quantum dot SLDs that they exhibit perfect photon bunching with a normalized 2nd order correlation coefficient of two, thus with a Bose-Einstein photon statistics of a thermal source [10,11].

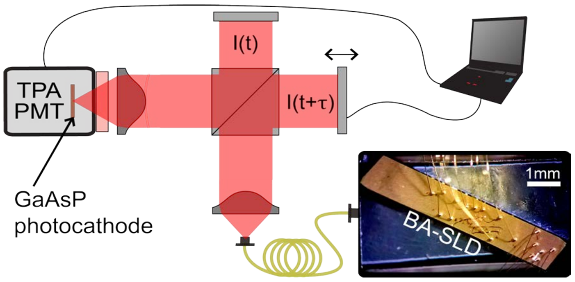

Figure 3. Interferometer-based TPA detection for measuring ultra-fast intensity auto-correlations: schematic setup. SMF, single-mode fiber; BS, 50:50 broadband beamsplitter; TPA-PMT, photomultiplier in TPA mode with a longpass filter in front; Inset: microscopic picture of the BA-SLD device from top.

3. GHOST IMAGING WITH SUPERLUMINESCENT DIODES

Ghost imaging (GI) is by far not a "spooky action" but rather a photon correlation imaging modality based on the fundamentals of quantum optics, either as entangled photons in the quantum GI version or with bunched photons from classical thermal sources. In contrast to conventional imaging systems, GI exploits intensity correlations of light to retrieve an image of an object. Ghost Imaging (GI) or photon-correlation imaging is one of the recent topics of quantum optics. GI exploits photon correlation for imaging [5]. After the first demonstration in 1995 with entangled photon [9] also classical GI [6,7,8] has been demonstrated with light emitted by rather complex, bulky thermal light sources. The name GI results from the fact that the image is formed by light which has never interacted with the object. Hereby, the total intensity of the transmitted or reflected light of an illuminated object and the spatially resolved intensity of a highly (position)-correlated reference beam which itself has never interacted with the object, are detected. The information of both intensities alone is not enough to form an image of the object. However, correlating the two intensities in terms of the intensity autocorrelation or second order correlation yields an image, the ghost image. Intriguingly, the spatial resolution of the ghost image is provided by the non-interacting reference beam. State-of-the-art classical GI light sources, as, e.g. pseudo-thermal light sources based on coherent laser light in combination with a speckle generating diffusive element or spectrally filtered incandescent lamps, however, are suffering strong losses of efficiency and directionality [12,13]. Here, in the framework of our performed comprehensive coherence analysis which shows clear evidence that the BA-SLD exhibits intrinsically all requirements as a classical GI light source, we propose a BA-SLD as a new light source for classical ghost imaging [14]. The implemented scheme in Fig. 4 represents such a GI configuration in which we exploit ultrafast two-photon absorption (TPA) detection in a TPA photomultiplier (PMT) [15] within a spatial HBT configuration.

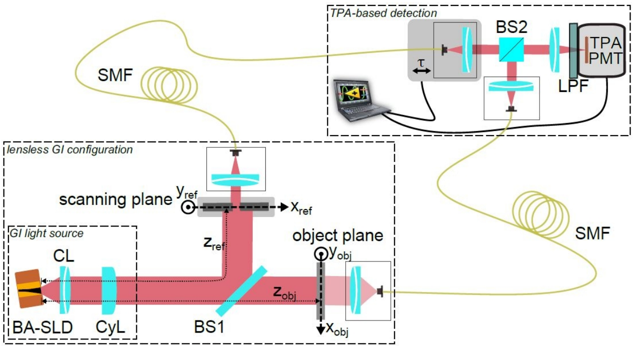

Figure 4. Schematic of the TPA based GI setup: free-space emitting BA-SLD as the GI light source, collimation lens (CL), cylindrical lens (CyL), two broadband 50:50 beam splitters (BS1, BS2), single-mode fibers (SMF), long pass filter (LPF) blocking fundamental absorptions (λ < 1000 nm, SCHOTT RG1000), and the photomultiplier in TPA mode (TPA-PMT).

In order to demonstrate a GI experiment with this novel source with an object of rather simple complexity, we place a double slit as the object (as depicted in Fig. 5B with its indicated dimensions) in the interferometer arm at the object plane.

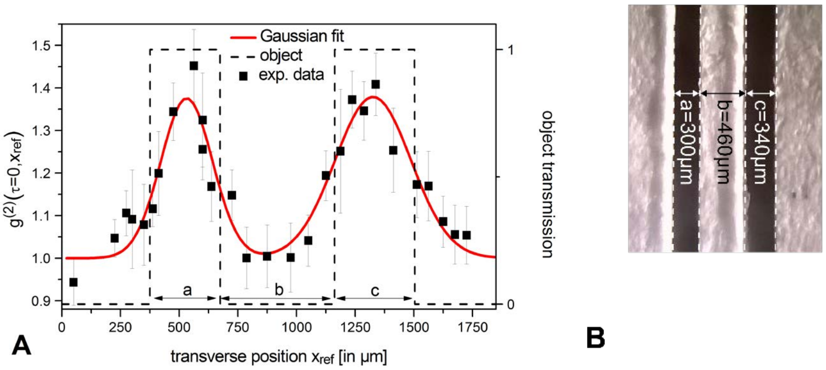

Figure 5: (A) Ghost image cross-section of a double-slit object. Experimental data (black squares) with error bars corresponding to the statistical variance of a set of three measurements, fitted double Gaussian function (red line) respecting the error bar weights and indications of the object dimensions (dashed line); (B) Digital camera record of the object through a microscope.

By scanning a single-slit aperture in the reference plane and performing the intensity correlation between the reference beam and the object beam with the TPA-PMT we obtain the normalized second order coherence degree $g^{(2)}(\tau = 0, x_{ref})$, i.e. the ghost image. Figure 5A depicts this ghost image in terms of the transverse position x_{ref}. As can be clearly seen from Fig. 5A, we are able to nicely reproduce the characteristic geometric object features. This demonstrates that we are able performing a GI experiment with our novel BA-SLD GI source, i.e. in reconstructing a double pinhole object with good visibility.

4. SUMMARY AND CONCLUSIONS

We have demonstrated the first GI experiment with intrinsically fully incoherent light by means of a BA-SLD. This semiconductor-based opto-electronic emitter unifies intrinsically all required coherence properties for GI which we analyzed in detail. We demonstrated that in the sense of their quantum optical properties, these semiconductor light emitters can be designed as being fully incoherent in their temporal and spatial coherence, i.e. incoherent in first correlation order, i.e. broad-band in their optical spectrum, fully incoherent in second correlation order, thus exhibiting ideal photon bunching like for thermal emitters, however with well-defined directional beam quality and finally spatially incoherent, the latter if we realize them technologically as broad-area (BA) SLDs, in analogy to dynamically filamenting broad-area lasers [16]. The here presented results have been enabled by bringing together carefully selected, mature semiconductor emitter technology and recent non-linear intensity correlation detection methods within a GI scheme. Thereby, a completely new type of light source has been introduced to the field holding interesting features in view of potential GI applications [17]. An interferometric two-photon detection technique was exploited in order to resolve the ultra-short correlation timescales. We thereby quantified the coherence time, the photon statistics as well as the number of spatial modes unveiling a complete incoherent light behavior. With a proof-of-principle demonstration, we introduce these compact emitters to the field of GI which could be beneficial for high-speed GI systems as well as for long range GI sensing in future applications [18]. Here, we demonstrated for the first time the exploitation of BA-SLDs, the world's most compact, ultra-miniaturized light source for GI, based on Amplified Spontaneous Emission (ASE) and discuss finally its ideas, functionalities and applications. This will allow enabling a broader dissemination of GI hence paving the way towards more applications which exploit the favourable advantages of GI.

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