# Characterization of the speckle pattern generated by nanolaser light with thermal and non-thermal statistics

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**Summary:** We study experimentally the speckle pattern generated by the light emitted by two coupled nanolasers. The setup allows, by slightly changing the position of the pump spot, to modify the coupling of the eigenmodes of the system, allowing in this way to generate light with thermal or with supra-thermal temporal statistics. We find that in both cases speckle patterns are consistent with Rayleigh statistics. The lack of non-Rayleigh statistics is interpreted as either due to the low intensity contrast of the speckle images, or as due to the time scale of temporal fluctuations, which render the speckle pattern almost uncoupled from the temporal intensity dynamics.

## 1 Introduction

While the granular structure of speckles is often a problem for the sensitivity of conventional, laser-based imaging techniques, speckle patterns can be, on the other hand, exploited for extracting information about the scattering medium (if the properties of the light source are known), or for extracting information of the properties of the light source (if the scattering medium is known). Here we take the second approach and use speckle as a tool for gaining insight into the statistical properties of nanolaser light. It has been recently shown that two evanescently coupled nanocavities, which have two coexisting modes (the B=bonding mode is a symmetric superposition of single cavity modes while the AB=anti-bonding mode is an anti-symmetric superposition), display a wide range of dynamical phenomena [1, 2]. This work is aimed at taking advantage of speckle images generated with a ground glass disk (GGD) for gaining insight into statistical spatial and temporal properties of the light emitted by the coupled nanolasers.

## 2. Experimental setup

The fabrication and characteristics of the nanolasers are described in Refs. [1, 2]. They consist of two evanescently coupled active photonic crystal L3 cavities (three holes missing) in a semiconductor free-standing membrane. The experimental setup is shown in Fig. 1. The nanolasers are mounted on a piezo stage so that they can be precisely positioned relatively to the pump beam (a 800 nm diode laser) which is focused by a X100 microscope objective. This objective is also used to collect the light and guided it to two identical low noise avalanche photodetectors (APDs) as well as to a spectrometer or to an infrared camera. Two single-mode fibers coupled to microscope objectives are used to spatially select two regions of the far field: the center corresponds to B mode intensity, and one of the lateral lobes to the AB mode. These optical signals are sent to the APDs for monitoring simultaneous in an oscilloscope the intensity fluctuations. The spectrometer allows checking the selected band before measurements (band selection by an angle-dependent spectral filter), as the modes are spectrally separated by just few nanometers. With the infrared camera, we can observe the near-field as well as in the far-field by inserting a lens in the beam path.

In order to generate a speckle pattern, a GGD and two confocal lenses (L1 and L2), in the beam path are used. The GGD scatters the light and imposes phase differences on the beam which lead to speckle. A third lens (L3) allows imaging the speckle pattern onto the camera sensor.

## 3. Results

The results of two measurements are displayed in Figs. 2 and 3. The differences in the temporal and spatial histograms are due to a slight change of the position of the pump spot in y-direction (realized using the piezo stage), which in turn changes the coupling of the modes of the coupled nanolasers. In Fig. 2 the temporal fluctuations have super-thermal statistics as the histogram of the intensity time series is long tailed. In contrast, in Fig. 3 the temporal fluctuations have thermal statistics as the histogram has a sharp cut off. The generated speckle pattern is, in both cases, consistent with Rayleigh statistics; however, we observe a change in the shape of the spatial histogram: when the temporal statistics is thermal, the histogram has a rather clear exponential shape over the whole range; in contrast, when the temporal statistics is non-thermal, the shape of the histogram is more irregular and the most probable intensity has a finite value.

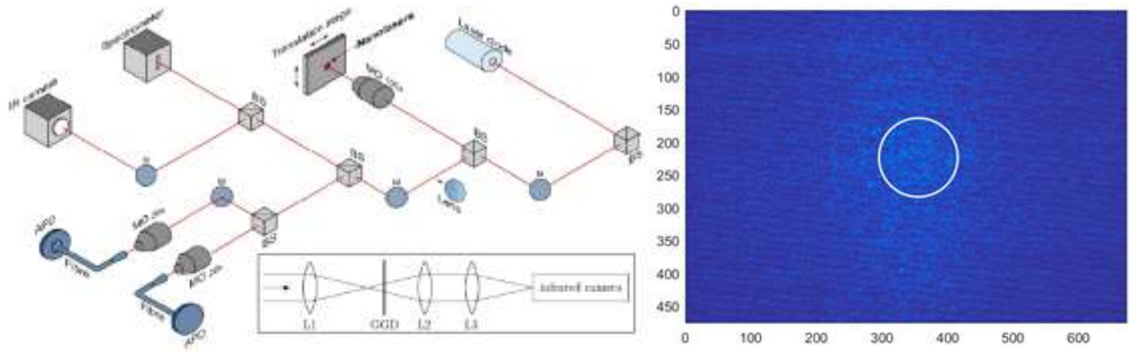


**Figure 1**: Experimental setup (adapted from Ref. [2], supplementary information) and typical speckle image. The circle indicates the region used to calculate the histogram.

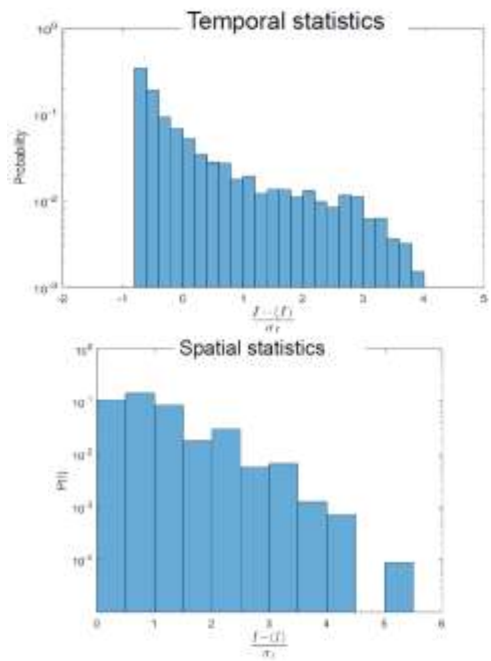


**Figure 2**: Histogram of the intensity time series (top) and of the intensity values inside the circle in the speckle pattern shown in Fig. 1 (bottom). In both cases the data is normalized to zero-mean and unit variance.

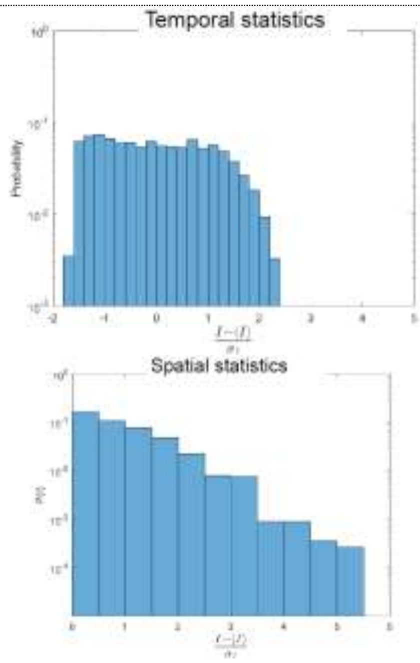


**Figure 3**: As Fig. 2, but changing slightly the experimental conditions such that the light has temporal thermal fluctuations.

## 4. Discussion and Conclusion

The lack of non-Rayleigh statistics can either be due to the fact that the speckle images have very low intensity values (high signal to noise ratio) and thus, the wide bins that need to be used to compute the spatial histograms, provide very low resolution. Alternatively, the observed Rayleigh statistics can be due to the fact that temporal fluctuations are too fast and render the speckle pattern almost effectively uncoupled from the temporal intensity dynamics. Future work is aimed at clarifying this point.

To summarize, we have analyzed experimentally the statistical properties of speckle patterns generated by the light emitted by two coupled nanolasers, using a setup that allows modifying the coupling between two eigenmodes of the coupled system, which in turn results in the emitted light having different temporal statistics. We found that both, thermal and non-thermal light generated speckle patterns which, while showing some differences between them, were both consistent with normal Rayleigh statistics.

## 5. References


[1] P. Hamel, et. al, "*Spontaneous mirror-symmetry breaking in coupled photonic-crystal nanolasers*", Nat Photon. 9, 311–315 (2015).

[2] M. Marconi et. al, "*Asymmetric mode scattering in strongly coupled photonic crystal nanolasers*", Opt. Lett. 41, 5628–5631 (2016).