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Optimum phase measurement in the presence of noise

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Single frequency lasers are an indispensable tool in many areas of scientific and engineering disciplines. The laser phase noise properties directly affect the precision and accuracy of several critical measurement techniques such as high-sensitivity laser-based spectroscopy and interferometry. The magnitude of laser phase noise is also a key limiting factor in applications based on transmitting laser light over an optical fiber, such as high-capacity coherent telecommunication, quantum cryptography and distribution of reference atomic clock signals. Accurate measurement of laser phase noise is therefore a topic of great fundamental and practical importance.

Even though the scientific field of laser phase noise measurement is more than 50 years old, the state-of-the-art measurement techniques still exhibit strong limitations in terms of the measurement sensitivity and the frequency range. The implication of these limitations are that it is not possible to: (i) accurately measure the fundamental laser linewidth (Schawlow-Townes limit), (ii) measure theimpact of optical amplifier noise on signal phase - an open problem since 1962, (iii) accurately measure phase noise of ultra-narrow linewidth lasers and (iv) provide a phase noise measurement of the emerging low-power nano-lasers. Advancing phase noise measurement techniques is thus important for providing answers to some of the fundamental questions which could potentially lead to improved laser phase noise performance.

In this talk, a fundamentally novel approach for phase noise measurement is proposed, by combining a heterodyne phase measurement with advanced digital signal processing methods aided by physical models. We thereby propose a practical phase noise measurement technique with an ultimate
accuracy that surpasses the limitations of the current techniques by the several orders of magnitude. The proposed technique provides the theoretically most accurate (optimum) measurement of a laser signal phase and approaches the quantum limit. Compared to the state-of- the-art techniques, the proposed measurement technique is not limited by the measurement noise, but rather by the fundamental quantum noise associated with the laser. We show that, in contrast to common beliefs, it is possible to measure the phase noise well bellow the conventional measurement noise floor, greatly enhancing the measurement frequency range and the sensitivity. A record measurement
frequency range and the sensitivity is achieved. This allows us to finally provide an answer to a longstanding question on the impact of amplifier noise on the signal phase. The method thus holds the potential to become a reference phase noise measurement tool.

It will also shown how the proposed approach can be extended to phase noise characterization of optical frequency combs. Finally, we introduce a novel method for noise characterization of frequency combs based on Bayesian filtering and subspace tracking. The method allows for identification and decomposition of noise sources associated with the frequency comb.

The talk will be based on the following references:

1. Darko Zibar, Jens E. Pedersen, Poul Varming, Giovanni Brajato, and Francesco Da Ros, "Approaching optimum phase measurement in the presence of amplifier noise," Optica 8, 1262-1267 (2021)
2. Giovanni Brajato, Lars Lundberg, Victor Torres-Company, Magnus Karlsson, and Darko Zibar, "Bayesian filtering framework for noise characterization of frequency combs," Opt. Express 28, 13949-13964 (2020)
3. D. Zibar et al., "Highly-Sensitive Phase and Frequency Noise Measurement Technique Using Bayesian Filtering," in IEEE Photonics Technology Letters, vol. 31, no. 23, pp. 1866-1869, 1 Dec.1, 2019, doi: 10.1109/LPT.2019.2945051.

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