Fundamental Detection Limit of Integrated Photonic Sensors

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Abstract: The quest for improving the sensitivity of optical sensors goes hand in hand with confining light in smaller volumes to increase light-matter interaction. I will show that this quest has reached a fundamental detection limit.

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1. Introduction

Photonic sensors are taking an increasingly important place in the society. There are used in applications as diverse as diseases screening, food quality analysis, and environment sensing. One of the challenge is to make them always more smaller and lighter without jeopardizing their detection limit. It is particularly important if they are implemented in drones, mobile phones or satellites. In this context, silicon photonics is a key technology that enables to tackle miniaturization issues.

Decreasing the size of photonic structures contributes to enhance light-matter interactions and consequently the sensitivity of the sensor. However, it does not mean that the detection limit is concomitantly improved. The reason is that, at micron scale and at room temperature, thermodynamic fluctuations start to play a significant role in a solid in thermal equilibrium.

We have recently investigated the impact of the fundamental thermodynamic fluctuations on the optical properties of integrated silicon nitride waveguides [1] and silicon photonic crystal cavities [2].

2. Thermo-refractive noise in integrated photonic waveguides

By investigating the optical spectrum of laser light having propagating in optical waveguides as shown in Fig. 1, we have unveiled and elucidated the presence of a fundamental noise contribution in the high-frequency part of the spectrum. I will discuss a theoretical model that reproduces the exponential shape of this noise contribution that is several orders of magnitude larger than what earlier models predict.

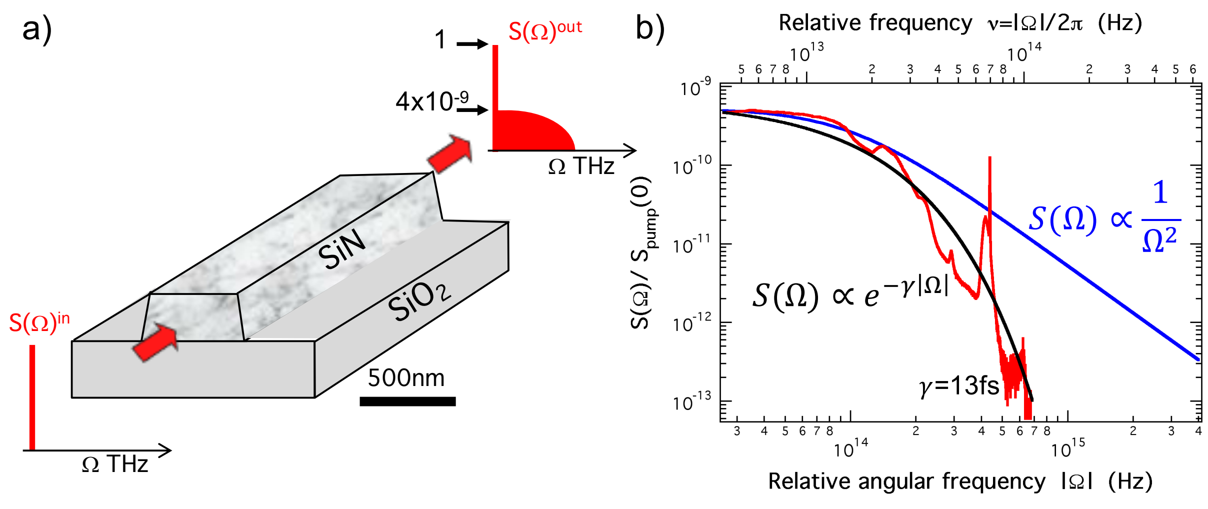

Fig.1. a) Schematic representation of the modification of the optical spectrum of a laser beam that propagates in a silicon nitride waveguide. b) Optical spectrum normalized according to optical spectrum of the input laser (pump); Red: Experimental spectrum, blue: Standard model, black: Current model with extended correlations.

This discovery is of paramount importance for our understanding of noise in light-matter interaction, and also for setting the intrinsic detection limit of advanced optical sensors, in particular for silicon nitride waveguide-based Raman sensors.

3. Thermodynamic limit in photonic crystal cavity sensors

By analysing the light scattered from integrated silicon photonic crystal cavities (PhC) at different acquisition speeds as shown in Fig. 2, we have identified the fundamental detection limit of such optical cavities. I will show that the fundamental thermal fluctuations set an intrinsic detection limit. This intrinsic limit can be translated in term of cavity frequency shift and corresponds to 1/2000th the linewidth of the optical spectrum for cavities of effective mode volume as small as $0.06\mu m^3$. Taking into account this intrinsic limit, our results indicate that photonic crystal cavities could enable fast real-time chemical and biological sensing, as well as find applications in medical diagnostics and hazardous aerosol investigations.

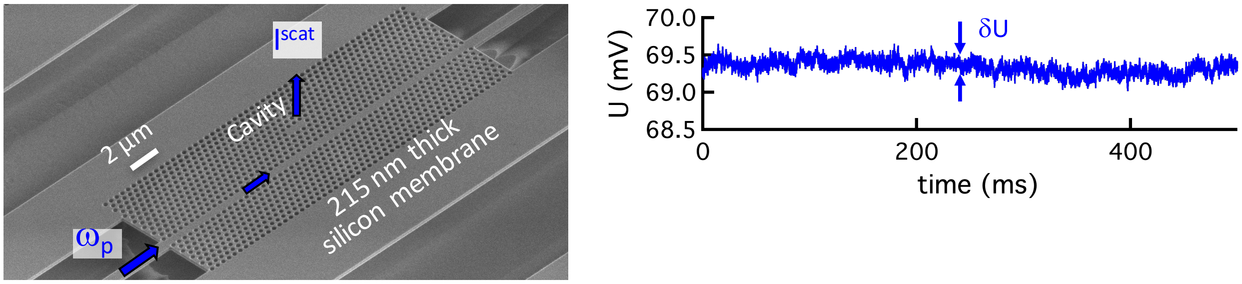

Fig.2. Left: Scanning electron micrograph of the top surface of an integrated L3 PhC cavity. The blue arroaws indicate the light path of the pump laser beam at a frequency ω_p. Right: Time trace of the photovoltage U induced by the collected scattered light I^{scat} for a detuning between the ω_p and the resonance frequency of the cavity, which highlights the presence of a phase noise due to the fundamental thermodynamic fluctuations.

[1] N. Le Thomas, A. Dhakal, A. Raza, F. Peyskens, R. Baets, "Impact of fundamental thermodynamic fluctuations on light propagating in photonic waveguides made of amorphous materials", Optica 5, 328-326 (2018).

[2] K. Saurav, N. Le Thomas, "Probing the fundamental detection limit of photonic crystal cavities", Optica 4, 757-763 (2017).