

Bio-inspired superconducting sensors for sub-THz technologies

Objective: The overall objective is to develop an ultrasensitive, on-chip sub-THz spectrometer that mimics the cochlea's remarkable ability to decompose complex audio signals. This will be achieved by combining *graded metamaterial designs* with the nonlinear dynamics of *superconductors*.

The human cochlea is an extraordinarily sensitive sensor that decomposes sound into spatially separated frequencies across three decades with a dynamic range exceeding 120 dB. At its core, the human ear is based on a collection of sub-wavelength non-linear resonators. In the sub-THz frequency range, the losses become too high to realize efficient detectors, but superconductors exhibit minimal ohmic dissipation and a kinetic inductance that varies quadratically with current $L_K(I) = L_K^0 + \Delta L \frac{I^2}{I_0^2}$ where I_0 is a critical current and L_K^0 is the linear inductance [1, 2]. For example, Fig. 1 **a** shows the dependance in temperature of a CPW resonator frequency due to this kinetic inductance L_K^0 .

The goal of this PhD project is to use this intrinsic non-linearity to mimic the non-linear amplification occurring in the cochlea, providing tunability and enhanced spectral selectivity. At first, the candidate will characterize the response of a few sub-wavelength superconducting resonators at 100 GHz. The measurement of the self-Kerr non-linearity will give access to the quadratic dependance on the current I inside the superconducting resonator (see Fig. 1 **b**). This will give the opportunity to study non-reciprocal behavior in non-linear systems which may have crucial applications in the field of quantum technologies.

The PhD student will then create a rainbow trap experiment in the sub-THz as depicted on Fig. 1 **c**. This structure introduces a radically new approach to sub-THz spectroscopy, inspired by the acoustic behavior of the human cochlea. Unlike conventional TDS systems relying on bulky optics and time-gating, it aims for a single-shot, fully integrated superconducting on-chip spectrometer that directly maps frequencies in space. Its originality stems from three main elements: bio-inspired active graded designs, superconducting metamaterials with minimal dissipation and intrinsic kinetic-inductance nonlinearities, and operation in the underexplored sub-THz regime, promising for molecular and quantum sensing. By exploiting the synergy between biological efficiency with quantum-graded materials, we aim to establish a new class of compact, high-performance spectroscopic sensors.

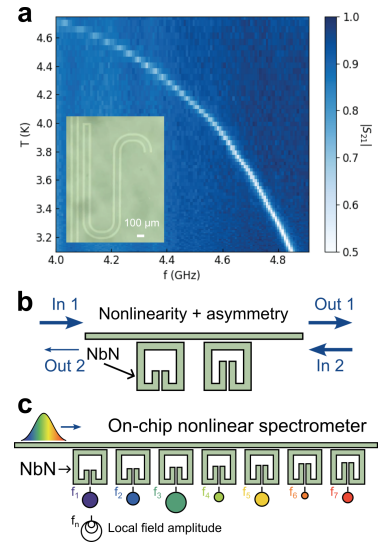


Figure 1: **a**, NbN resonator measured below its critical temperature **b**, Nonreciprocal transmission within a planar superconducting metamaterial based on the nonlinear inductance of NbN. **c**, Rainbow trap geometry

- [1] B. Ho Eom, P. K. Day, H. G. LeDuc, and J. Zmuidzinas, "A wideband, low-noise superconducting amplifier with high dynamic range," *Nature Physics*, vol. 8, no. 8, pp. 623–627, 2012.
- [2] J. Luomahaara, V. Vesterinen, L. Grönberg, and J. Hassel, "Kinetic inductance magnetometer," *Nature Communications*, vol. 5, no. 1, p. 4872, 2014.