An on-chip FTS for millimeter and sub-millimeter applications

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Abstract

Fourier Transform Spectroscopy (FTS) is a versatile technique widely used in astronomy, molecular spectroscopy, and materials science, enabling broadband, multi-resolution spectral measurements through interferometric acquisition and Fourier analysis. Conventional FTS instruments, however, are often bulky and mechanically complex, limiting their operation in cryogenic or spaceborne environments and their scalability for next-generation experiments. Recent advances in on-chip technologies offer a promising alternative, enabling compact, robust, and scalable architectures well suited for space missions and large detector arrays.

We present the development of an on-chip FTS operating in the W-band (75–110 GHz) as a test platform, integrated with a Kinetic Inductance Detector (KID). We discuss the design optimization, electromagnetic simulations, material characterization, and the current status of prototype fabrication and cryogenic testing. This work demonstrates the potential of compact and scalable on-chip FTS systems for **atmospheric monitoring**, remote sensing, and astrophysical and cosmological applications, including Cosmic Microwave Background (**CMB**) and Line-Intensity Mapping (**LIM**) studies.

Design and optimization

We are developing a W-band (75–110 GHz) device, fabricated on a silicon (Si) substrate with niobium (Nb) microstrip lines and coupled to a titanium-aluminum (Ti-Al) coplanar waveguide Kinetic Inductance Detector (KID). This design can be scaled to higher frequency bands (120–170 GHz and 190–240 GHz). The device integrates a twin-slot antenna, an interferometric FTS module (splitter, phase shifter, and combiner), and a superconducting detection stage.

Antenna

A planar **twin-slot antenna** [1] couples incoming radiation into the device, converting free-space electromagnetic waves into a guided mode on the transmission line. The antenna acts as an interface between the propagating plane wave and the FTS, enabling efficient signal collection. While this design shows a limited bandwidth, ongoing optimization aims to extend its coverage to higher frequencies.

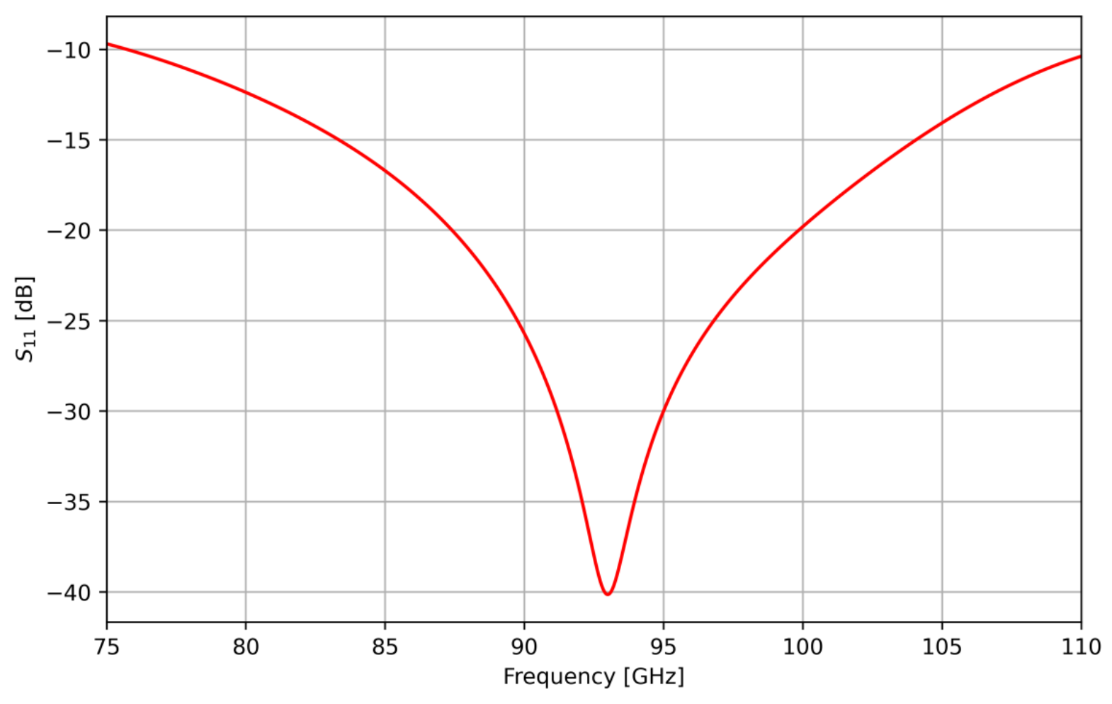

Fig. 2 Input reflection coefficient (S_{11}) over the W-band of the twin-slot antenna, designed and optimized at 90 GHz.

Phase shifter

The phase shifter plays the role of the moving mirror in a classical FTS and **determines the spectral resolving power**: larger phase-shift dynamics correspond to higher spectral resolution. We investigated phase tuning based on either **resistance or kinetic inductance modulation** on the transmission line. Both approaches are viable and are currently undergoing prototyping and experimental validation to determine the most suitable solution in terms of performance and feasibility. These technologies enable resolutions up to $R = \nu/\Delta\nu \simeq 1000$ [2].

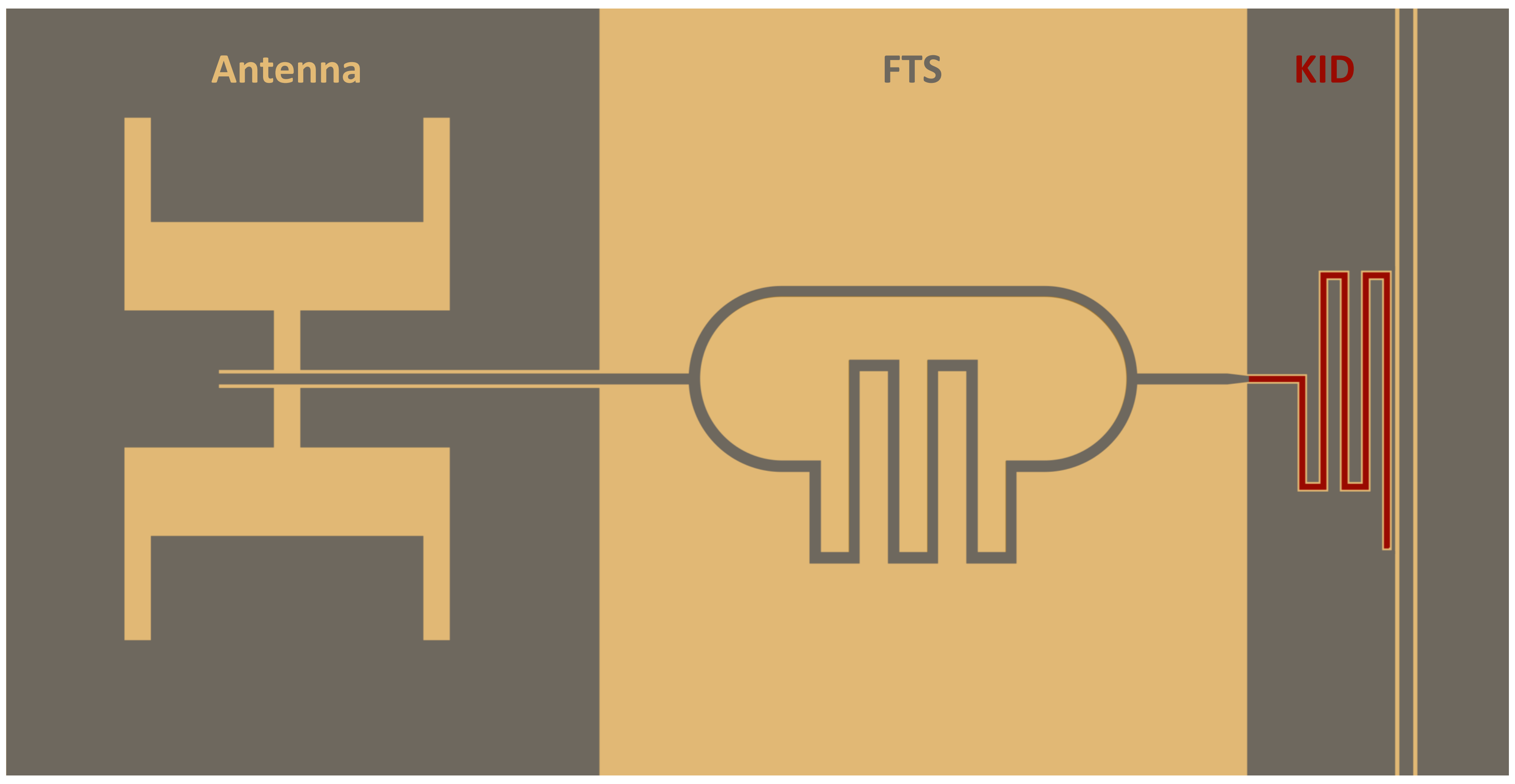

Fig. 1 Schematic view of the on-chip FTS setup (not to scale). The beige silicon substrate hosts niobium components shown in gray, while the red strip corresponds to the titanium-aluminum element.

Splitter and combiner

Signal splitting and recombination are implemented using $\lambda/4$ **Wilkinson power dividers** [3], which act as the beamsplitter in a classical interferometer. The network provides equal (3 dB) power division between the two FTS arms, with a resistive element ensuring output isolation and impedance matching. The device remains lossless under matched conditions, with dissipation occurring only for reflected power.

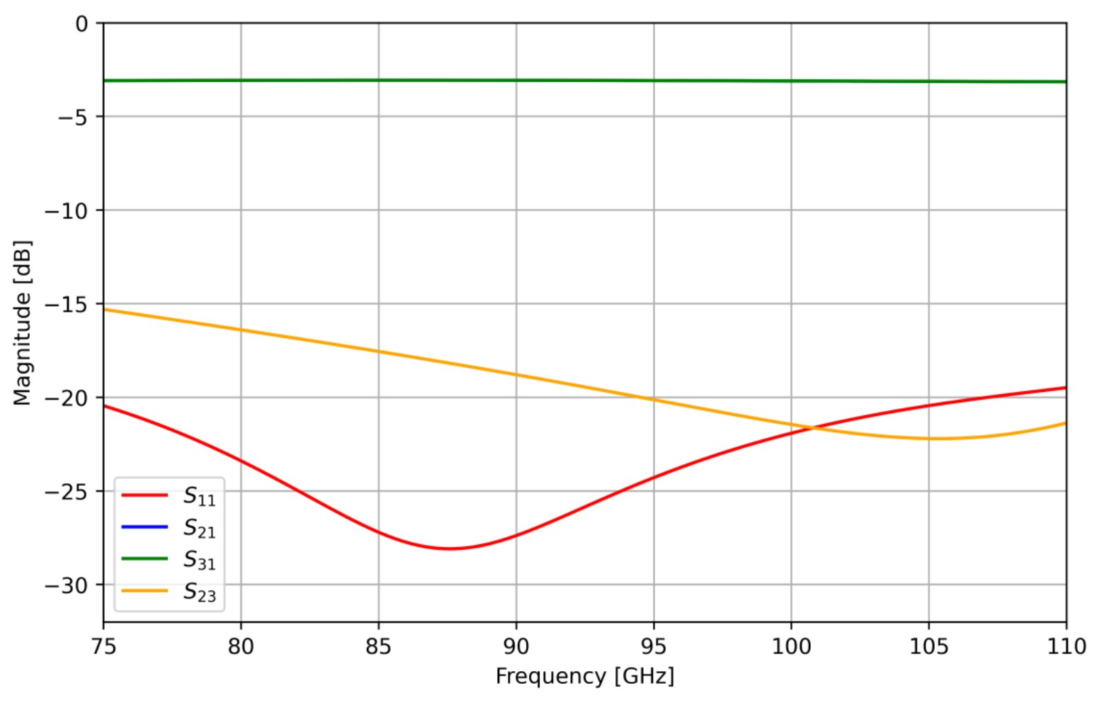

Fig. 3 *S*-parameters for the Wilkinson power divider. Note that the green and blue curves are superimposed (equal division).

Kinetic Inductance Detector and its working principle

KIDs are fast, low-temperature superconducting microwave resonators that detect incoming radiation through changes in the kinetic inductance of a superconducting film. When photons with $h\nu > 2\Delta(0) \simeq 3.5\, k_B T_c$ (Cooper pair binding energy) are absorbed, they can break Cooper pairs, modifying the quasiparticle density and thus the kinetic inductance.

The superconducting film serves as the inductive element of a high-quality factor **RLC resonator** fabricated on a dielectric substrate. Variations in the kinetic inductance produce shifts in the resonance frequency and quality factor, measured through changes in the amplitude and phase of the transmitted bias signal in the feedline [4].

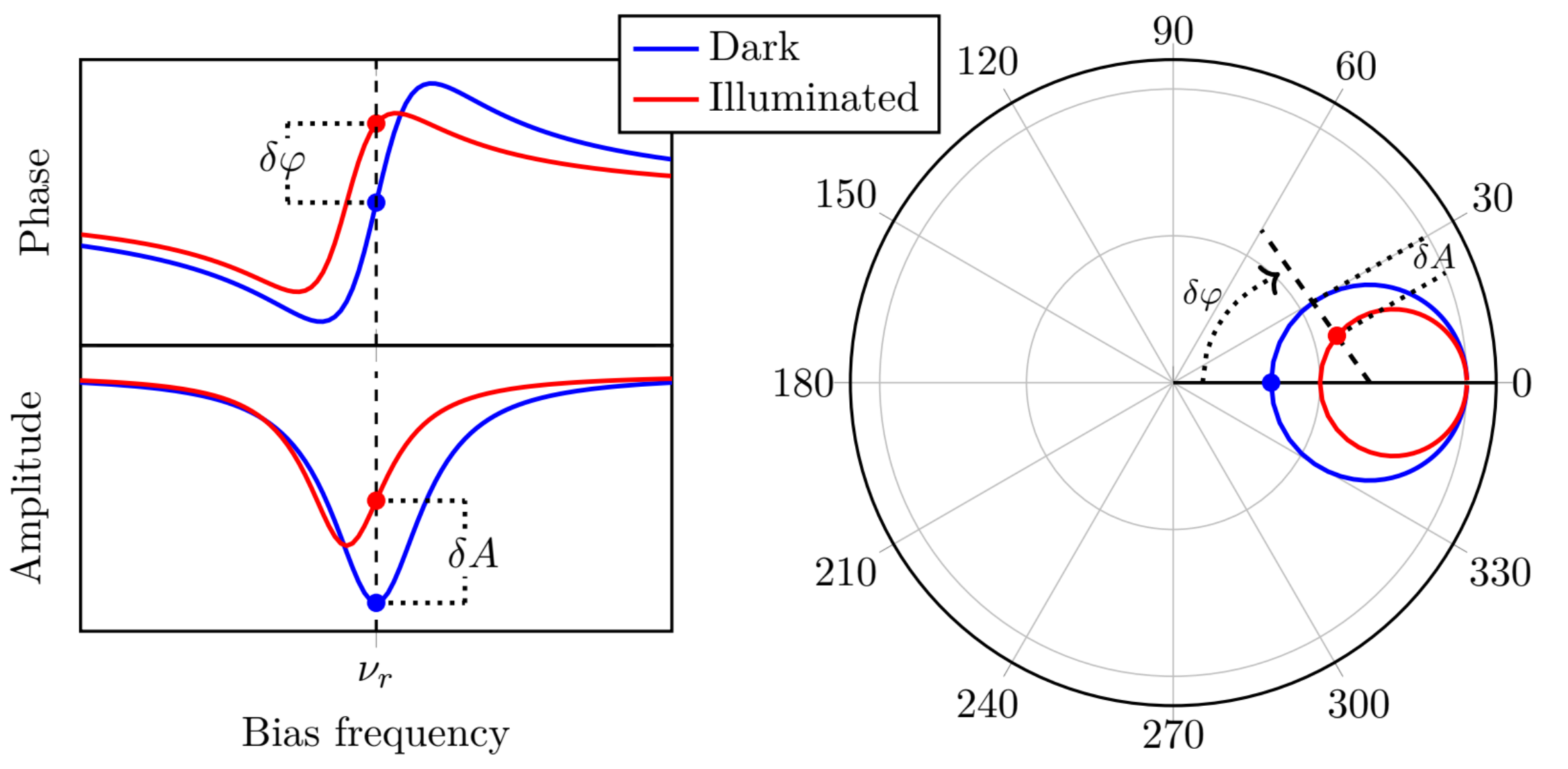

Fig. 4 Qualitative S_{21} response of a KID: photon absorption increases the kinetic inductance, shifting the resonance frequency and modifying the amplitude and phase response (*left panel*), with a corresponding change in the resonance circle in the complex plane (*right panel*) [5].

Materials

The active KID strip is made of Ti-Al, where Cooper-pair breaking occurs. To ensure fully superconducting signal propagation and enable a large-dynamic-range inductance-based phase shifter, a different material with a $T_c \gtrsim 2$ K is used for the FTS and all ground planes.

We characterized a Nb film on a Si substrate, measuring a critical temperature $T_c = 6.67$ K and a sheet resistance $R^*_\square = 0.203\ \Omega/\square$. The value of the sheet kinetic inductance obtained from this measurement is:

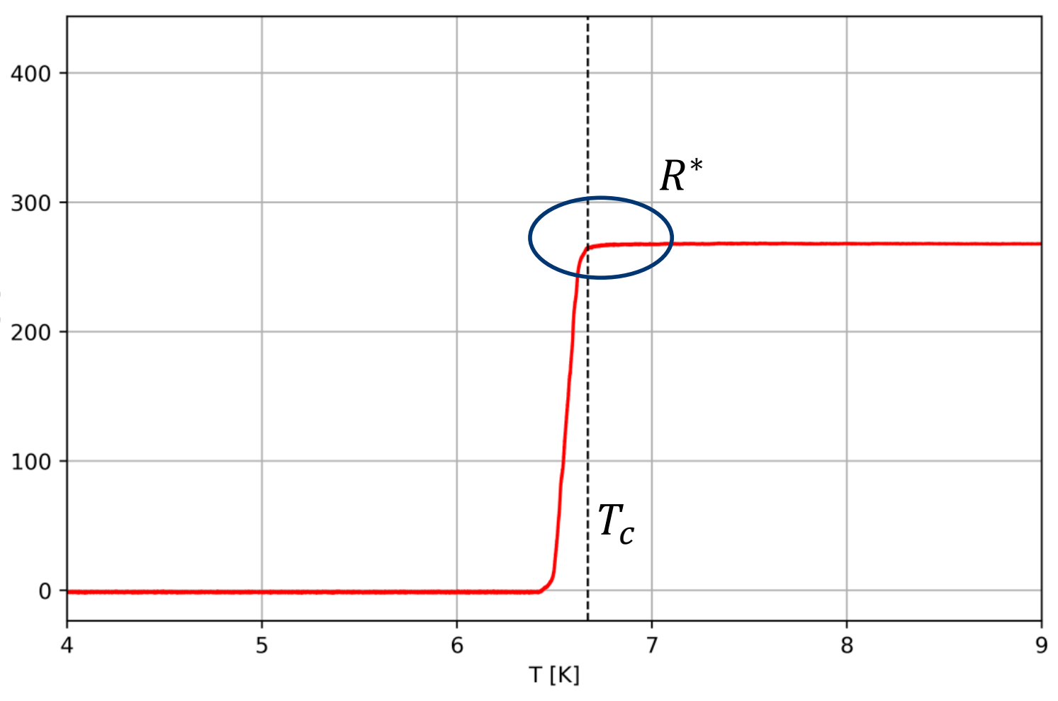

Fig. 5 Nb superconducting transition.

$$L_{k,\square} = \frac{\hbar R^*_\square}{\pi\Delta(0)} = \frac{\hbar R^*_\square}{1.764\,\pi k_B T_c} = 0.042\ \mathrm{pH}/\square$$

Dedicated characterization of Nb shows that its measured sheet kinetic inductance is **insufficient** to achieve a satisfying **phase-shifting dynamics**; alternative materials such as **NbN** and **NbTiN** are therefore under consideration.

Conclusions and future perspectives

The design of the W-band on-chip FTS with KIDs is nearly complete, and prototype fabrication is underway. Cryogenic testing will validate the performance of the antenna-KID system and compare it with simulations. Future steps include full device calibration and on-sky tests to demonstrate readiness for balloon or satellite missions.

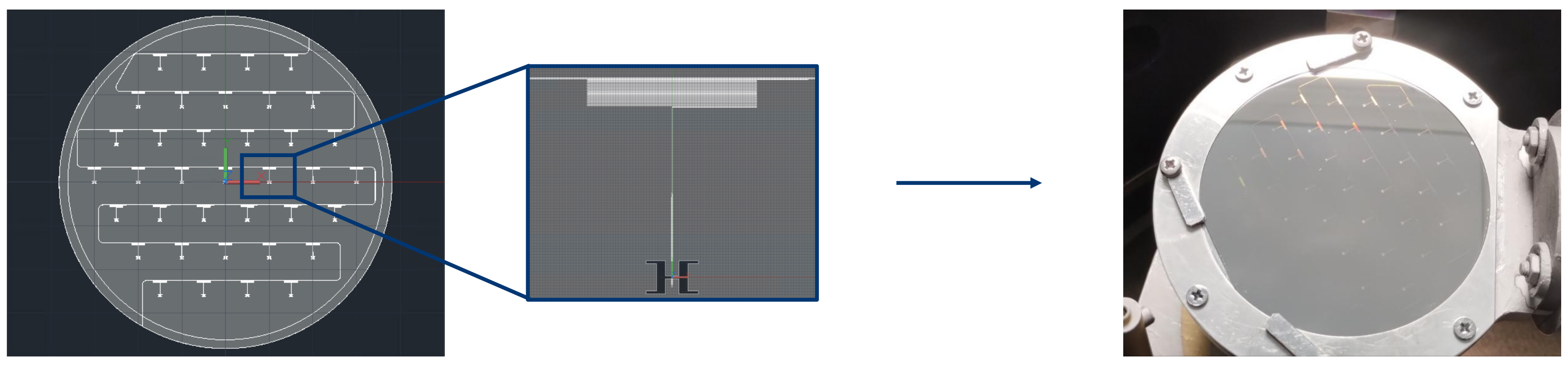

Fig. 6 *Left panel*: CAD of the 37-pixel, antenna-coupled KID array, with a zoomed-in view of a single pixel. *Right panel*: picture of the array prototype, during the microfabrication process.

References

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