Superconducting On-chip Fourier Transform Spectrometer

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Abstract Kinetic inductance in thin film superconductors has been used as the basis for low-temperature, low-noise photon detectors. In particular thin films such as NbTiN, TiN, NbN, the kinetic inductance effect is strongly non-linear in the applied current, which can be utilized to realize novel devices. We present results from transmission lines made with these materials, where DC (current) control is used to modulate the phase velocity thereby enabling an on-chip spectrometer. The utility of such compact spectrometers are discussed, along with their natural connection with parametric amplifiers.

Keywords Cosmology, CMB, kinetic inductance, parametric amplifier, interferometer

1 Introduction

In thin-film superconductors inductance is the sum of a constant value from device geometry (Lg), and a kinetic component (Lk) due to quasiparticle motion. Lk nonlinearly depends on the super-current (I), and for superconducting resonators / transmission lines the resonance frequency / transmission speed can be adjusted with a DC current [15,16]. The total inductance is expressed as \( L(I) \approx (L_g + L_{k,0}) \left( 1 + \alpha I/I_\ast \right)^2 + \alpha' I/I_\ast \), where \( I_\ast \) is a current-scale for non-linearity, \( \alpha < 1 \) is the canonical kinetic inductance fraction and \( \alpha' \) is material and geometry dependant constant. The phase-velocity (u) in a superconducting transmission line (STL) can thus be current-controlled, see Eqn. [1] where the per-unit-length
inductance/capacitance are $L/C$ respectively. Note that $C$ and $L$ (geometric) can be designed during fabrication, while kinetic inductance is DC tunable. Therefore phase-velocity is engineerable and controllable around desired values.

$$u(I) = 1/\sqrt{C'(L_k + L_{g,0}) (1 + \alpha(I/I_0)^2 + \alpha' (I/I_0)^4)}$$

Utilizing phase velocity control, we demonstrate a Superconducting On-chip Fourier Transform Spectrometer (SOFTS). Two STLs are fed with identical inputs obtained from a source via a splitter. Each STL is one arm of a Mach-Zehnder interferometer and the phase velocity/delay is independently controlled. The interferogram obtained from the summing the STLs’ outputs gives the source-spectrum via a Fourier transform, Fig. 1. For currents $I_1 = 0$ and $I_2 = I$, the phase delay and velocity are related as

$$\Delta \phi(I) = 2\pi v x (u(I) - u(0)),$$

here the photon frequency is $v$, and STL physical lengths are $x$.

**Fig. 1** SOFTS schematic: each STL is modeled as current controlled LC circuit (dashed boxes). STLs are capacitatively coupled (Cc) to an antenna (ANT, left) receiving broadband power, and a summing junction (SUM, right) where the phase delayed signals are added and sensed by a detector (TES /MKID).

Such devices can be easily arrayed into wide-band imaging × spectral kilopixel Integral Field Unit (IFU). A common IFU can serve a wide variety of science cases, especially with bandwidth and resolution being engineerable. This new technology can replace meter-scale opto-mechanical FTSs and grating spectrometers with cm-scale electronic devices. Such unique IFUs enable a new class of instruments for measuring CMB spectral distortions which probes cosmology from pre-recombination epoch, studying physics from the epoch of reionization via line intensity mapping, as well as individual astrophysical objects like galaxy-clusters (SZ effect). Additionally such IFUs readily extend capabilities to map localized dusty regions, vital to understanding galaxy and star formation and for foreground cleaning for probes of inflation such as PICO and CMB-S4.

2 STL design and fabrication

The STLs used were originally designed for wideband, high dynamic range, low-noise superconducting amplifiers. These are microstrip transmission lines, each device fabricated with 35nm layer of NbTiN on top of a crystalline Si substrate. Above the transmission line is 190nm of amorphous Si dielectric that separates it from the top layer of a 50nm NbTiN ground plane. The transmission line is 250nm wide and has periodic 250nm wide fingers for...
added capacitance and impedance matching, Fig. 2. These thin-films have a superconducting transition at $T_c \approx 15K$, therefore in application to sub-mm science we have significantly broad bandwidths ($\lesssim 1$THz). Loss at the high frequencies will determine the optimal STL design, a topic of active research beyond the scope of this article. However we note several sub-mm projects have devices operating over 200 GHz\textsuperscript{11,12}.

### Fig. 2
A “zipper” STL: 115mm total length, on-chip length 24.7mm.

### Fig. 3
Micrograph (zoom in) of STL near a bondpad.

#### 3 STL performance

#### 3.1 Phase delay measurements

The crux of both parametric amplification and interferometric operations is sufficient slow down of light-speed and therefore controlled phase delay. Our measurements and fit model are shown in Fig. 3.1 and Eqn. 2. The model has two parameters ($a_I, b_I$) and the coefficient $K$ is extracted from data by fitting the phase at zero current with frequency. The summary of our measurements are presented in Table 3.1. All parametric errors $< 3\%$. Since these STLs have $\alpha \to 1$, we may infer $I_s = a_I = 3\text{mA}$, which implies $\alpha' = 3.16$.

| $K$ (radians/GHz) | $u(0)/c\%$ | $I_c$ (mA) | $a_I$ (mA) | $b_I$ (mA) |
|------------------|-------------|------------|------------|------------|
| 319.4            | 0.75        | 0.86       | 3.00       | 2.25       |
Fig. 3.1 Data and fit of phase delay in STL with DC biasing.

Fig. 3.1 shows that with 0.7 mA current we obtain phase shifts $\sim \mathcal{O}(10)$ radians/GHz. Ideally $4 \times 2\pi = 25$ radians of phase-delay is sufficient to resolve one wavelength. In this device, for 30 GHz (the lowest frequency of interest for sub-mm science) we will obtain 300 radians. This implies that for such science as Line Intensity Mapping and Cosmic Microwave Background, we can shorten our STLs from 24.7 mm (chip length) to < 5 mm, and fabricate densely packed pixels. Broad-band antennas and low noise detectors to complete a focal plane of such SOFTS is now standard, and ever improving technology.

4 Demonstration of a Superconducting On-chip FTS

4.1 Interferometric setup and data

The interferometric setup to realize one SOFTS device is shown in Fig. 4. We use a splitter to halve the input signal (Port 1, 100 pW, high pass filtered > 1 GHz) and distribute it to two STLs. Each STL is current biased, with a low pass filter (6 kHz, via bias-tee) whilst being capacitively coupled to the splitter. The signals from the two STLs are summed on a broadband Wilkinson combiner. For a single tone input on Port 1, on Port 2 we should observe an interferogram that is a cosine modulation, $P_\Sigma = \frac{1}{2} (1 + \cos(\Delta \phi))$, following canonical FTS formalism. Unlike a traditional optical FTS, we have fixed physical paths, and we change the phase velocity to introduce delay ($\tau(I) = x/(u^{-1}(I) - u^{-1}(0))$), viz. $\Delta \phi = 2\pi \nu \tau$. Measurements at some frequencies is shown in Fig. 5. Details on data/ fits presented thereafter.

4.2 Discussion on measurements

Fig. 5 shows that we observe the expected cosine modulation, up to some amplitude decay (discussed in detail below). The $S_{21}$ corrected interferogram for input frequency $\nu$ is shown

\[ \Delta \phi(I) = K \left[ 1 - \sqrt{1 + \left( \frac{1}{|a_I|} \right)^2 + \left( \frac{1}{b_I} \right)^2} \right] \]

\[ (2) \]

\footnote{Maximum voltage applied was 1.84V via 2.66 k$\Omega$ resistor.}
We scale the interferograms appropriately by the individually measured $S_{21}$s of each STL, following Eqn. 3. During the interferometric data collection, the voltages were increased with time, and over this time temperatures increased monotonically by 0.5K, thus we expect some unbalanced profiles, or “decay” as seen in Fig. 5, particularly at higher frequencies. To analyze these data we therefore fit with a decaying cosine modulation, and compare the extracted frequencies to the input from the VNA.

Our frequency fitting error is $\approx 1$ MHz, and the distribution of the difference in input frequency and fit frequency has a standard deviation of 5 MHz, shown in Fig. 6. The expected resolution is $\Delta \nu = \frac{\delta \phi}{2 \pi \Delta \tau_{\text{max}}}$. It is the inverse of the maximum delay, scaled with the minimum phase $\delta \phi$ we can resolve. We measure $\delta \phi \lesssim 0.04$ radians, $\Delta \tau_{\text{max}} \approx 1.5$ ns and we therefore expect $\Delta \nu \approx 4.2$ MHz.

Fig. 4 Experimental setup.  
Fig. 5 Summed power as function of delay $P_\Sigma(\tau)$: data and fits to data for frequencies from 2-10 GHz.

Fig. 6 Distribution of the input minus fit frequencies.

5 Conclusion

We demonstrate a novel application of current controlled phase velocity modulation with thin film NbTiN superconducting transmission lines. A pair of these lines were used to make
a Superconducting On-chip Fourier Transform Spectrometers (SOFTS). Our SOFTS device has a physical length-scale of 25mm, and a resolution of 5 MHz. For an optical FTS with such specifications, the physical size would have to be $\gtrsim 15$ meters. We show that this on-chip device has more than sufficient delay for sub-mm science. Our measurements indicate that individual cm-scale pixels can be fabricated; where each pixel is a SOFTS. Thus with standard broad-band antennas and low-noise detectors (TES / MKID) a kilopixel integral field unit (IFU) for sub-mm cosmology and astronomy is realizable, Fig. 7 schematically shows the promise of SOFTS enabled IFUs, trade off between number of imaging pixels and number of spectral channels may be eliminated.

Fig. 7 A broad survey of mm/submm experiments expressed as number of frequency channels versus number of spatial pixels where a clear trade-off is seen, SOFTS technology can potentially break the trade-off, enabling $> 10^3$ spectral channels for all spatial pixels (shaded region).

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