W-band Lumped Element Kinetic Inductance Detectors array for large ground-based telescopes

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Abstract

We describe the development of a W–band Lumped Element Kinetic Inductance Detectors (LEKIDs) array for large ground–based telescopes like the Sardinia Radio Tele-scope (SRT). Starting from our previous experiences we decided to use a bi–layer (10 nm thick Ti+25 nm thick Al) able to cover frequencies greater than 65 GHz, and an electrical architecture similar to that of the OLIMPO LEKIDs, capacitively coupled to a feedline.

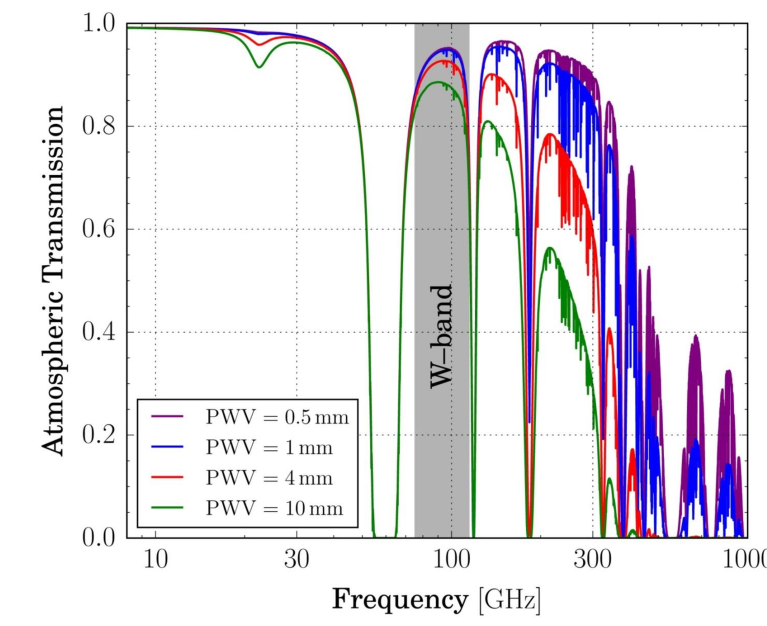
The optical simulations have been performed using ANSYS HFSS to optimize the absorber geometry, the illumination configuration and the thickness of the dielectric substrate. Simulations suggest that the best absorber is a front–illuminated III order Hilbert with a Si substrate 235 μm thick, coupled to a single–mode circular waveguide.

The electrical simulations have been performed using SONNET to complete the design of the detectors by choosing the size of the capacitor, the bias coupling and the feedline. In addition the electrical simulations allow us to verify the lumped condition, to tune the feedline impedance and the resonant frequencies, constrain the coupling quality factor and minimize the electrical cross–talk between different pixels of the same array.

Introduction

The W–band (75 to 110 GHz) is very appealing for CMB and astrophysics observations thanks to the high transparency and low noise of the Earth atmosphere.

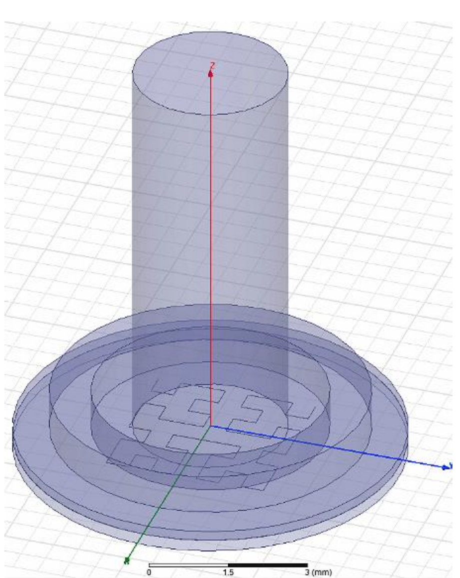
In this band the Galactic foreground emission has a minimum, where the transition between frequencies where the Galactic emission is dominated by free–free, synchrotron and spinning dust and frequencies where is dominated by thermal dust takes place. For a T_c = 812 mK we investigated a bi–layer Ti–Al resonator (10 nm thick Ti + 25 nm thick Al, as proposed by [7]) and we demonstrated that it responds starting from 65 GHz [8].



Design and Simulation

Goal: design a W-band camera, sensitive to total power, working in the focal plane of a large ground-based telescope. This means that the coupling quality factor has to be moderate and much lower than internal quality factor: we chose $Q_c \approx 15000 << Q_i$. In this way Q ($Q^{-1} = Q_c^{-1} + Q_i^{-1}$) is dominated by Q_c, is high enough to guarantee a good responsivity

Optical Simulation

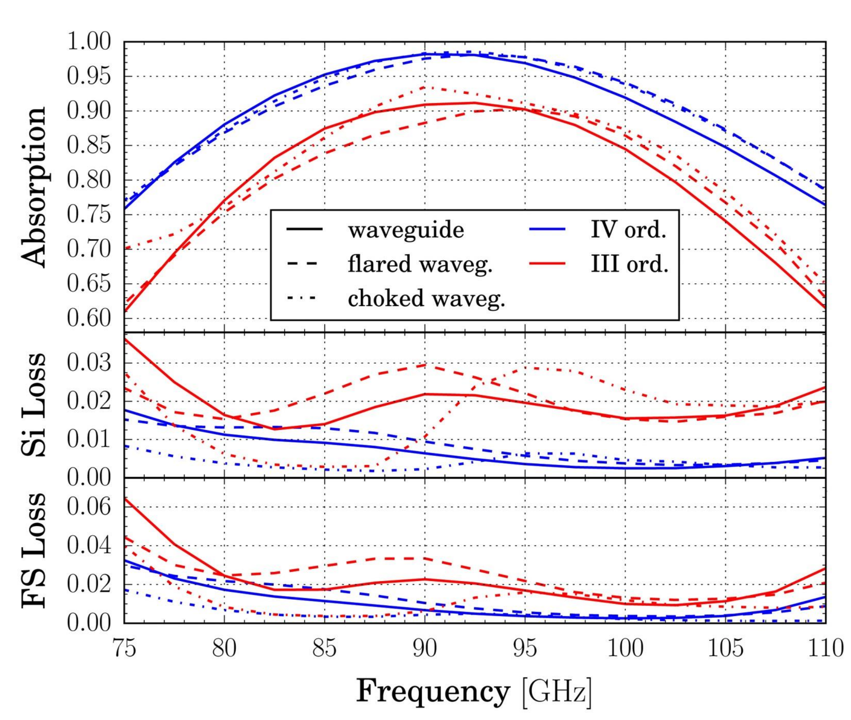


The material and thickness of the superconducting film is constrained by preliminary measurements [8], and the illumination configuration by the experience of the OLIMPO experiment [10]: 10+25 nm Ti–Al bi–layer and front illumination.

For the absorber geometry we have examined the III and IV order Hilbert curves

Results of the optical simulations for the different receiver geometries.

The values of the absorption and losses are integrating over the W–band



Absorber geometry			Radiation Coupler	Absorption	Losses
Hilbert order	s_h [μm]	w_h [μm]			
III	450	2	waveguide	81%	< 2%
			flared waveguide	81%	< 2%
			choked waveguide	83%	< 1.5%
IV	270	2	waveguide	90%	< 1%
			flared waveguide	91%	< 1%
			choked waveguide	91%	< 0.5%

$$\mathscr{R}_{opt} = \eta_{opt}\mathscr{R}_{elec}$$

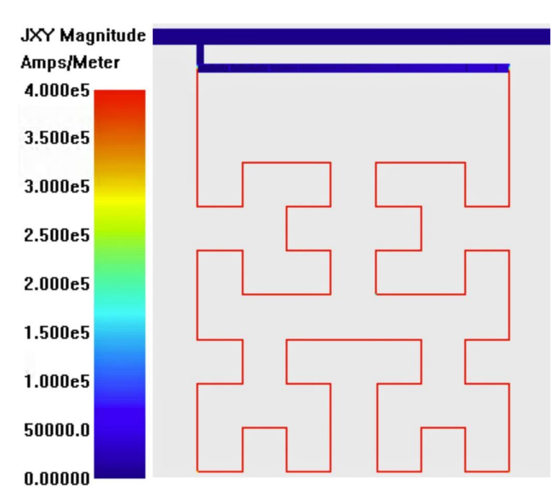
$$\mathscr{R}_{elec} = -\frac{\eta_{pb}\tau_{qp}}{\Delta}4Q\frac{\delta x}{\delta N_{qp}} \propto \frac{Q}{V}\alpha_k$$

$$\frac{\mathscr{R}^{III}_{opt}}{\mathscr{R}^{IV}_{opt}} \propto \frac{\eta^{III}_{opt}}{\eta^{IV}_{opt}}\frac{\ell^{IV}_{abs}}{\ell^{III}_{abs}} \sim 2.2$$

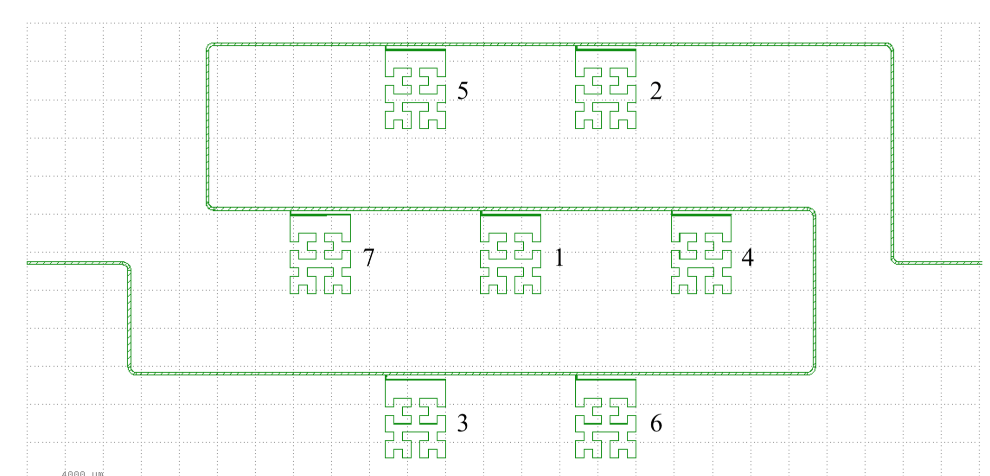
In terms of optical responsivity, the III order Hilbert geometry is thus preferable compared the IV order and we used that geometry as the inductor of the resonators.

Electrical Simulation

The design of the resonator has been completed with the electrical simulations, performed with the SONNET software, defining the capacitor and the coupling to the feedline, in order to constrain the resonant frequency and the coupling quality factor.



The lumped element condition is verified: the current is uniform in the absorber/inductor and null in the capacitor



We designed and electrical simulated a 7–pixel prototype (2 inches diameter) to be coupled to the feedhorns (the spacing of which is fixed by the horn aperture).

The feedline is shaped in such a way that the same scheme can be used for a more densely populated array "directly" (without radiation couplers) coupled to the radiation.

#	Design		SONNET	
	ν_r [MHz]	Q_c	ν_r [MHz]	Q_c
1	409.7	14000	473.1	14500
2	416.8	15000	480.4	15000
3	421.7	15000	485.4	14000
4	426.7	15000	490.5	13500
5	432.0	16500	495.8	14500
6	437.5	16000	501.0	14500
7	446.1	15000	508.9	14000

The comparison between design constraints and SONNET results for the resonant frequencies and coupling quality factors.

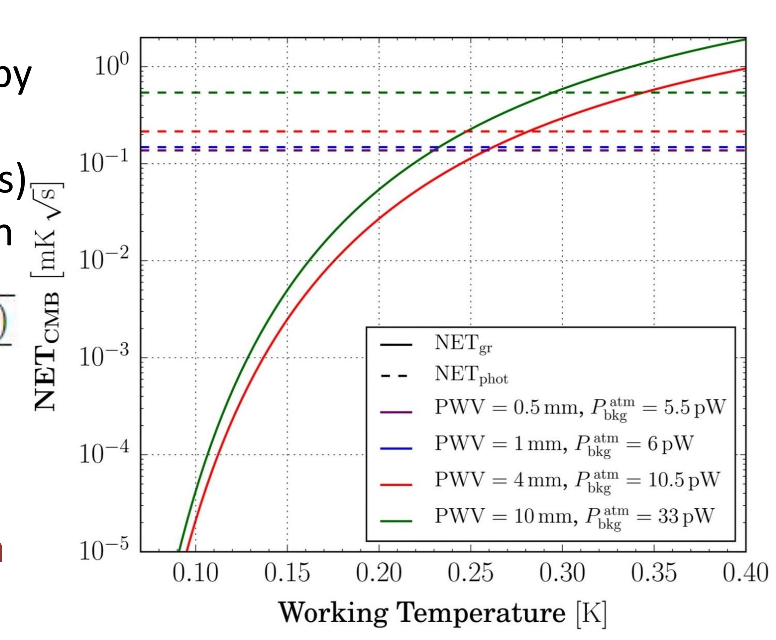
This prototype is ready to be fabricated.

Optimal operation temperature

For ground–based observations in the W–band, the detector noise is limited by the atmospheric background and its fluctuations.
The comparison between the noise equivalent temperature (NET in CMB units) of the detectors, assuming that it is due only to generation and recombination fluctuations of quasiparticles:

$$\mathrm{NEP_{gr}}\left(P_{\mathrm{bkg}},T\right) = \frac{2\Delta\left(T\right)}{\eta_{pb}\eta_{opt}}\sqrt{\frac{N_{qp}\left(P_{\mathrm{bkg}},T\right)}{\tau_{qp}\left(T\right)}}$$

and the photon NET , expected for the SRT site, is shown in the figure:



The usual situation for the SRT site is 4mm<PWV<10mm, and therefore an operation temperature of 280mK is sufficient.

Conclusion

We report the status of the development of a W–band camera, designed to fit a large ground–based telescope, as the SRT.
We optimized the geometry of the absorber/inductor and the radiation couplers through optical simulations: front–illuminated III order Hilbert geometry coupled to the radiation via single–mode choked waveguide.
The electrical architecture of the resonators was optimized by choosing the resonant frequencies and constraining the coupling quality factors to 15000.
Finally, we studied the optimal working temperature of such camera if operated in the focal plane of the SRT: 280mK seems to be enough to have detectors with photon–noise–limited performance.

References

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[3] A. Paiella et al., J. Cosmol. Astropart. Phys. 01, 039, (2019)