An on-chip filter bank spectrometer based on transition edge sensors for meteorology and climatology

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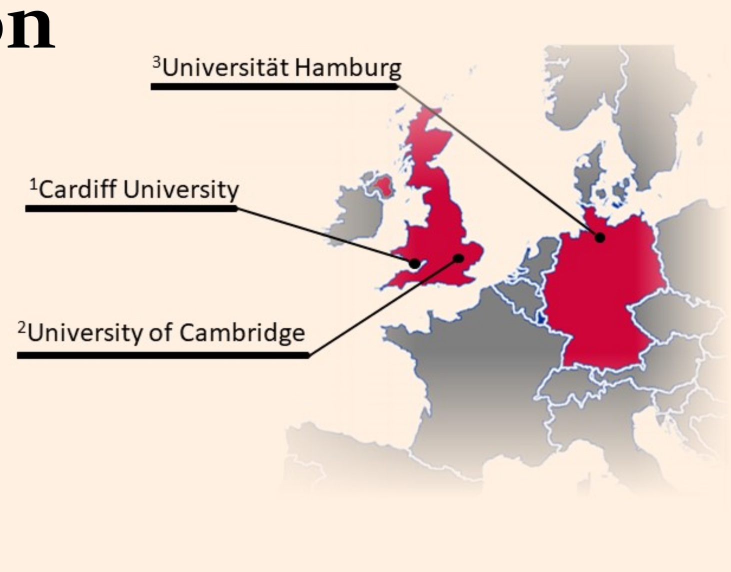

Introduction

We introduce the Hyperspectral Microwave Atmospheric Sounder, HYMAS, a new satellite instrument concept for meteorology and climatology applications. HYMAS is an on-chip spectrometer based on superconducting filter banks coupled to Transition Edge Sensors (TES). HYMAS will greatly increase the number of sounding channels and sensitivity, compared to existing microwave (MW) atmospheric sounders, improving Numerical Weather Prediction (NWP) and Global Circulation Models (GCMs). Kinetic Inductance Detector (KID), based filter bank spectrometers [1][2][3] are limited to sensing frequencies above ~100GHz. Importantly, HYMAS will be capable of reaching the important temperature sounding O_2 absorption lines at 50-60GHz, currently unavailable with KID-based solutions.

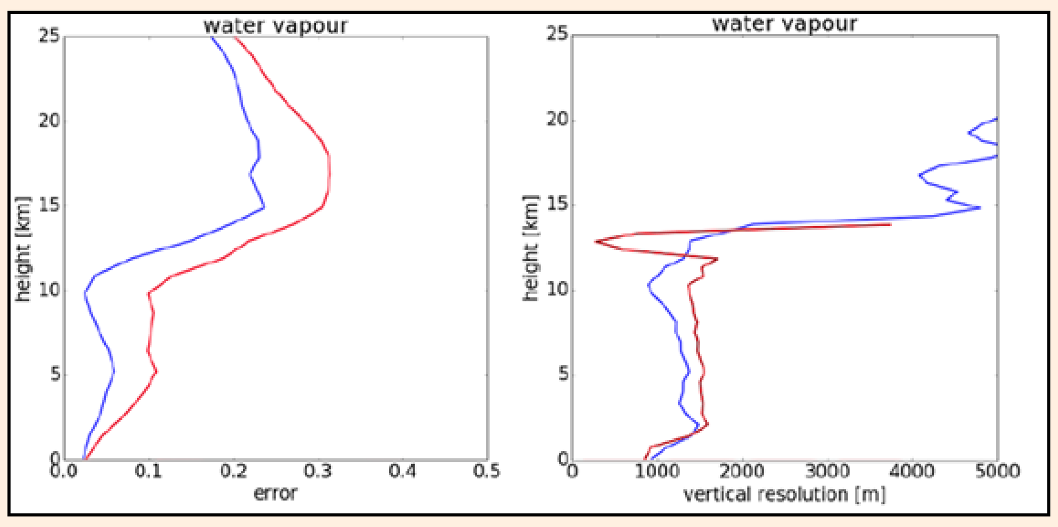

Figure 1. *Left*, Retrieval error and *right*, vertical resolution for an Infrared (IR) instrument in *red* by comparison with a KID based MW instrument in *blue*. Similar performance as could be expected from a TES based instrument.

Preliminary end-to-end retrieval simulations indicate that a hypothetical KID-based hyperspectral instrument could match the performance of hyperspectral IR instruments as shown in Figure 1. This is highly significant, as we would have the high data quality of IR hyperspectral instruments, but for all-sky conditions, not restricted to just clear sky. Note also that these simulations were carried out for frequencies above 100 GHz, without the contribution from the critical O_2 temperature sounding lines at 50-60 GHz. It is expected that the addition of sounding channels in this region will significantly improve the resolution and accuracy of the retrievals, and possibly surpass the performance of IR instruments.

Few-Mode Ballistic TESs

TESs traditionally require long support legs for high sensitivity. This is not compatible with highly compact filter bank arrangements. The current proposed solution is to utilise novel few-mode ballistic transition edge sensors [4]. These possess support legs only 1.0-5.0µm long, 1.0µm wide and 0.2µm thick. The ballistic legs support only 5-7 fundamental elastic modes, an example is shown below.

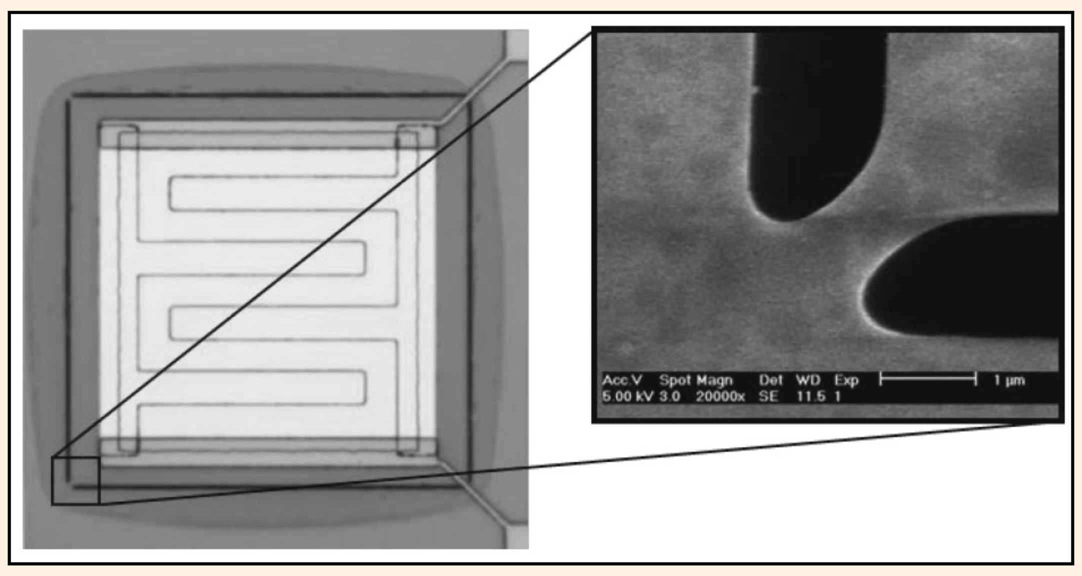

Figure 2. (*Left*) Image of a few-mode ballistic TES. (*Right*) displays a Scanning Electron Microscopy (SEM), image of the dielectric support legs [4].

One key aspect of few-mode ballistic TESs is that their thermal behaviour is independent of length, leading to no $1/L$ dependence. This allows for compact optical designs, with a lower variation in the thermal conductance G, leading to high levels of uniformity. With the above properties few-mode ballistic TESs have been considered to be the ideal solution for HYMAS.

HYMAS Concept

By utilising on-chip superconducting microstrip filters, HYMAS benefits from a reduced phase velocity v_p, not only due to the dielectric but also kinetic inductance effects. This leads to a much reduced on-chip wavelength, leading to a reduction in the required optical and cryogenic mass. Current and future planned MW sounders are based on heterodyne technology, with large quasi-optical networks to separate the relatively low number of channels. HYMAS offers significant volume and mass reduction, with greatly improved channel count and sensitivity, at the expense of requiring active cooling in low Earth orbit (LEO).

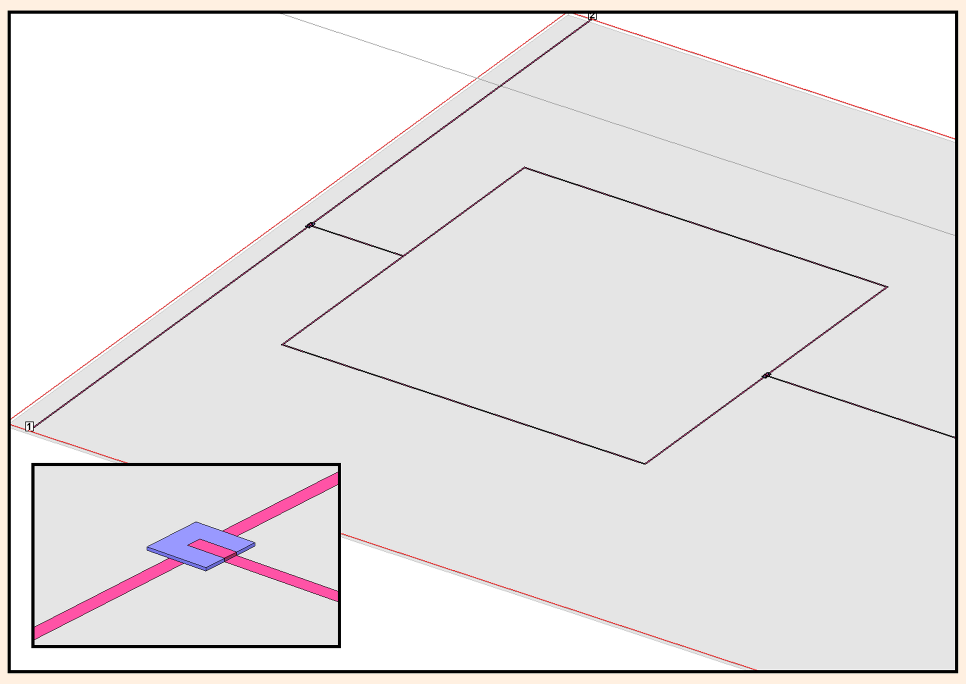

Figure 3. Initial HYMAS designs, utilising a square closed loop resonator. *Inset* displays a zoom in on the overlap capacitor.

Current designs for HYMAS are an evolution of the CAMbridge Emission Line Surveyor (CAMELS) [3]. This utilises a closed loop resonator coupled using an overlap capacitor to couple each individual filter to a single feedline. The microstrip is comprised of Niobium and is 2.5µm wide, with a resonator at the desired frequencies measuring hundreds of micrometres. The initial demonstrator will be designed with a spectral resolution, R, up to 1000. The chip will possess a small number of channels in order to characterise the filter bank.

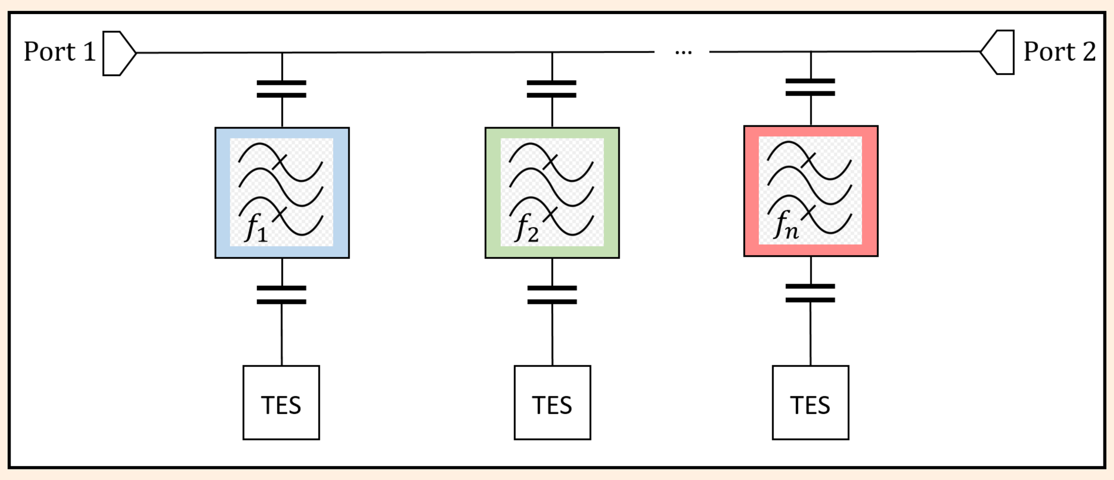

Figure 4. Displays the basic filter bank design used for illustration and networking of filters within Sonnet.

Each filter will be coupled via microstrip to an individual few-mode ballistic TES, read out by a Superconducting Quantum Interference Device (SQUID). This is suitable for the low number of channels in the initial demonstrator. Later designs will increase the channel count to hundreds with the possibility of using frequency division multiplexing to achieve this.

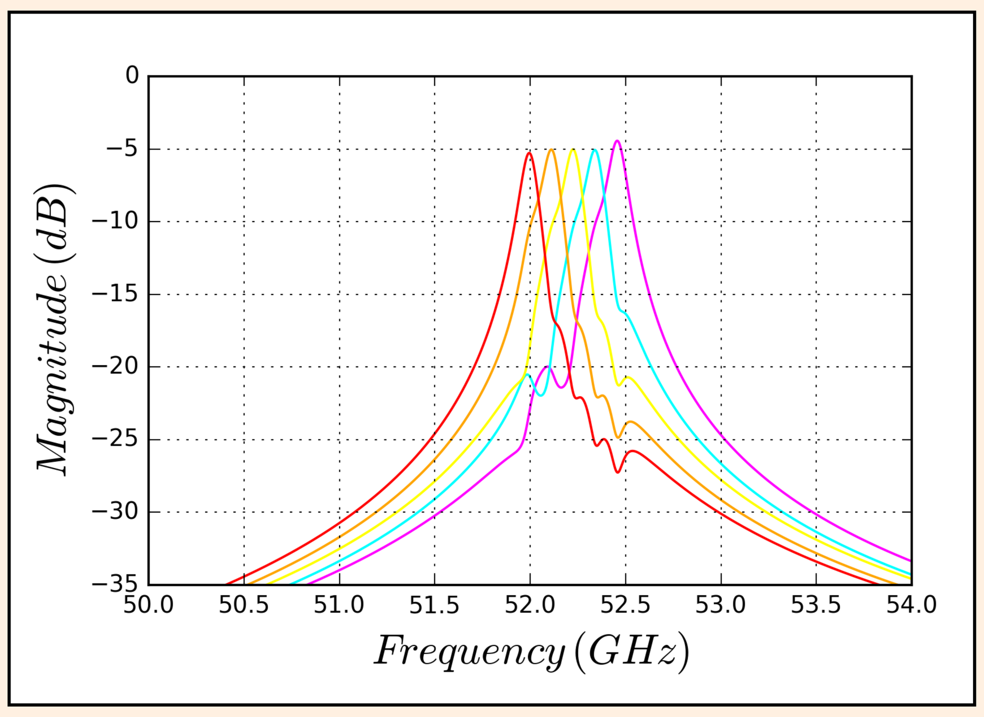

Figure 5. Displays the transmission profiles for five networked filters with R = 500, based on closed square loop resonators from early designs near the target frequency. Displaying S_{31},S_{41},S_{51},S_{61},S_{71}.

Conclusion

An initial demonstrator for HYMAS is currently in the design and modelling phase. The test bed required to evaluate the fabricated chips is in the process of being designed and constructed. TES and coupling designs and performance modelling is also underway. Demonstration devices will be fabricated and tested in the critical 50-60GHz region for key performance parameters. After demonstration of these reduced channel set devices, we aim to develop a full filter bank, covering many hundreds of channels to sample absorption features such as O_2 and H_2O, across the 50-850GHz region. This will be followed by an airborne demonstration programme as a necessary next step towards space-flight qualification. Such an instrument will have a significant impact on improving the accuracy of NWP models, including constraining essential climate variables in GCMs.

Future Work

HYMAS is currently designed with a closed square loop filter, however at the desired frequencies the resonator size can be significant. In order to minimise the resonator geometry a fractal based design such as in figure 6, can be employed [5].

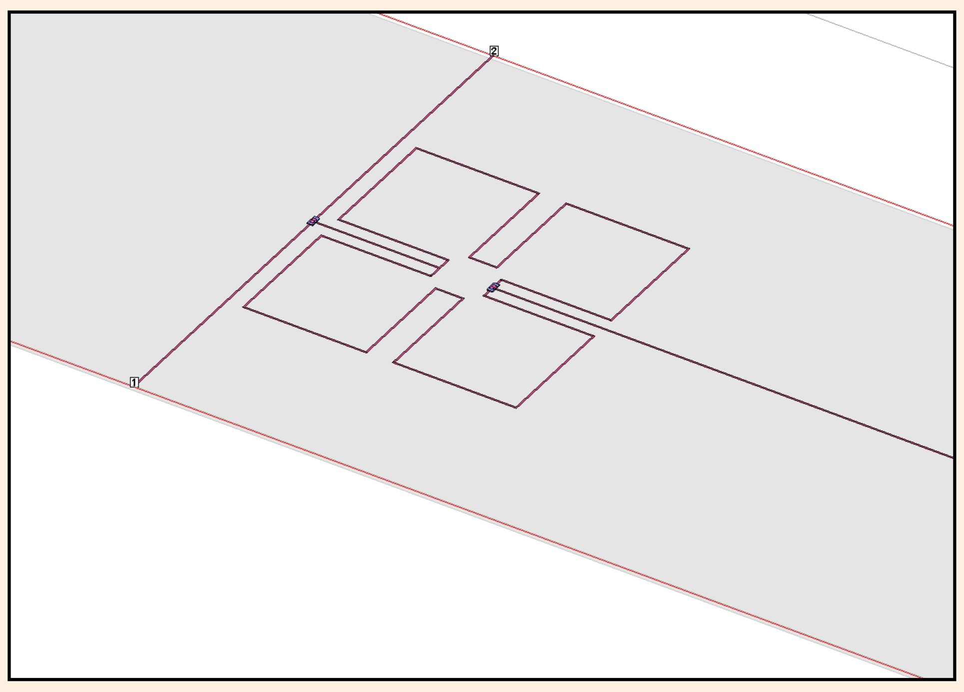

Figure 6. Initial HYMAS designs based on Minkowski-like fractals.

This first order Minkowski-like fractal arrangement can reduce the size of the ring resonator by 36%. This arrangement possess no change in filter response compared to the design seen in figure 3. The use of multiple filters can also be considered to alter the passband.

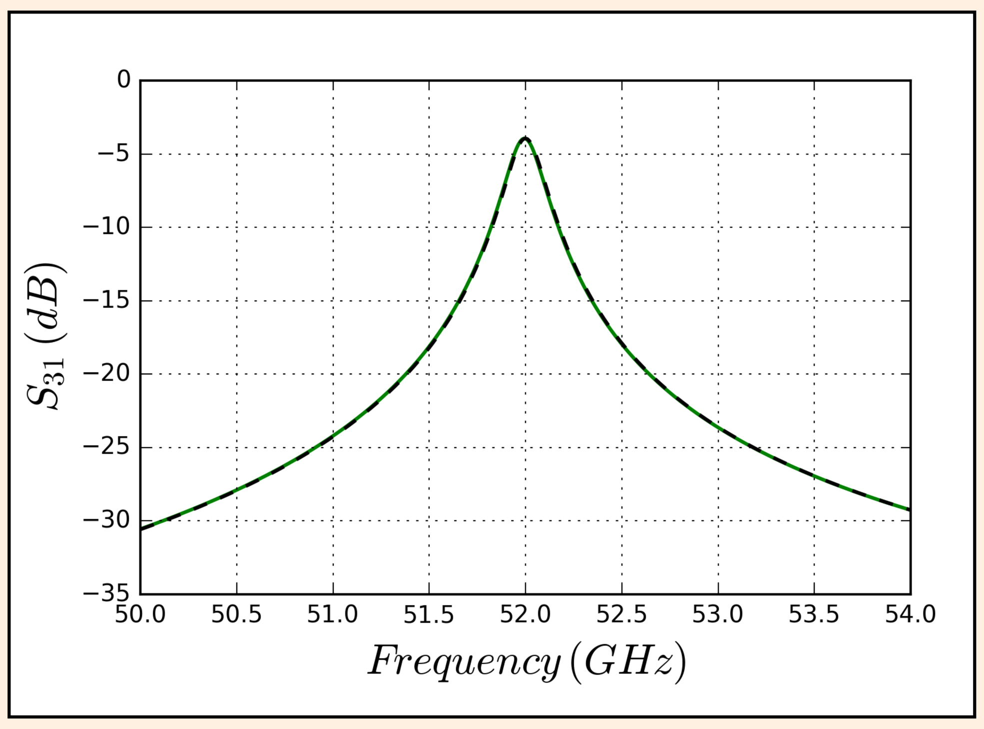

Figure 7. Displays comparison of fractal variant (*dashed black line*) with traditional square loop resonator (*solid green line*).

The few-mode ballistic TESs demonstrated by Cambridge [4], are constructed from a Molybdenum-Gold bilayer. Investigations into the use of Niobium or Niobium Nitride could yield suitable TESs with a higher operating temperature. A future cryogenic study with industry partners, identifying a suitable cooling solution with the use of a mechanical coolers in low Earth orbit is also planned to increase HYMAS's overall technology readiness level.

Acknowledgements

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