Electron Spin Resonance to enhance Neutron scattering measurements

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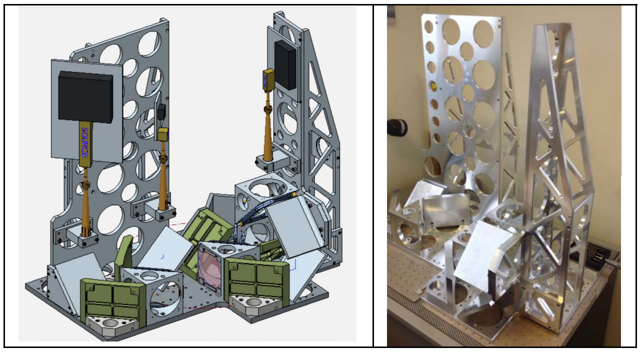
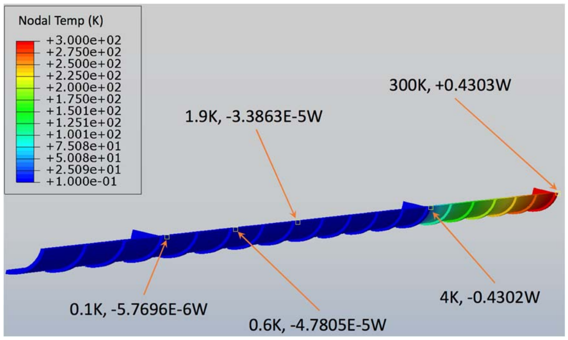
***Abstract*—We present the design and implementation of a novel 108 and 215 GHz Quasi-Optical Bridge and HE11 probe system to polarize the electron system of quantum materials. The out of equilibrium state will then be probed in-situ using elastic and inelastic neutron scattering.**

Quantum materials are at the heart of current research in solid state physics as they promise to offer more energy efficient electronic technologies and maybe essential to realize quantum computing [1]. Excitations in quantum materials govern their properties and have an energy scale that is matched by microwaves in the mm-regime. Hence, microwaves are the ideal radiation to excite and drive these materials out of equilibrium. Neutron scattering, on the other hand, is a powerful technique to probe such excitations. The Quasi-Optical Bridge and HE11 probe system described in this article is at the heart of an upcoming microwave pump – neutron probe setup to study quantum materials far from equilibrium. For the success of these experiments three aspects are essential: (i) A high population of excited states must be achieved to allow statistical meaningful measurement, as neutrons only interact weakly with the sample and neutron sources are weak compared to e.g. X-Ray sources. (ii) The sample must be kept at very low temperatures (<1K) to extend the life time of excitations into an observable regime. (iii) Integration into existing neutron scattering spectrometers like the Multi Axis Crystal Spectrometer MACS is necessary [2]. To probe excitations in a large fraction of momentum space the sample together with the microwave components and the cryostat must be rotated to fulfill the neutron scattering condition. These requirements drive the development of our Quasi-Optical Bridge and HE11 probe system



The QO Bridge drawn in Pro/E CREO & as manufactured



Heat flow analysis down the HE11 probe

Drawing upon experience developed over the last 20 years of building microwave ESR bridges, we have designed and manufactured a compact three-dimensional Bridge and HE11 probe which transfers (Virginia Diodes Inc, VDI) mm-wave power at 108 and 215 GHz, to the sample held within a neutron beam at cryogenic temperatures within a superconducting magnet.

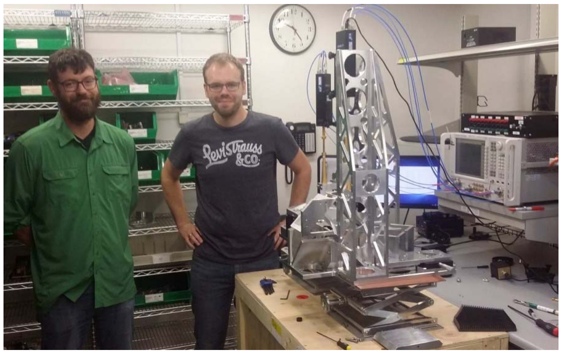
Key Features of the QO transmission system are

- Low-loss transport of mm-waves from source to sample and back to Schottky detectors, giving both co and cross-polar (inductive mode) returns.
- 3-D structure giving compact solution, with extensive weight lightening to avoid stressing the moving cryomagnet beneath, while supporting the Bridge.
- Sums-of-focal-length optics give frequency-independent operation to allow 108 and 215 GHz signals to use the same optical structure
- Sources isolation provided via polarizing wire grids and free space Faraday 45 degree rotators
- Martin-Puplett (M-P) Interferometer at the HE11 input allowing the injected polarization to be adjusted on a great circle on the Poincaré sphere

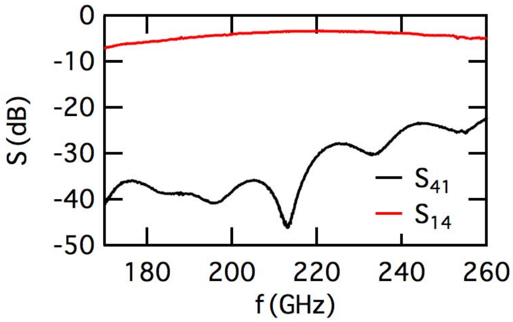
The low-loss HE11 probe design has required careful attention to both conduction and radiation heat leakage from ambient. A thermal analysis, based upon experimentally determined parameters, was used to optimize the design. The German Silver probe incorporates low pass filters (at 300 K, 77 K ,4 K and1 K, QMC Instrument Ltd) which allow delivery of mm-wave power to the sample, while minimizing the conductive and radiative heat load on the cryogenic cooling system. The hardware will shortly be deployed to the neutron source in Gaithersburg, MD.

Initial measurements on the Bridge have now been performed at VDI’s facilities in Charlottesville, VA. The image below shows a Vector Network Analyzer being used to measure transmission and return loss (Sxx) over the set of ports: Source

Port (S1), Co-polar Return Port (S3) and Inductive Mode Cross-polar ESR Detector Port (S4). A flat or roof mirror reflector could be placed at the beamwaist position (S2) forming the input to the vertical HE11 guide. The roof mirror could be used to alter the return polarization.



The QO Bridge undergoing VNA Sxx measurements at VDI



S14 and S41 (Source/ESR detector) measurements showing 3.35dB loss in the forward direction and quantum of 40dB of isolation in the reverse direction.

The presence of both Faraday rotators and the M-P interferometer means that the QO Bridge function is more complex than might be expected. The VNA allow us to confirm the operation of the Bridge as follows

We started by noting that the Bridge is a linear device: If there was no absorption (in the Ferrite, mirrors and horns) or scattering, one could form a 3 by 3 scattering matrix which (as a function of both frequency and interferometer position) would give complex coupling fractions between the ports. Those amplitude coefficients would, when converted into powers, sum to one. If the system did not have either an isolator or a M-P Interferometer, then the matrix would be symmetrical: i.e. S14 would be the same as S41.

The Faraday rotator generates non-reciprocity, so that S14 does not equal S41. That forms the basis of the circulator - which sends returning power to the power monitor (S3), rather than back to the source.

The operation of the M-P Interferometer is quite subtle: Trivially, when there is no path difference, the interferometer does nothing.

When the path difference is at +/-1/4 lambda, it acts as a quarter wave plate and can inject Counter Clockwise (CCW) or Clockwise Circular (CW) Circular Polarization (CP) into the HE11probe, giving higher ESR signal at the sample. On might expect 3dB better in power, or factor of root 2 increase in B1 field signal at the sample. Note that the unwelcome non-ESR absorptive heating should not increase, which is important given the specific heat capacities of materials and available cooling power at sub Kelvin temperatures.

As one moves the interferometer's path length between these positions the polarization entering the HE11 guide moves from Vertical, CCW CP, Horizontal, CW CP with elliptical polarization states in between.

Starting with a flat mirror as the returning surface we were able to alter the balance of power going to S3 (ESR) and S2 (Power Monitor) by adjusting the path difference in the M-P: With the path length zero the power was routed back to the Power Monitor, S3. This will be the position to perform inductive-mode ESR, as the cross-polar return goes to S4. With lambda/4 path difference, all of the power ended up in S3. This is because the reflected CP changes its sense of rotation on reflection[1] and the returning passage though the Interferometer (acting as a quarter wave plate) then converts this to the orthogonal polarization.

Replacing the flat mirror with a roof mirror, set parallel to the Interferometer's grid, these effects are reversed: With the path length zero, the power was routed back to the ESR detector, S4, as the linear polarization is rotated by 90 degrees by the roof mirror, and this rotation is preserved in the interferometer, and picked up by the inductive mode grid. With lambda/4, all of the power ended up in S3. Unlike the flat reflector, the roof mirror does not reverse the sense of rotation of the reflected CP beam.

ACKNOWLEDGEMENTS

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[1] Consider viewing a corkscrew in a mirror. Photons carry angular momentum which - being described by an axial vector - is reverse on reflection