Creating the microwave laboratory at The Institute of Composite Sciences Innovation (InCSI)

Summarised and composed

by

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Bench measurements

Over the past four years, the Institute of Composite Sciences Innovation (InCSI),[1] Zhejiang University has undertaken significant efforts to create a laboratory to study the electromagnetic properties of composite materials in the microwave range. The laboratory began to develop around the most complex and expensive device – Vector Network Analyser (VNA) ZNB20, 100 kHz – 20 GHz, bought from Rohde&Schwarz (R&S, Germany).[2] We chose this company based on its reputation as a leading supplier of the electronic test equipment. Their VNAs, along with the companies Keysight (USA) and Anritsu (Japan),[3,4] have a well-deserved reputation for being the most accurate and reliable instruments in the network and spectral measurement product line. Also, R&S is known for its well-organized technical support. German companies are eager to work with China and promote their advanced technologies. Our institute cooperates with R&S and Zwick/Roell (German supplier of mechanical testing machines).[5] Both companies have offices and plants in China. Ceyear is a rising star in the Chinese electronics industry,[6] which has started making pretty decent clones of Keysight's VNAs, including interfaces. In the future, we should pay attention to this company due to significantly lower prices compared to global brands.

The initial step in creating the laboratory was to master the standard techniques in coaxial and rectangular waveguides for measuring the dielectric permittivity and magnetic permeability of small composite samples in the range 8 – 18 GHz. Software, including TRL (THRU-REFLECT-LINE) and SOLT (SHORT, OPEN, LOAD, THRU) calibrations, as well as the waveguides and the corresponding calibration kits were provided by R&S and their partners, see Fig. 1.

Fig. 1. Coaxial and square waveguides, and the calibration kits for them provided by R&S and their partners.

Then we started developing techniques for measuring magneto-impedance (MI) in ferromagnetic wires in the presence of tensile stress and magnetic fields up to several tens of oersteds. Composite samples with ferromagnetic wire inclusions of various shapes and dimentions (long parallel strings, short dipoles, micro-coils or spiral, etc.) demonstrate unique microwave properties that can be controlled by external parameters such as magnetic field, tensile stress, or heating. The developed techniques for studing individual impedance properties of such wires in the frequency range 100 kHz – 20 GHz, including measurement automation programs written in National Instruments LabVIEW 2015,[7] are entirely self-made and have no commercial analogues. This work has already been highly recognised, having won the third prize in the international competition organized by Zwick/Roell.[8,9] Also, a Chinese patent has been submitted.[10] The implementation of magneto-impedance measurement techniques has required an expansion of the list of devices used. In addition to the VNA, it now includes a R&S function generator HMF 2550, R&S digital multimeter HMC 8012, and a power amplifier to feed a Helmholtz coil [11] by the offset voltage steps received from the function generator. The synchronous operation of VNA, function generator, and digital multimeter, required for the magneto-impedance measurememts, are controlled by several LabVIEW programs depending on the type of measurements: (i) scanning magnetic field at a fixed freuqncy or (ii) scanning frequency (dispersion) at a fixed magnetic field or tensil stress. Full automation of measurements became possible due to the fact that all used devices support the SCPI standard for executing script commands sent from the control program.[12] The task was further simplified since LabVIEW contains ready-made functional blocks, called “VI” – virtual instruments, which allow performing sets of standard measurement and formatting commands, and then transferring data to a PC. At this stage, the laboratory was mounted on a trolley accommodating all the measurement devices, see Fig. 2, which made it possible to park it near the stress machine or other measurement arrangements.

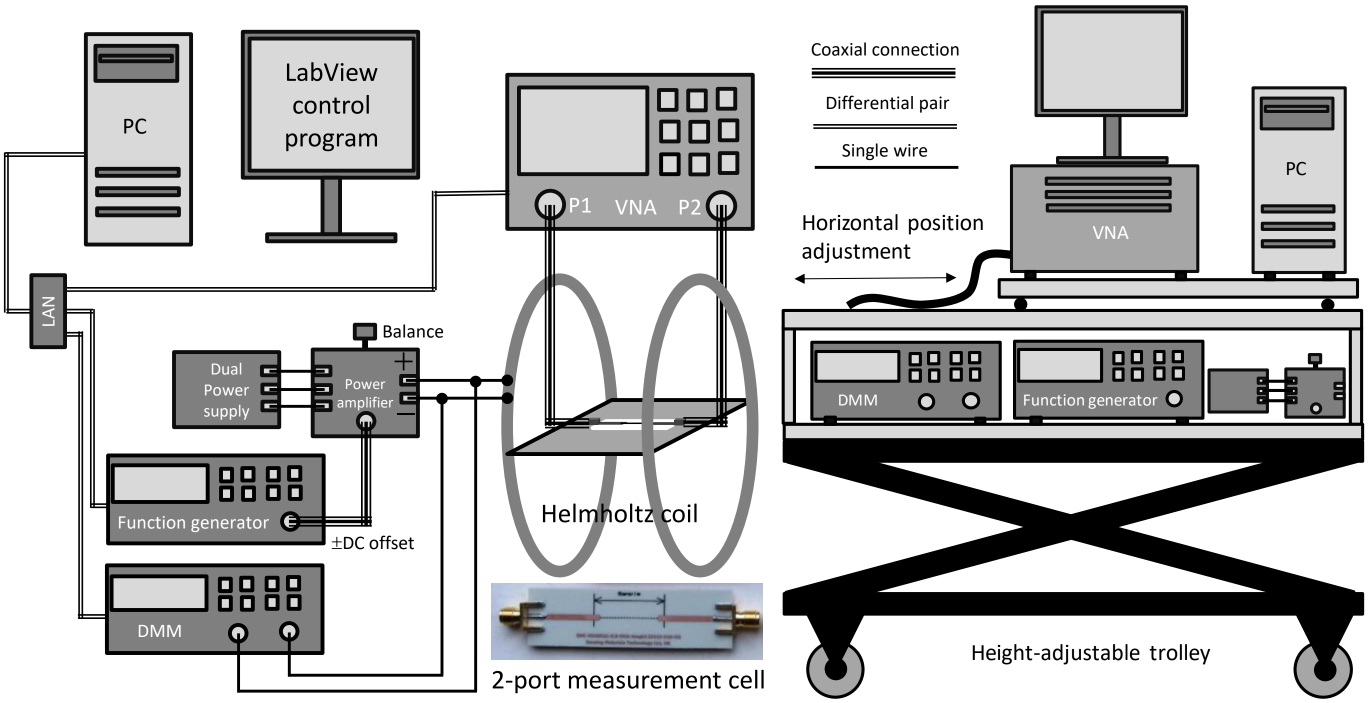

Fig. 2. A trolley accommodating all the measurement devices.

To measure the high frequency impedance in the presence of tensile stress and DC magnetic field, we have developed a special dog-bone PCB cell, shown in Fig. 3, that allow two external stimuli applied simultaneously. For this measurement arrangmets, we have proposed a two stage calibration procedure explained in Fig. 4. At the first stage, VNA and coaxial cables are calibrated using a standard coaxial calibration kit provided by R&S. After this calibration, the reference plane will be established at the cable and PCB cell coaxial connectors. At the second stage, the reference plane is extended up to the microstrips ends, using the surface mount non-coaxial SOL terminations and the 3-term error correction model. A wire above the ground plane represents a waveguide that introduces additional phase distortions that cannot be eliminated by a calibration. To compensate this phase distortion, we proposed a simple phase unwrapping technique. Also, in modern VANs, the delay time associated with the phase incursion can be compensated using a fixture elimination option.

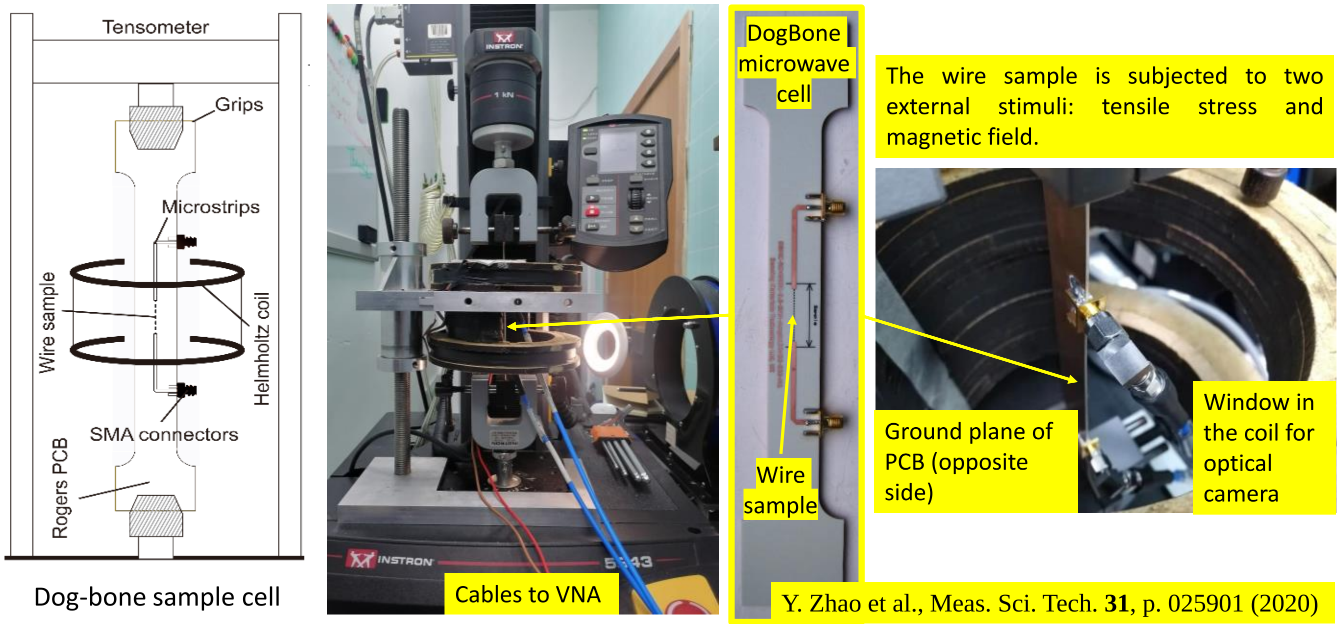

Fig. 3. A specially designed PCB cell for measuring the high-frequency impedance in ferromagnetic wires subjected to a DC magnetic field and tensile stress. The trolley with the measurement devices (see Fig. 2) was parked by an Instron testing machine.

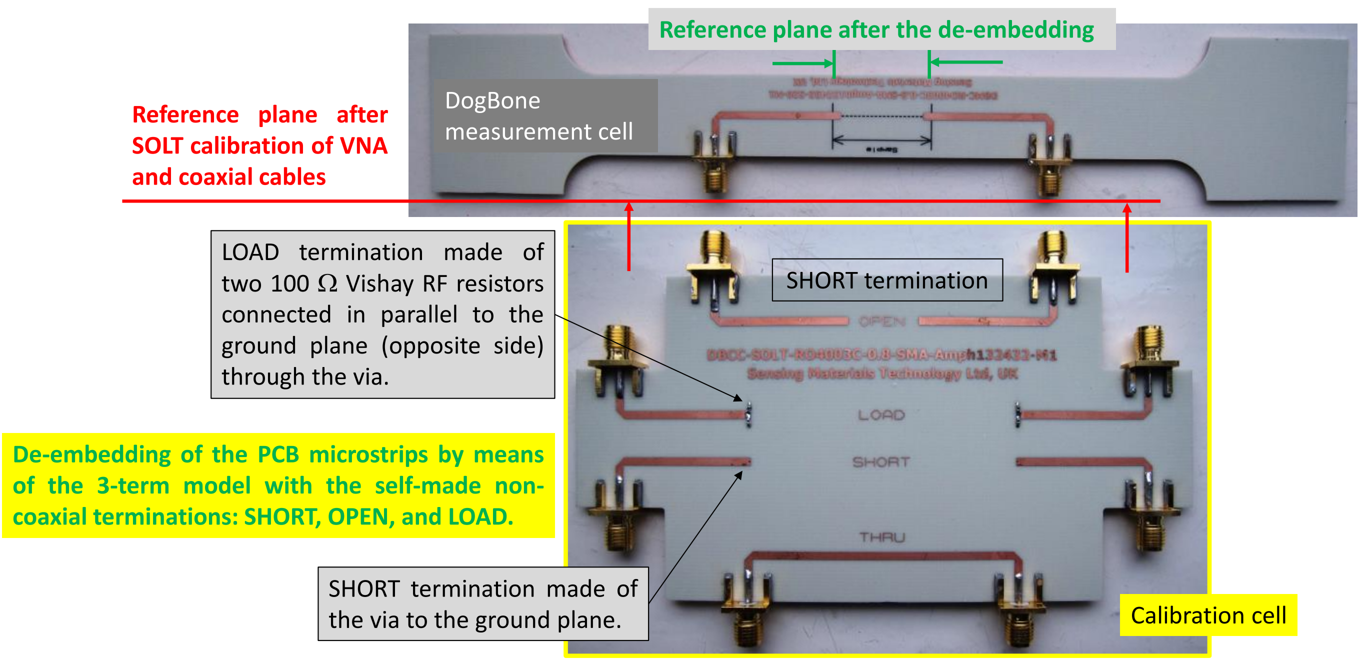

Fig. 4. Two stage calibration technique using coaxial standards for the SOLT calibration of VNA and cables and a PCB cell with surface mount non-coaxial terminations for extending the reference plane beyond the coaxial connectors.

Free space microwave measurements

Free space microwave measurements by themselves are nothing new. In this regard, we could mention the pioneering work of the Varadan's group, who began using TRL calibration to measure the free space S-parameters from flat samples and convert them into effective permittivity and permeability.[13-15] Currently, Keysight and R&S, or their partners, provide such measurement systems, including software for the frequency and time domain measurements. However, it should be understood that we are talking about bench systems suitable for measurements in a rather narrow frequency range, starting from a few gigahertz, when the transmitting and receiving horn antennas can be equipped with compact focusing lenses. In this case, the principles of quasi-optics are applicable, which make it possible to localize the irradiating spot on the sample under test in a region smaller than its dimensions. Also, commercial systems do not imply any external stimuli that are required in our project. This is where we come to the technical specifications that necessitated the development of a self-made measurement system:

- Frequency measurement range from 500 MHz up to 20 GHz
- Composite specimens of various dimensions (flat or 3D), which can be exposed to external stimuli such as DC magnetic field up to tens of Oersted, tensile stress, or heating up to several hundred degrees
- At least two calibration techniques in the free space, Response&Isoltation and TRL
- Integration of bench and free-space measurements into a single system
- Future adaptability of the system for scanning wavefronts emitted by horn atennas or other active or passive radiating surfaces.

First of all, the selected frequency range (500 MHz – 20 GHz) does not allow assembling a bench system, especially with focusing elements. As soon as we were provided with a room for the installation of the measurement system (rather small), it was decided to divide it into two parts: (i) measurement anechoic chamber and (ii) operator room. The implementation of room partitioning is shown in Fig. 5. The operator room housed the trolley with devices, a compact Instron testing machine, and a self-made microwave switching matrix that multiplexes signals between the bench and antenna measurements. The switching matrix shown in Fig. 6 consists of a 12 V, 75 W DC power supply, two microwave SP6T Teledyne LeCroy microwave switches (12 V, 18 GHz),[16] an Arduino Mega 2650 microprocessor,[17] and semiconductor switches connected to the Arduino's 5 V GPIO. The solid state switches controls the states (ON/OFF) of SP6T in the box, as well as two additional SP4T Teledyne LeCroy microwave switches located in the antenna pillars, see Fig. 7. In addition to multiplexing signals between the bench and antenna measurements, the switching matrix is used to automatically calibrate VNA and the cables connected it to VNA. To do so, SP6T switches are terminated with the SOLT coaxial calibration standards at the box front panel, see Fig. 6. For each standard, its unique S1P (SOL) or S2P (T) Touchstone files were preliminarily measured by VNA and saved.

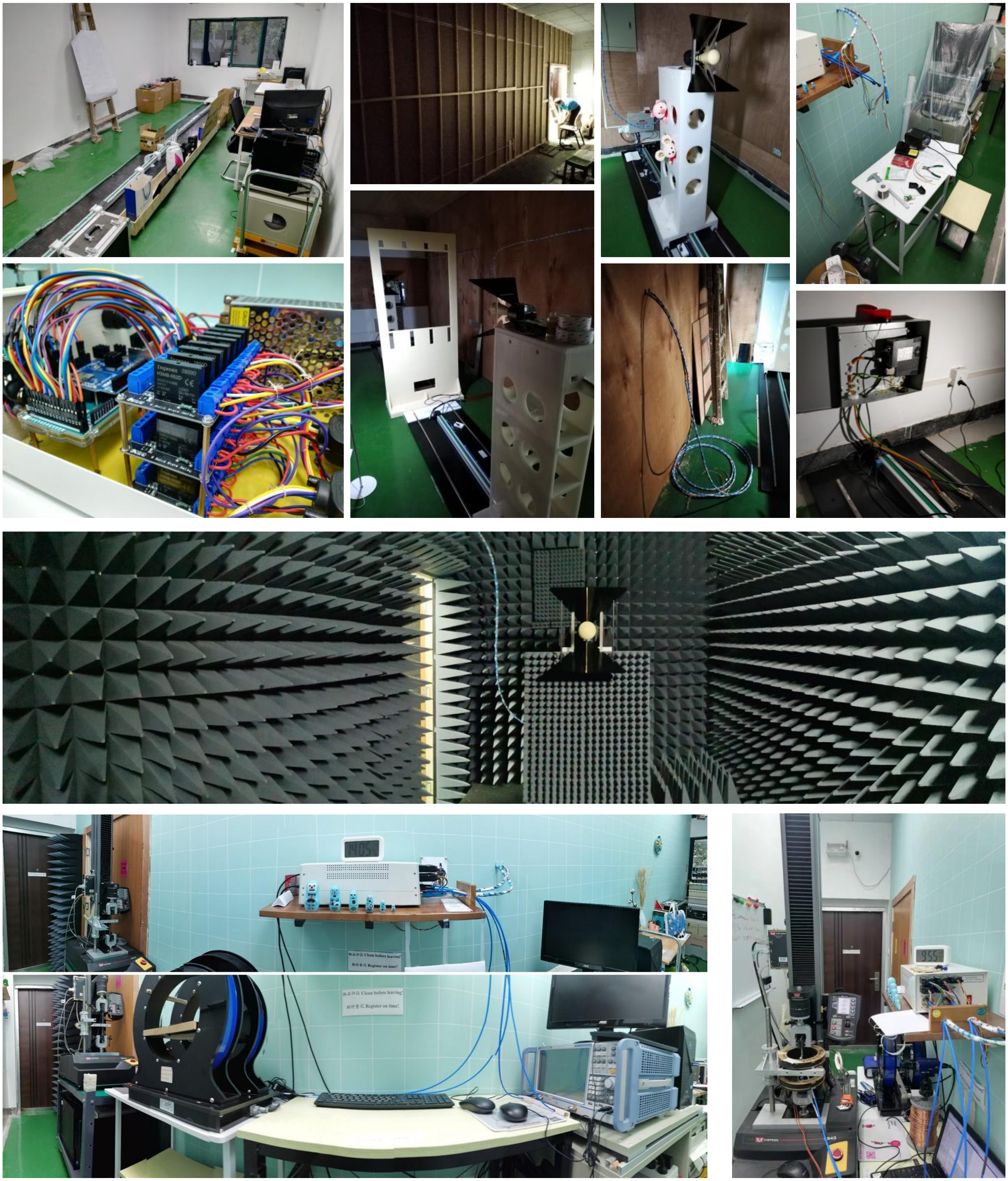

Fig. 5. Implementing the room partitioning for the bench and free space measurements.

Fig. 6. Self-made switching matrix.

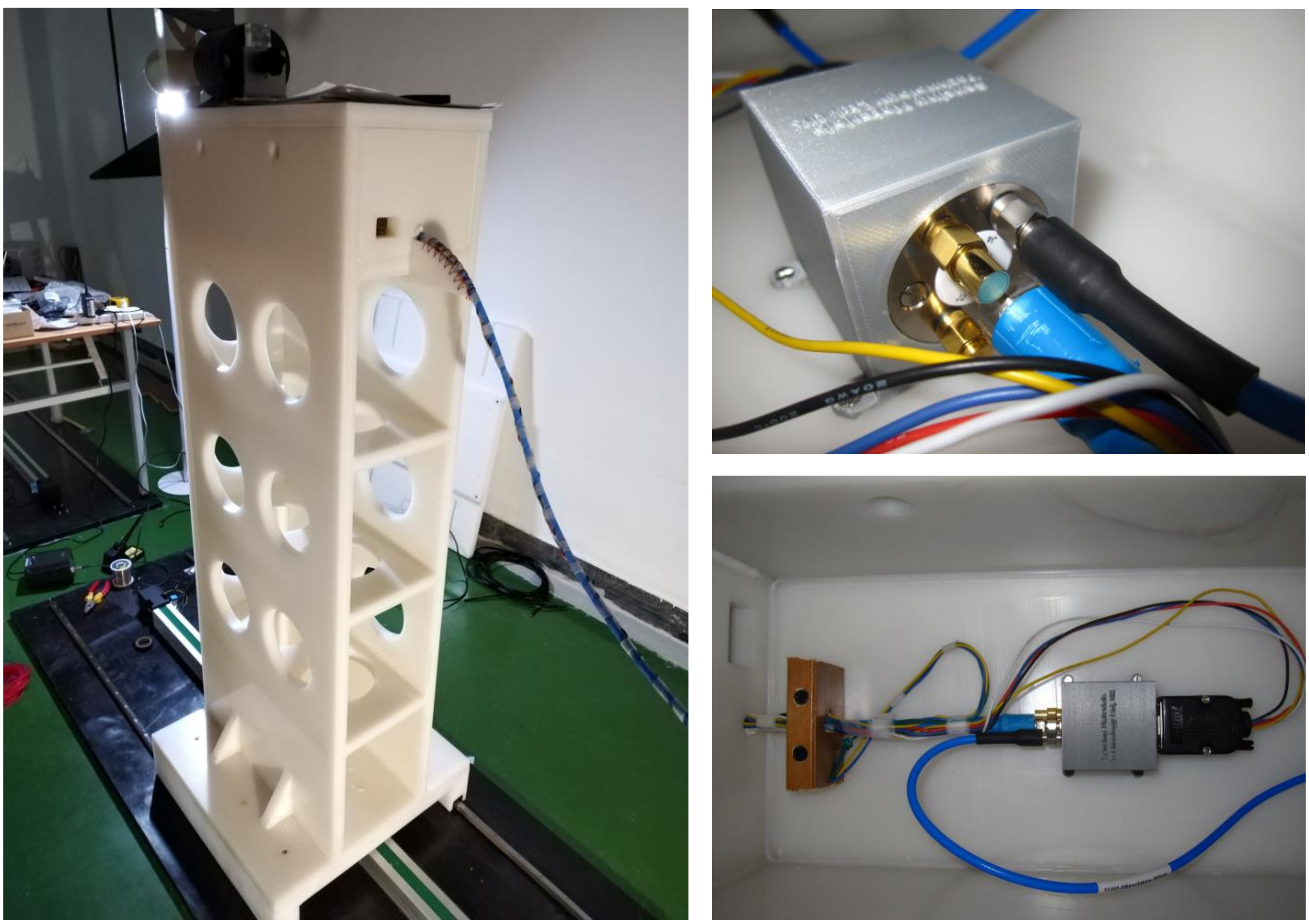

Fig. 7. Antenna pillars with SP4T microwave switches inside.

The calibration is carried out in three stages automatically. First, VNA and the cables connecting it to the switching matrix are calibrated using the SOLT coaxial terminations at the box front panel (see Fig. 6). After this calibration, the reference plane is shifted at the box front panel. The long antenna cables (6 meters) coming into the antenna pillars from the switching matrix are connected to the SP4T microwave switches, which, in addition to the output directly to the horn antenna, have three outputs terminated with the SOL standards. For them, unique S1P Touchstone files were preliminarily measured by VNA and saved. At the second stage, the already calibrated VNA measures signals in the long antenna cables reflected from the standard SOL terminations inside the antenna pillars. Using these three measurements and the 3-term error model, the complete S-parameter model of the cable can be created. After that, the long antenna cables can be virtually de-embedded. As a result, the reference plane will be transferred to the outputs of SP4T switches. The rest of the measurement track, including the short cables from SP4T to the horn antennas and free space between the antennas and the sample, is calibrated using the free space TRL or Response&Isoltation procedure. All three calibration stages are shown schematically in Fig. 8. At the calibration stage 3, it would be useful to minimize reflections from surrounding objects. For this, the walls, ceiling, and floor of the measurement chamber were covered with pyramidal RF absorbers. This work was done by a Chinese contractor.

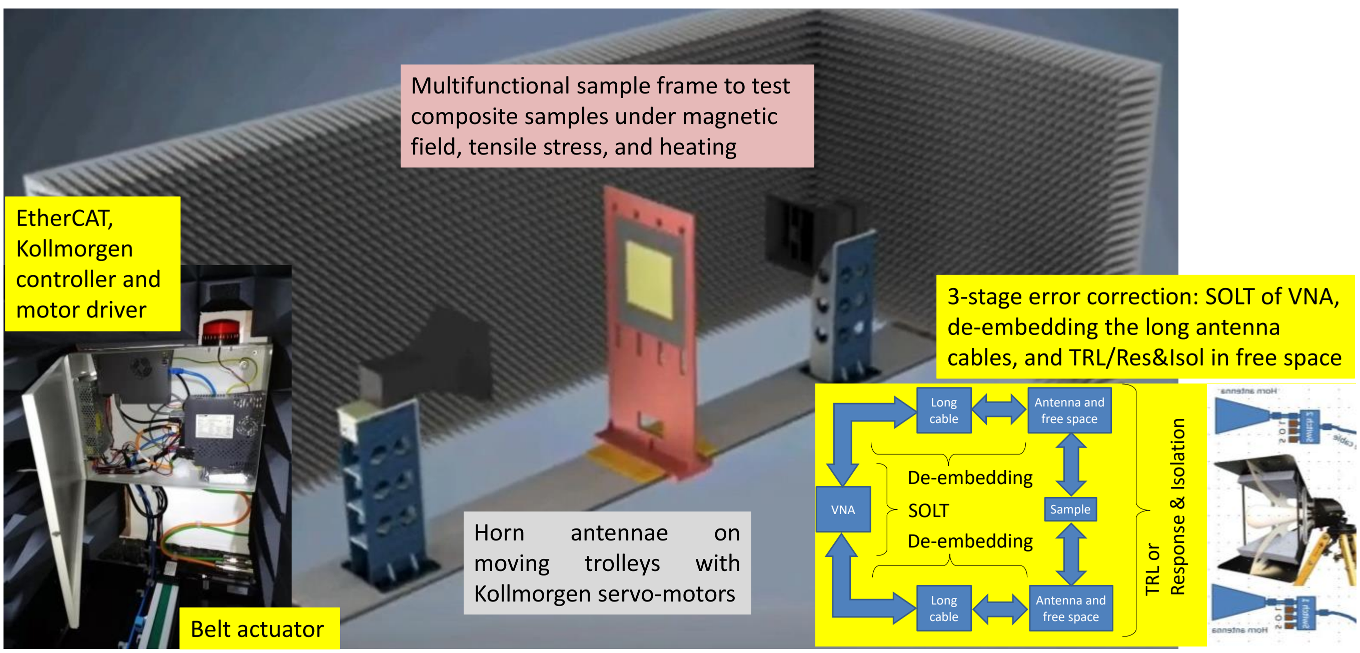

Fig. 8. The measurement anechoic chamber that provides the calibration stage 2 and 3, and then free space measurements of the sample under test placed into the frame.

For free space measurements, we chose the broadband horn antennas DE0518 from Diamond Engineering Inc (Canada).[18] The antennas are mounted on the pillars placed on the rail carts that are driven by the belt actuators [19] and the Kollmorgen's servo-motors and drivers.[20] At current stage, actuators are needed to accurately position the antennas during the TRL calibration. However, in the future, we plan to expand the range of experimental tasks by including measurements of wavefronts from horn antennas or other radiating surfaces (passive or active). The two possible measurement arrangements – material properties and wavefront measurements, are shown in Fig. 9.

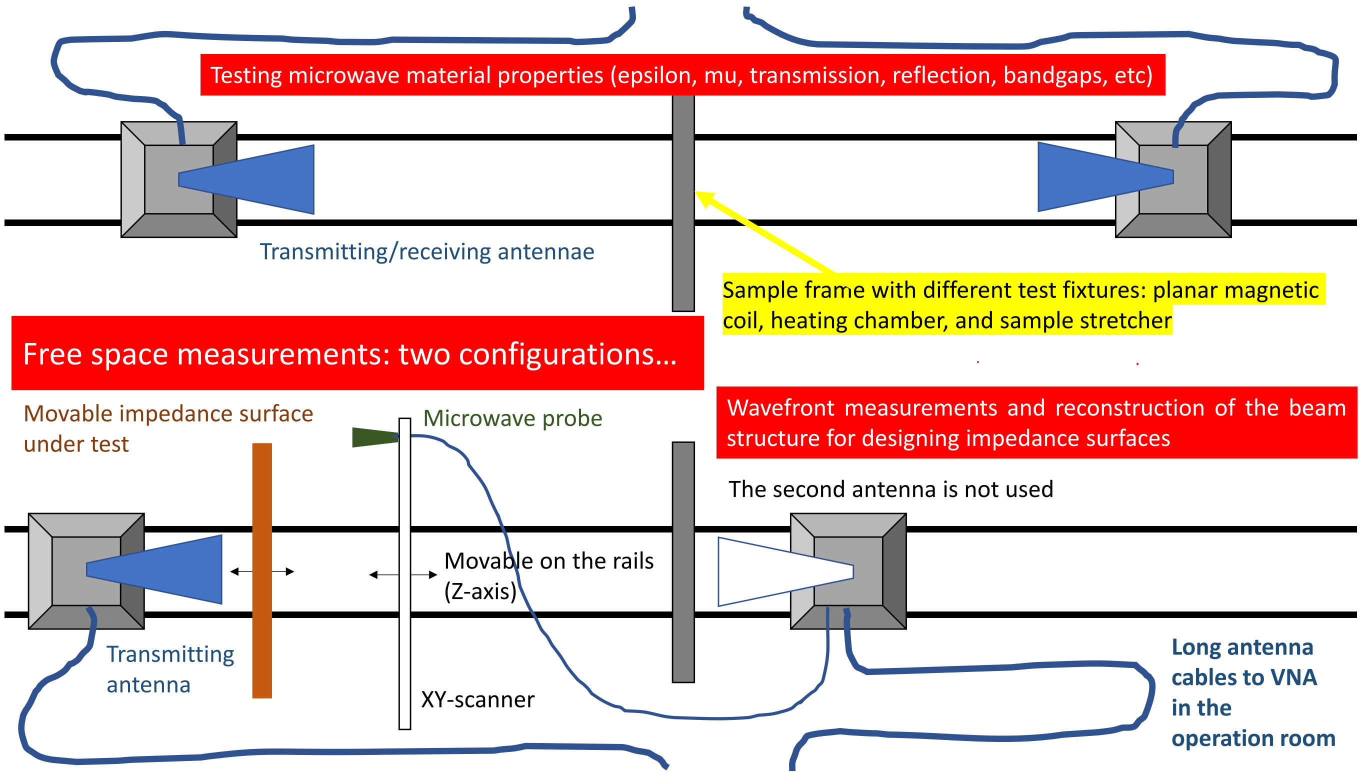

Fig. 9. Two possible measurement arrangements – material properties and wavefront measurements.

All mechanical components for the projects were designed at InCSI using a CAD drawing program. The most sophisticated component is the multifunctional sample frame, the drawing of which is shown in Fig. 10 (also see Fig. 8). It consists of two parts: base and window. The frame must not only keep the sample, but also provide external stimuli such as DC magnetic field, tensile stress, and heating. At the moment we have implemented only the magnetic field which is generated by a planar Helmholtz coil shown in Fig. 11. Later, the base will accommodate a stretching mechanism that provides tensile stress for the sample. The window keeps the sample and the planar magnetic coil. In the future a heating chamber can be placed there as well. Also, the window might accommodate a XY-scanner for measuring the wavefronts.

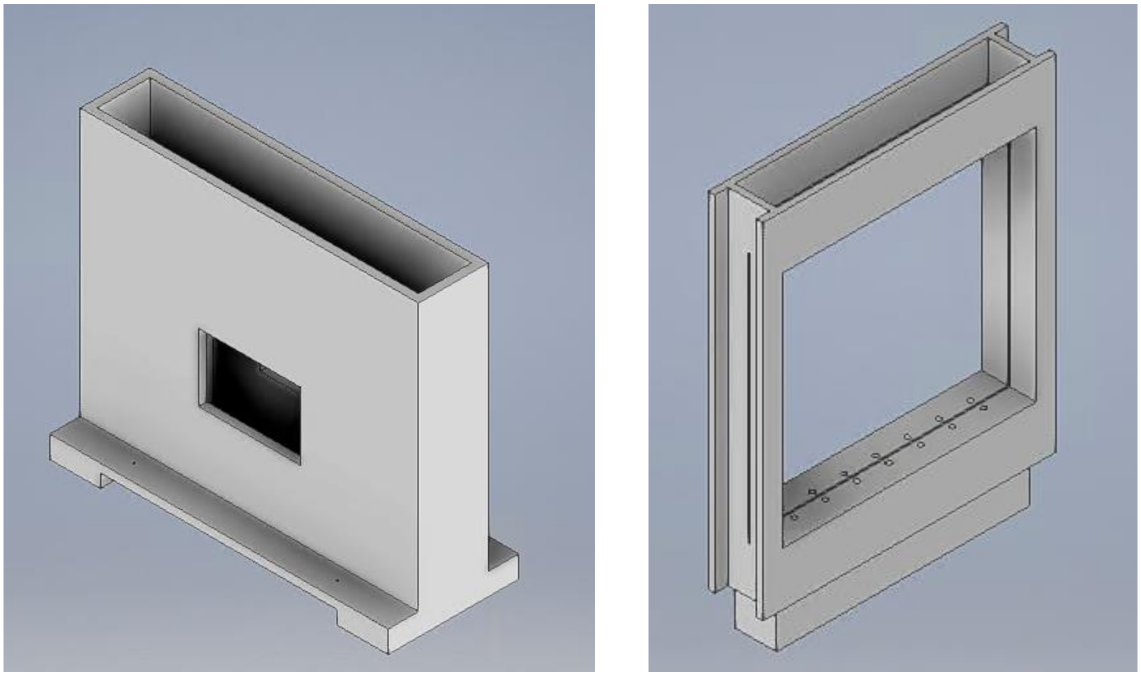

Fig. 10. The sample frame consisting of two parts: base and window.

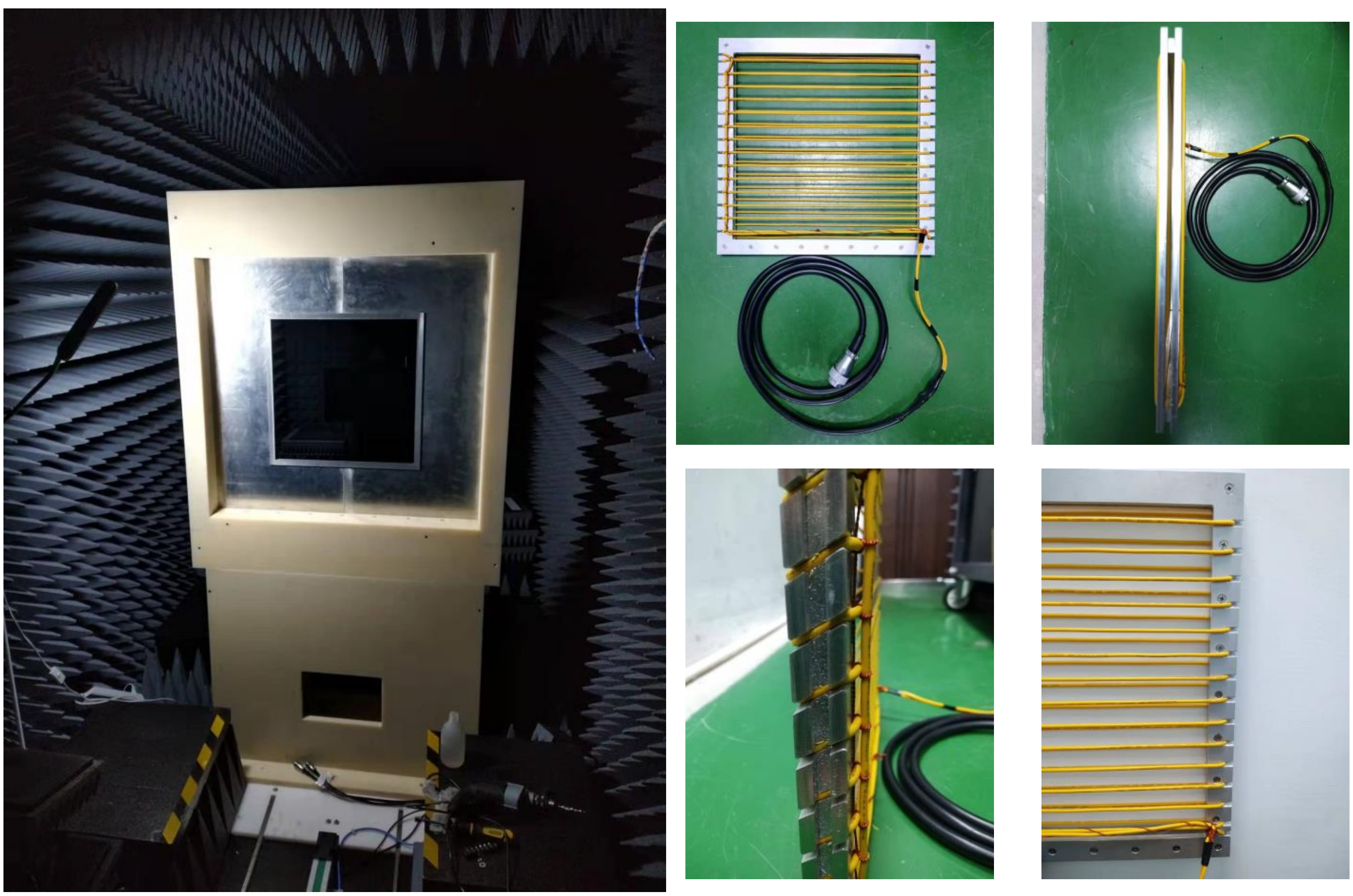

Fig. 11. Assembled sample frame (without absorber shell) and planar magnetic coil that is placed into the window together with a composite sample.

The whole measurement system, including the bench and free space measurements, is shown in Fig. 12 at the level of functional blocks. For automating free space measurements and controlling Kollmorgen's servo motors, we decided to use Python programming language together with Node-Red graphical user interfecase.[21] The use of the ideas of IoT (Internet of Things [22]) will allow raising automation to a new technological level, which is still rare for research laboratories. This becomes especially relevant in the time of COVID pandemic, when face-to-face collaborative ties have been disrupted. Industry leaders have already begun to respond to this challenge. For example, Keysight is actively developing remote access technologies for experimental laboratories. In Hangzhou, we have already implemented remote control using VNC server and viewer, which allow joint programming and measurements with researchers located on the other side of the globe.

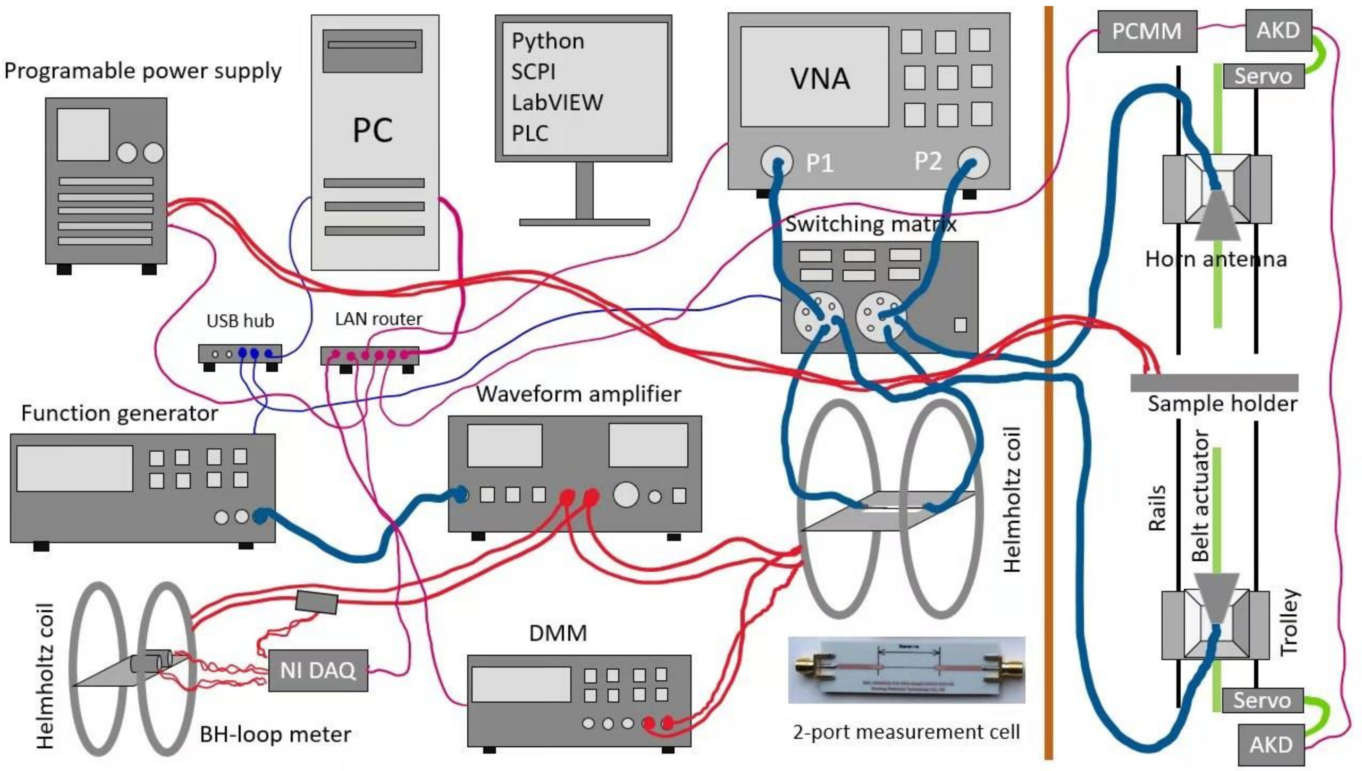

Fig. 12. The whole measurement system, including the bench and free space measurements.

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