A Portable Through-Wall Microwave Imaging System

Huseyin Aniktar

Sensor and Antenna Systems Group
Tubitak Bilgem, Gebze, Kocaeli P.O. 74, 41470, Turkey
huseyin.aniktar@tubitak.gov.tr

Abstract **─** A microwave imaging system requires the design and implementation of an imaging algorithm, a sufficiently sensitive/accurate vector network analyzer, and antennas. This work presents a simple imaging algorithm, design and implementation of a low-cost VNA and antennas that are able to operate at 4 - 6 GHz. The commercial VNAs are of general purpose and are too expensive for microwave imaging applications. The design trade-offs applied to VNA are presented and implemented circuits are demonstrated. Using the presented VNA, a hand-held imaging system is implemented that extracts scattering parameters to create the target image. S-parameters obtained from the pre-selected filters with the designed VNA are provided to demonstrate the quality of the design. Target images are created for a couple of commonly used walls to demonstrate the overall system performance.

Index Terms **─** Vector Network Analyzer, imaging and scattering, through-wall imaging.

I. INTRODUCTION

Microwave imaging systems have received more attention from researchers and engineers over the last decade. Especially, they have a frequent usage and importance in biomedical applications [1 - 4]. Typically, these systems collect the scattering parameters while the target object is illuminated with a microwave source. The scattering parameters are used to detect any disease signature and 2D/3D image creation. In the literature, different inversion algorithms are applied to the collected scattering data to create the target image [1 - 3, 7 - 9]. The hardware used to collect the scattering parameters must be able to differentiate the returning microwave energy when the target is available or not.

Another application area of the microwave imaging systems is in defense industry [5, 6]. Through-wall imaging utilizes the inverse-scattering techniques to create the image of the room. Nowadays, through-wall imaging technology is an important element of the counter-surveillance applications for most cities. The electromagnetic inverse-scattering approaches require the measurement capability of signal parameters like the magnitude and the phase. Most of the works presented in the literature use costly and heavy network analyzers to generate and receive microwave signals. In this work, a low-cost vector network analyzer (VNA) is designed and implemented for hand-held microwave imaging purpose. The implemented network analyzer is low cost, low power, light, and compact. The network analyzer has moderate performance according to its size, cost, and power consumption.

Microwave imaging has lots of application areas. Some of them are briefed as follows. A microwave imaging system with a portable and low-cost form might be a good option for these applications:

- Medical imaging for seeking diagnoses.
- Civil engineering purposes for examining deterioration and strength of structures.
- Security reasons for seeking bug, weapon and any other objects.

The paper is organized as follows: Part 1 is the introduction. Part 2 is the system description which explains the microwave imaging main ideas. Part 3 gives the VNA implementation steps and procedure. Part 4 gives the measurement results for both as a point of VNA and as a point of microwave imaging system. In Part 4 VNA performance is also compared to a COTS product to show the system performance level. The last part concludes the paper.

II. MICROWAVE IMAGING SYSTEM DESCRIPTION

The implemented microwave imaging system is presented in this section. The block diagram of the imaging system is given in Fig. 1. As shown in Fig. 1, the system consists of an antenna, RF/microwave circuit optimized for system specifications, digitizer, DSP (Digital Signal Processing) unit, and the main CPU (Central Processing Unit) to run the user imaging application. RF/Microwave circuit, digitizer, and DSP processing blocks constitute the main elements of a Vector Network Analyzer. The implementation detail of VNA is introduced in the next chapter.

The fundamental idea of microwave imaging systems is based on the measurement of reflected

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electromagnetic energy from the target. The simplest scenario occurs when the target is placed in the same environment with the antenna without any obstacles between them. An amount of electromagnetic energy is absorbed by the target object and the rest is reflected back to the antenna.

The system will capture the returning energy to measure the inverse-scattering parameters in order to create the image. The system must be able to capture the differentiation at the inverse-scattering parameters when an object is placed in front of the antenna. When the antenna is placed over (X, Y) axes and electromagnetic energy flows through Z axis. Assume that the target object is placed at Z axis with a distance of 'z' from the antenna. g(z) is defined as scattering function for the points reflecting electromagnetic energy back to the antenna. The reflected electromagnetic field expression is written when we assume that the phase differentiation happens only at Z axis,

$$G(f) = \int_{-\infty}^{\infty} g(z) e^{-j2kz}\, dz\,, \qquad (1)$$

where G(f) is the reflected electromagnetic field expression, and k is the wave number. In order to pass from frequency domain to space domain the expression given in (2) is used,

$$g(z) = \int_{-\infty}^{\infty} G(f) e^{-j2\pi fz}\, df\,. \qquad (2)$$

It is easily seen that g(z) and G(f) constitute the Fourier Transformation pair. Therefore, the object image, g(z), is formed by applying Inverse Fourier Transformation to the reflected electromagnetic field expression of G(f) [8].

However, a target object is nearby to some other objects or in a different environment than the antenna in most of the applications in real world. In these cases, the clutter coming from unwanted objects or environment must be removed from the analysis as much as possible in order to obtain a meaningful image.

An example application is the through-wall imaging (TWI) [6 - 8]. In this kind of problems, the wall is between the target and antenna. The reflection from wall must be subtracted to measure the inverse scattering parameters reflected back from the target object. Therefore, the clutter reduction techniques must be applied to remove wall effect from the measurements [8].

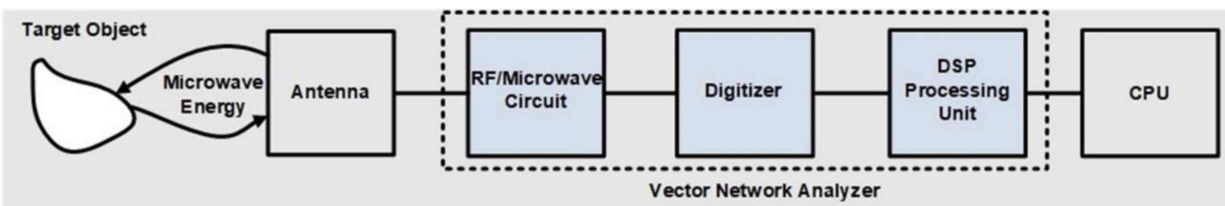


Fig. 1. The block diagram of implemented microwave imaging system.

III. VECTOR NETWORK ANALYZER IMPLEMENTATION

A network analyzer is a measurement equipment used to characterize a circuit (DUT- device under test) behavior. It draws out the transfer function of the DUT according to the known input signal and extracts the vector scattering parameters such as the complex reflection and the transmission coefficients.

Network analyzers might be considered in three categories. Scalar Network Analyzer (SNA) is a network analyzer that just characterizes the amplitude response of DUT. Vector Network Analyzer (VNA) characterizes both the amplitude and the phase response of DUT and extracts S-parameters. Vector Network Analyzers may be constructed incoherent or noncoherent fashion [12]. Recently, coherent VNA architectures are the most commonly used in measurement equipment since they provide larger measurement dynamic range, lower noise floor and ease of control. Coherent VNA's require tuned RF receiver/transmitter circuits and they require highly stable Phase Locked Loops to maintain the coherency. Noncoherent VNA designs are cheaper and simpler alternatives to expensive and complex coherent VNAs. Noncoherent VNAs consist of a kind of a Scalar Network Analyzer and some additional blocks to extract the vectorial information. Some examples for the noncoherent vector network analyzers are given in [10 - 13]. The third group is Large Signal Network Analyzers (LSNA) and they characterize the large signal behavior of DUT like linearity, harmonics, etc.

This work presents the implementation details of a coherent vector network analyzer to be used in a microwave imaging system. The description for the complete microwave imaging system is also provided.

A. Implementation details of VNA

The fundamental assessment of VNA lies on the sensitivity for the extraction of frequency response of a DUT. In order to achieve this, the system generates a signal at the target operating frequency and sends to DUT. Some of the electromagnetic energy is reflected back to the antenna and the system must be able to capture it. VNA has separate signal paths for the reference and the measurement channel. By utilizing the reference and the measurement channel signals, the phase and the magnitude responses of DUT are going to be calculated. This chapter presents the design of a miniature sized VNA and the design trade-offs.

VNA is commonly used as a laboratory measurement system. These systems are quite costly, heavy and it is almost impossible to utilize it in a portable system. There are different techniques to design low cost, miniature sized VNA in the literature. The operating frequency of VNA is one of the most important design parameters similar to other RF systems. As the operating frequency increases, the behavior of circuit/ system components changes and VNA performance starts to deviate from the design specifications. Therefore, at higher frequencies, the error of VNA starts to increase as well. For very high frequency applications, highly sensitive circuits and components must be used to bound the generated error. The most important design specification for VNA is the phase synchronization of a system at the operating frequency band. In order to satisfy this requirement, RF signal sources and the reference clock source for the digitizer must be common for the measurement and the reference channel. Another important design hint for the phase synchronized VNA design is the signal path equalization of the reference and measurement channel.

Each component in reference or measurement channel has its own phase and magnitude response. It is a good design practice to balance the circuit path for measurement and reference channel to reduce the mismatch between reference and measurement channels. The layout of the RF and the digitizer circuits is another important design concern since the path equalization is a critical requirement for the accuracy of phase and magnitude measurement. Wire lengths and properties are equalized for respective parts on the measurement and reference channels. It compensates the distortions generated by the circuit layout. The most challenging issue when to balance the reference and measurement channel is the input power levels that flow on each channel. The power level for the reference channel is a lot higher than the measurement channel. When the same circuit component is used on both channels, it puts a limit on the dynamic range of VNA. Still, it is impossible to get rid of all unbalances between the reference and measurement channel. The calibration procedure will be implemented to remove the residual errors on the measurements.

VNA is composed of four main blocks namely RF signal source, downconverter block, digitizer, and DSP block as shown in Figs. 2 and 3. Figure 2 shows S11 configuration of VNA, and Fig. 3 shows S21 configuration of VNA. Details of the DSP block are illustrated in Fig. 5. The first block is RF signal source and it generates the RF signal at a given frequency. RF signal is sent to target object by means of an antenna. Simultaneously, the generated RF signal is fed to the reference signal channel by utilizing a coupler. The critical design metric for the coupler is the RF isolation between the reference and the measurement channels. For the ideal VNA design, none of the reflected signals should be available on the reference channel and vice versa. On the other hand, in practical VNA systems, the reflected electromagnetic signal enters to the reference channel as well and it degrades the accuracy and the sensitivity of these systems. The reflected electromagnetic signal is fed to the measurement channel by use of a coupler. The sent and the received RF signals must be down converted to an IF frequency in order to get digitized.

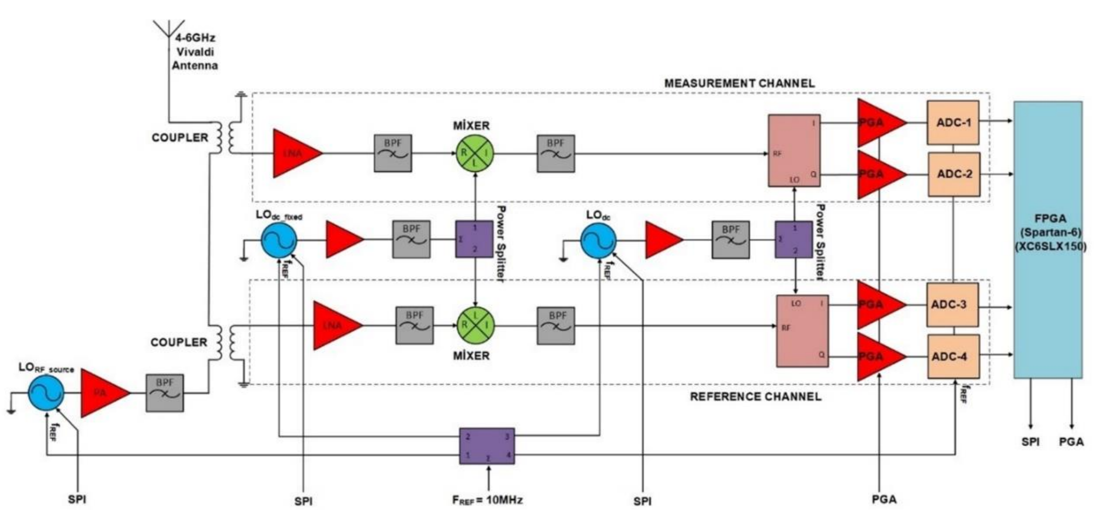


Fig. 2. Block diagram of implemented VNA as S11 configuration for imaging purpose.

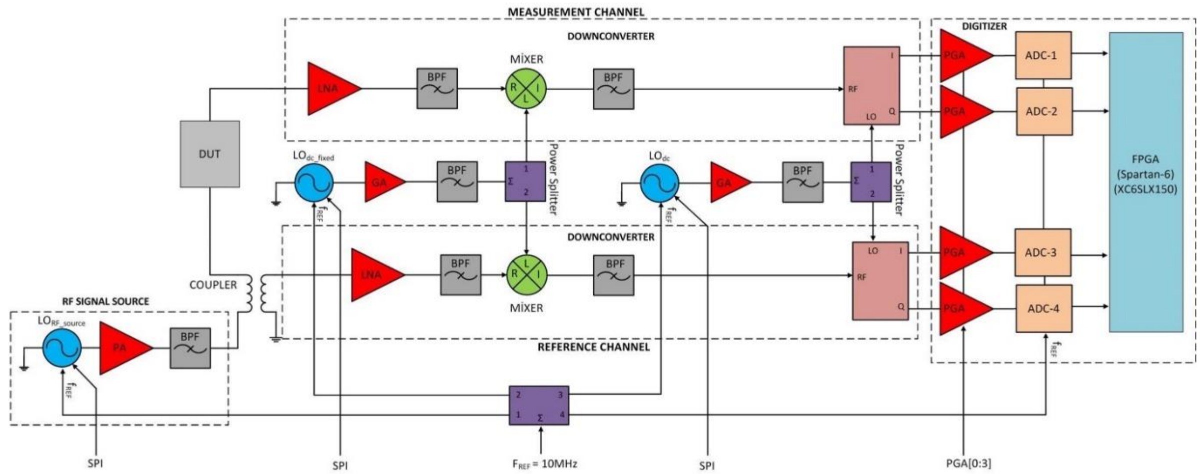


Fig. 3. Block diagram of implemented VNA as S21 configuration for component test.

The second part of the VNA system is the downconverter block. The RF signals on the measurement and reference channel must be down converted to an IF signal that can be properly digitized by an available ADC. In order to prevent any phase mismatch between the reference and magnitude channel, the same local oscillator (LO) outputs must be fed to the mixer stage with the symmetrically designed layout. Homodyne and heterodyne are two design options for the downconverter implementations. We designed two stages heterodyne downconverter scheme. It allows us to use an I/Q demodulator to generate quadrature signals as presented in Fig. 2. Heterodyne downconverter allows us to increase the operating bandwidth of the design. The photography of the implemented circuit blocks is given in Fig. 4. The coupler is used as COTS product from Lynx Components. It is a 10 dB coupler from 2 GHz to 8 GHz with around 40 dB isolation.

Fig. 4. Photography of the circuit blocks. (Downconverter, RF signal source, and FPGA block).

The digitizer is the third block of the VNA system, and its task is to convert the analog signals coming from I and Q paths on the reference and the measurement channel. Therefore, four ADC channels are required, and they must be simultaneously sampled channels. The digitizer is based on FPGA block and ADC unit. FPGA block is used as COTS product from Opal Kelly. This FPGA block is on our implemented four channel ADC mezzanine board. The most critical issue with this block is the successful implementation of phase synchronized design. The sampling clock for each ADC must be synchronous with each other. Otherwise, the measured phase and magnitudes include a large amount of error. In order to alleviate this design constraint, a quad 14-bit ADC chip with a single encode clock (Linear Technology LTC 2171) is utilized. The encode clock is fed to PLL block to generate the sampling clock and it is distributed to all ADC cores within the same IC. The digitized outputs are in serial LVDS (Low Voltage Differential Signaling) format and deserialization is implemented by the FPGA core. The serial LVDS output format is used to reduce the pin count needed to capture ADC data by FPGA core since there are 4 ADC cores in the system. The digitized data from four channels will be used to calculate the phase and the magnitude of each signal at the reference and measurement channels. It will be discussed in the digital signal processing part.

The last element of VNA is the Digital Signal Processing block. This block performs the data capture, and the arithmetic calculations implemented within FPGA fabric. The quad ADC outputs are converted to parallel data format by SerDes (Serializer/Deserializer) using the common frame and data bit clocks. This common clocking scheme ensures the phase coherency at the digitizer part. The applied arithmetic operations are given in Fig. 5. Phase Comparator operator shown in Fig. 5 is used to project all phase results to a defined range of [-π, π] as defined in (3):

$$\begin{matrix} \text{phase}=\text{phase} \ ,\pi>phase>-\pi \\ \text{phase}=\text{phase}-2\pi \ ,\text{phase}>\pi \\ \text{phase}=\text{phase}+2\pi \ ,\text{phase}<-\pi \end{matrix} . \tag{3}$$

The phase and magnitude calculations are averaged over 128 measurement samples to reduce erroneous measurements as shown in Fig. 5. The averaging method fails to provide the accurate results when the phase result approaches to limits namely {-π, π} since calculated phase values may cancel each other. In order to prevent this possibility, Phase Corrector operator is used. The operation of this block is defined in (4). Phase [0] is the first element of 128 measured phase results. In this way, the phase calculations at the limits are successfully implemented:

$$\begin{matrix} \text{phase}=-\text{abs}(\text{phase}), -170^{o}>phase[0]>-180^{o} \\ \text{phase}=\text{abs}(\text{phase}), 180^{o}>phase[0]>170^{o} \end{matrix}, \quad (4)$$

Thru calibration is handled to extract the innate phase and magnitude calibration parameters to cancel the effect imposed from VNA hardware. The S parameters are obtained after canceling out the thru calibration parameters as shown in Fig. 5.

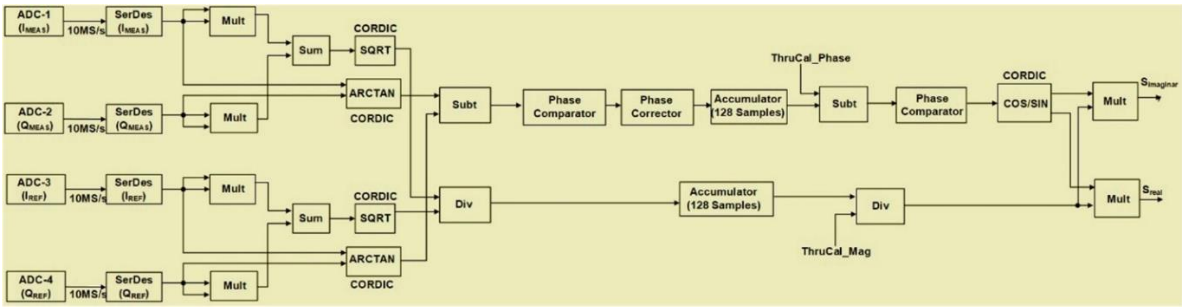


Fig. 5. Block diagram of DSP data path for S-parameter measurements.

Another important design metric of VNA is the sensitivity. The sensitivity of the system is determined by the noise figure, IF bandwidth and the sensitivity of the down converter and ADC bit width. The circuit sensitivity is calculated as follows:

Sensitivity = -174dBm + NF + SNR + 10log (BW), (5)

where SNR is the signal-to-noise ratio, and NF is the circuit noise figure in dB, BW is in Hz.

IF bandwidth is 100 kHz and operating frequency band is 4 - 6 GHz. The measured dissipated power is 19.424 W when the system is fully functional. The power dissipation map for each voltage source and circuit block is given in Table 1. The performance values handled on the VNA are listed in Table 2.

For SNR value of 10 dB, NF value of 14 dB and IF bandwidth of 100 kHz, the system sensitivity is estimated approximately as -100 dBm.

Table 1: Power map for each voltage source

Voltage Source (V)	RF Circuit (mA)	Digitizer & FPGA (mA)	10 MHz Clock (mA)	Total Power (W)
1.8	-	200	-	0.36
3.3	288	-	910	3.95
5	634	1728	-	11.81
12	275	-	-	3.3

Table 2: Implemented VNA specifications

Frequency (GHz)	IF BW (kHz)	Resolution (MHz)	NF (dB)	User Interface
4 - 6	100	1	14	USB

B. 4 - 6 GHz Vivaldi antenna

The Vivaldi antennas are traveling wave antennas having UWB (ultra-wideband) impedance matching and endfire radiation characteristics. The biggest advantage provided by the microstrip structure is its ability to be connected directly with the TR (Transmission-Receiver) modules placed behind it. The antenna needs no additional component for impedance matching with its integrated balun structure. This type of antenna is more suitable for imaging applications since its electrical characteristics [14, 15].

The antenna used for microwave imaging application is 4 - 6 GHz Vivaldi antenna. In the design and optimization of the antenna, numerical studies are carried on by using Computer Simulation Technologies Microwave Studio (CST MWS) which is mathematically based on Finite Integration Technique (FIT) [16]. It is very beneficial methodology to solve geometrically and structurally complex electromagnetic problems. In FIT, integral form of Maxwell's equations are discretely reformulated and then they become more suitable for computer calculations both in frequency and time domain analyses. The calculation domain is chosen in the beginning of the simulations and a proper meshing algorithm is applied on the geometry to split it several small grid cells. These cells should be dense enough to represent the curves and inclines very accurately. However, resource requirements are linearly increasing with the numbers of mesh nodes and problem size. A real-world electromagnetic problem usually includes more than one medium such as metallic surfaces and dielectric substrates. FIT allows to analyze a grid cell including two different materials which provides sparser mesh. Hence, electrically large structures can be simulated with minimum computational cost. User interface of CST MWS offers time and frequency domain solvers. The number of the simulation runs are proportional to the field monitors having discrete frequencies in frequency domain solver. In this study, time domain solver is used because it has ability to define and calculate a large number of filed monitors for the whole operating frequency band in one simulation run. FR-4 material is employed as substrate and its' specifications are used as in material library of CST MWS. The metallic parts of the antenna are assigned as perfect electric conductor (PEC). The antenna is meshed by using hexahedral mesh type resulting in approximately 5 million grid cells. Antenna port impedance is chosen as 50 Ω and it is excited by a Gaussian pulse which is default excitation waveform of CST MWS. The simulation is terminated when remaining energy in calculation domain reaches 40 dB less than of its' maximum value.

The photography and radiation pattern of the designed antenna is given in Figs. 6 and 7. Far-field gain of the antenna is measured as 5.8 dBi and 6 dBi at 4 GHz and 6 GHz respectively. S11 measurement results are -14.57 dB at 4 GHz and -18.75 dB at 6 GHz. The size of the antenna is 42 mm x 82 mm.

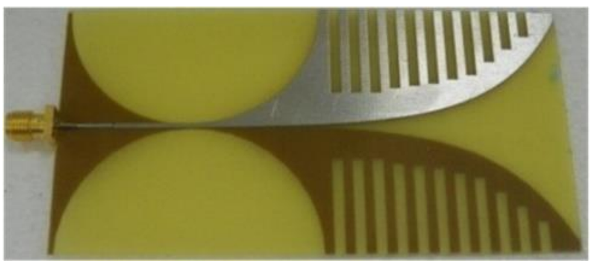


Fig. 6. 4 - 6 GHz Vivaldi antenna photography.

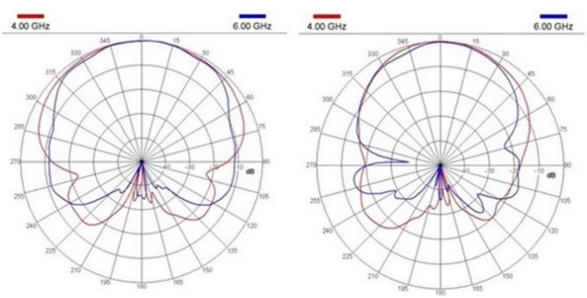


Fig. 7. Azimuth and elevation radiation patterns.

C. Calibration

One port calibration (Short, Open, Load) SOL method is applied to measure the errors and calibrate the VNA measurement system [10]. Scattering parameters are all about power; both reflected and the incident in a linear two-port system. It assumes that the system must be treated like a transmission line system. At first, the VNA system assumes that there is no measurement error and then short, open and load calibration kit measured respectively. The reference and the measurement channels are saved simultaneously. The phase coherencies of both channels are important for exact calibration. The magnitude and the phase errors between the reference and measurement channels are calculated. In the end, the correction factors are used to calculate the S parameters of DUT.

IV. MEASUREMENTS

In this section, S11-S21 magnitude and phase measurements with our low-cost miniature VNA and Agilent E8362C network analyzer are compared. The low-cost VNA is also used in the application of through-wall imaging system. Imaging system performance is also illustrated in this section.

A. S-parameter measurements

The low-cost miniature VNA performance is compared with Agilent E8362C VNA network analyzer as a reference. For comparison purpose, a bandpass filter is selected as a sample circuit namely Lorch 5000 (center frequency is 5 GHz and passband is 1.1 GHz, from Lorch Comp.). The filter response is measured with the Agilent VNA and the implemented low-cost VNA system. 2001 data points are collected between 4 - 6 GHz and the results are provided in Figs. 8 and 9. Magnitude and phase measurements of S11 and S21 with COTS and implemented VNA are reasonably close to each other.

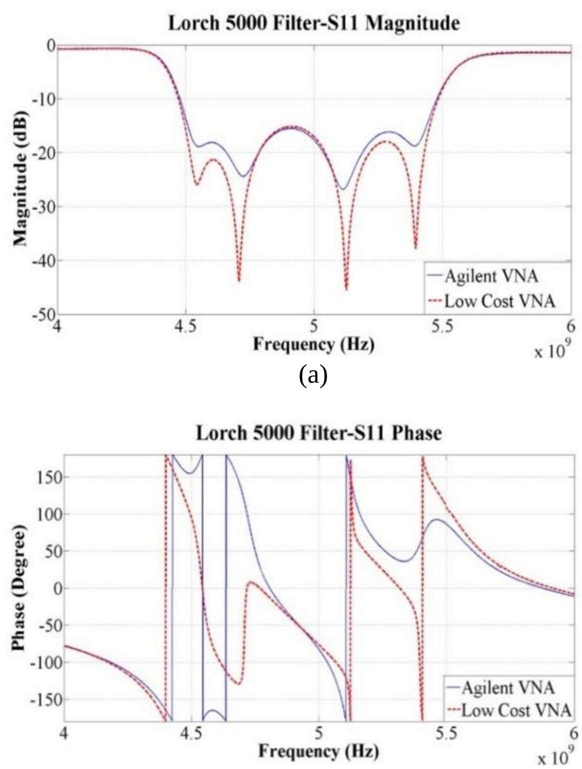
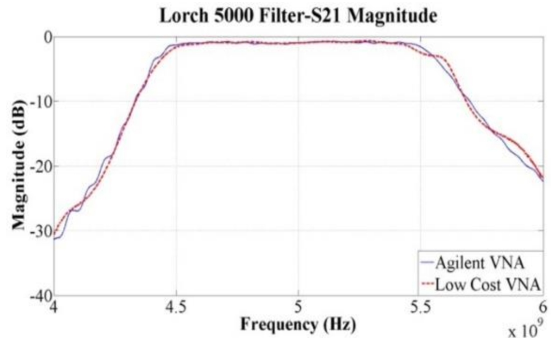
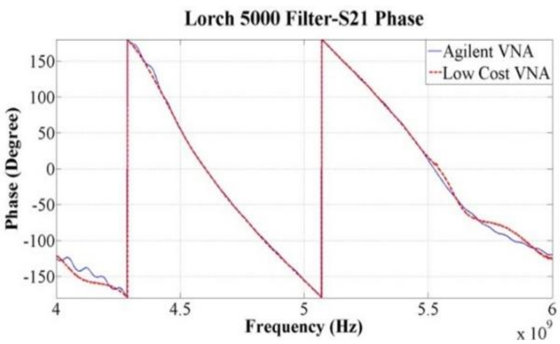


Fig. 8. Magnitude (a) and phase (b) measurements of S11 for Lorch 5000 filter.



(a)



(b)

Fig. 9. Magnitude (a) and phase (b) measurement of S21 for Lorch 5000 filter.

B. Through-wall imaging measurements

Through-wall imaging (TWI) is targeting to illustrate the physical position and the orientation of objects behind the wall. As aforementioned, it is possible to create such an image by measuring dielectric properties of objects sitting another side of the wall. The differentiation of these properties makes it possible to create a snapshot of the target region. The system must be able to send high-frequency electromagnetic waves to the wall and measure the returning waves. The S-parameter measurement setup given in Fig. 1 used along with the DSP algorithm given in Fig. 5 is realized. The antenna is shown in Fig. 6 is used in the system.

In this work, S11 radar imaging method is implemented based on IFFT which is expressed in (1) and (2). Imaging antenna is moved on (X, Y) coordinates with 2 cm steps to cover 50 cm x 50 cm scanning region. The designed VNA scans from 4 GHz to 6 GHz with 1MHz steps and measures the S11-parameter at each (X, Y) point and this data converted to space domain by applying (2). This is basically a "Step Frequency Continuous Wave Radar" application. VNA system collects 2001 frequency data for each (X, Y) coordinate with 2 GHz bandwidth and 1 MHz step size. 4 - 6 GHz operating frequency selection is based on penetration depths on wall and resolution. When the frequency is lower, the penetration capability is better. On the other hand, when the frequency is higher, target resolution is better. There is a tradeoff. Bandwidth is also another important parameter for range resolution which is inversely proportional.

S11 measurements are taken at 625 points with 25 x 25 coordinate points. At each point reflected electromagnetic energy (G(f)) is measured on z-direction. For each (X, Y) coordinates, an image is composed based on reflected energy. Image resolution is improved by using bicubic interpolation.

The wall has a 5 cm thickness and 3 different objects are placed behind the wall. Measurement test setup and the prototype of the portable microwave imaging system are illustrated in Fig. 10. Red object is 4 x 50 x 4 cm^3 iron pipe, the yellow object is 4.5 x 4.5 cm^2 aluminum plate, and the gray object is 6 x 6 cm^2 printed circuit board. The covered region is 50 cm x 50 cm and the spacing resolution is 2 cm. 25 x 25 measurements are taken. S11 measurements are taken at 625 points.

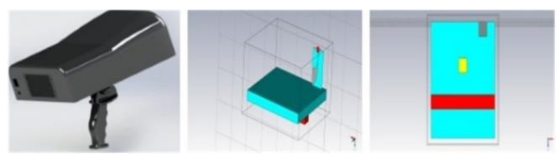


Fig. 10. Prototype of the imaging system and test setups illustrated in CST Microwave Studio.

The S parameter measurement results are fed to host PC with USB 2.0 connectivity to capture results and generate the image of the target region. In order to generate the image of the target region, the position information of the antenna is required and it is measured with a laser sensor that is connected to the sensor head. The measured S-parameters and calibration data are fed to the imaging algorithm based on IFFT [7]. The user must provide the frequency range and the frequency resolution information to FPGA and the final S-parameter results are fed back to the host user. The obtained S-parameter values are fed to final image creation algorithm. The outputs of IFFT are used to create the image of the target object using position information coming from laser sensors. Laser sensors are connected to the host PC with a RS232 interface.

In the development of the imaging algorithm, CST MWS is used to simulate the test environment. Time domain solver is also employed during these simulations and accuracy level is chosen as -40 dB with approximately 150 million meshes. The target objects and the test environment are modeled for the electromagnetic simulation to get accurate results to compare the actual result with the simulations. The S-parameters collected from the electromagnetic simulation is applied to image creation algorithm to create the images. In this way, the algorithm development becomes faster and easier. The image creation algorithm is optimized by using this method.

The image created from real data with portable microwave imaging system and the EM simulation data are illustrated in Figs. 11 and 12. The results are quite similar, and it shows that the model parameters for the environment and the target objects are properly set.

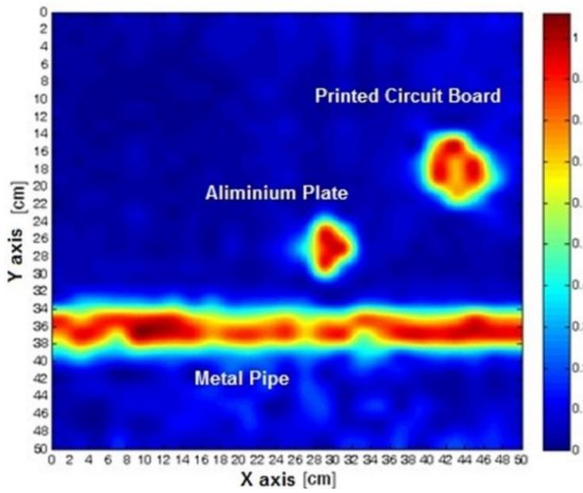


Fig. 11. Created image with portable imaging system.

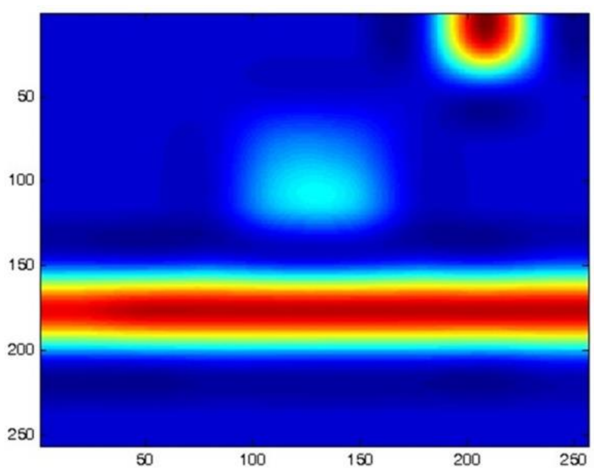


Fig. 12. Simulated image on CST MWS.

The same measurement setup is used to create the image of the object at different depth behind a wall made of different materials. In this way, it is possible to draw a relation between wall materials and wall thickness. The target object is a 5 cm x 5 cm metal plaque and the wood is the worst wall that can be imaged. In Table 3, through-wall imaging measurement results are given for different materials and depths. TWI radar has the capability to detect any objects through the wall based on dielectric contrast from the surrounding medium. The reflected signal depends on the size of the object and wavelength.

Table 3: Imaging performances for different walls

Smooth Plane Material	Target Object	Depth (cm)	Target Object Resolution
YTONG	Metal	10	5cm x 5cm
MARBLE	Metal	12	5cm x 5cm
WOOD	Metal	4	5cm x 5cm

V. CONCLUSION

In this work, a portable network analyzer, antenna and imaging algorithm design and implementations are presented. A low-cost portable VNA implementation is described step by step. Implemented network analyzer is capable to measure the S-parameters with a sufficient accuracy. The implemented microwave imaging system is capable of creating images of objects behind the wall with a simple IFFT imaging algorithm. Even high performances in harsh environments will be possible by employing more sophisticated algorithms.

Implemented portable VNA size is approximately 20cm x 30cm x 11cm, the weight is about 2kg, and the cost is less than 1500 dollars.

Portable imaging systems are good candidates for using on the investigation of infrastructure, wall and building strengths. It is also capable of using for medical imaging and electronic intelligence purpose.

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Huseyin Aniktar Ph.D. was born in Istanbul, Turkey, in 1977. He received the B.Sc. degree in Electronics Engineering from the Istanbul Technical University, in 1998, and the M.Sc. degree in Electrical and Electronics Engineering from Middle East Technical University, Ankara, in 2001 and Ph.D. degree in electronics engineering from the Aalborg University, Denmark, in 2007. His main areas of research interest are RF and microwave circuits and systems.