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Wireless Power Transfer Test Bed for Rectenna Characterization

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14. ABSTRACT

A rectifying antenna – commonly referred to as a rectenna – converts the AC current induced by incident electromagnetic (EM) waves into DC current. Rectennas are increasing in utilization primarily because of their application to wireless power transmission. To understand and characterize the performance of a rectenna, we illuminate it in the far field using EM waves at radio frequencies (RF) and measure its output with an instrument capable of measuring the rectified voltage. The far field of an antenna is generally understood to start at a distance of 2D2/λ where D is the largest physical linear dimension of the antenna and λ is the wavelength of the incident EM. This region allows for a flat magnitude and phase across the antenna aperture. These requirements made the modification of our small anechoic chamber ideal as an RF source, positioning equipment, and acquisition software were already in place. However, the challenge was to measure the resultant DC voltage at each aspect angle as a function of the power density incident on the rectenna under test (RUT).

15. SUBJECT TERMS

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WIRELESS POWER TRANSFER TEST BED FOR RECTENNA CHARACTERIZATION

1. INTRODUCTION

This report details the modification of the small anechoic chamber in the Code 5317 Antenna/RCS Measurement Facility for the measurement of rectifying antennas, which the NRL Radar Division has been recently designing. A rectifying antenna – commonly referred to as a rectenna – converts the AC current induced by incident electromagnetic (EM) waves into DC current, making them a critical component of wireless power beaming systems.

To characterize a rectenna's performance, it is illuminated by an EM wave of known power density while the output DC voltage is measured. These measurements are often performed in the far field, where the wavefront incident upon rectenna aperture can be approximated as an ideal plane wave. These requirements are similar to those of basic antenna pattern measurements, except that a DC voltage would be recorded instead of complex field values.

So, a modification of our small anechoic chamber was an ideal approach to the measurements, as the chamber already included an RF source, positioning equipment, and data acquisition software. However, the challenge would be to measure the resultant DC voltage at each aspect angle as a function of the power density incident on the rectenna under test (RUT).

The resulting modification to the current capabilities of the small anechoic chamber is called the "Wireless Power Transfer Test Bed for Rectenna Characterization." This report will not focus on the rectenna itself. Instead, it will concentrate on new measurement capabilities by outlining the modification of existing electronics and acquisition software to support rectenna measurements.

2. MEASUREMENT SETUP

2.1 Existing Hardware and Software

The small anechoic chamber in the Naval Research Laboratory Radar Division's Code 5317 Antenna/RCS Measurement Facility is a 20'(h) x 20' (w) x 30' (l) room lined with 12" pyramidal absorber. It is a multi-purpose range used for antenna patterns, impedance measurements, electromagnetic interference studies, and a variety of other projects that require isolation from external stimuli. There is an Orbit/FR positioning system that includes a 20' linear floor slide assembly, an AL-860-1 positioner assembly, an offset slide assembly, and an AL-4369-1 positioner assembly mounted on a three-part mast. This setup allows for various test configurations and geometries, such as standard azimuth and elevation antenna patterns while keeping the antenna under test over the axis of rotation to maintain an accurate phase center. This same positioning system can be utilized for rectenna pattern measurements.

The chamber also includes an Agilent E8364B (10MHz-50GHz) Network Analyzer (PNA), which is a critical component of standard antenna pattern measurements. The facility utilizes the Microwave Vision Group (MVG) Orbit/FR FR959 Spectrum software platform for automation of (1) the acquisition and analysis of PNA data and (2) the control of positioning equipment. The measurement of a rectenna can also be performed using this setup, utilizing the auxiliary input/output (AUX I/O) connector on the back of the PNA to measure DC voltage. However, the software platform must be modified, as discussed in Sec. 2.2.

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2.2 Modifications for Rectenna Measurements

The measurement setup is provided in Fig. 1. The rectenna is mounted a distance d away from the source antenna on a positioner that allows for azimuth and elevation pattern measurements. In fact, the rectenna measurements are handled much like a standard antenna pattern measurement, except for two key differences: (1) the received signal is a DC voltage rather than a complex electromagnetic field value and (2) the power density incident upon the rectenna aperture must be calibrated and swept.

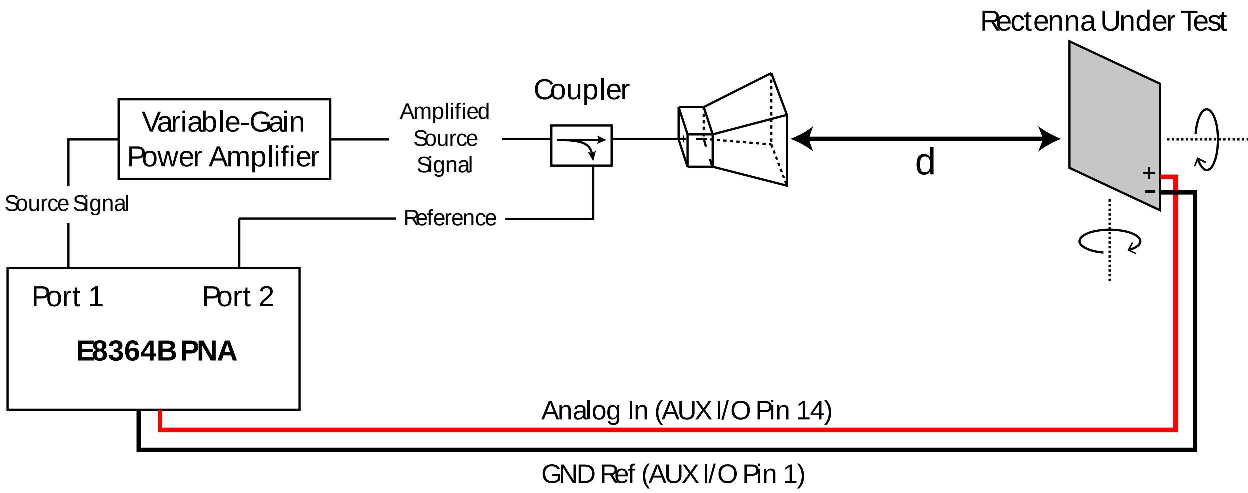

Fig. 1 – Rectenna measurement setup

2.2.1 Modification #1: Automated DC Voltage Measurement

As mentioned in Sec. 2.1, the DC voltage can be measured via the PNA's built-in voltmeter accessed via the AUX I/O port, which is a DB-25 male connector located on the rear of the PNA. The AUX I/O port contains a variety of analog I/O, digital I/O, timing I/O, and power supply lines. Pin 14 is the analog input terminal of the voltmeter while Pin 1 is its ground reference terminal. The voltmeter has an input resistance of $100k\Omega$ and an input voltage range of −10 to +10 VDC.

The settings of the AUX I/O connector can be changed through SCPI (Standard Commands for Programmable Instruments) and COM (Command) programming commands. Using these commands to modify the pre-existing software developed for automated antenna pattern measurements, the PNA can act as both the RF source and the DC receiver in automated rectenna measurements.

2.2.2 Modification #2: Power Density Calibration and Sweeping

Characterization of a rectenna requires plotting the DC output voltage versus incident power density, which must be calibrated and swept. Moreover, the levels of power density are often much higher than a typical antenna measurement. As a result a variable-gain, continuous-wave (CW), power amplifier with high output power (> 20 W) is required (see Fig. 1) to tune the power density. The power output of the PNA itself is also used to tune the power density. In addition, an antenna of known gain and a power meter are required for proper calibration, as discussed in Sec. 3.1.

3. MEASUREMENTS

3.1 Power Density Calibration

The rectenna was measured at a fixed distance of d = 2 meters from the source antenna with various CW power densities: 25, 50, 100, 500, and 1000 mW/m^2. To properly calibrate these power densities, an antenna with a known gain was positioned at the precise location where the RUT would be placed. A Narda 640 X-band reference horn antenna was used as the calibration antenna because the aperture size (7.8cm x 5.9cm) is close to the rectenna dimensions (7.3cm x 5.0cm), making the mounting fixture easy and compliant with both. An X-Band pyramidal horn with a larger aperture was used as the source antenna to provide a high gain. The output of the Narda 640 horn was measured directly with a power meter and recorded. A Pasternack PE9856-20 horn was also measured in place of the Narda 640 for calibration verification.

The incident power density P_d at the plane of the reference horn is given by

$$P_d = \frac{P_r + L_s}{A_{eff}}, \quad (1)$$

where P_r is the power measured by the power meter, L_s are system losses between the reference antenna and the power meter, and A_{eff} is the effective area of the reference antenna, which is related to its gain G by

$$A_{eff} = \frac{G\,\lambda^2}{4\pi}, \quad (2)$$

where λ is the free-space wavelength at the operating frequency. The system loss L_s was estimated to be 0.2 dB. The effective area A_{eff} of the Narda horn and the Pasternack horn are approximately 30 cm^2 and 80 cm^2, respectively, throughout measured set of frequencies, which is: 9.8 – 10.2 GHz.

The output power of the PNA and the gain settings of the power amplifier to realize each given power density are recorded, so that any given power density can be applied later during measurements.

3.2 Measurement Example – A Single Rectenna

The first device tested was a single rectenna comprised of a left-hand circular-polarized (LHCP), 4-element subarray connected to a single rectifier and fabricated on a 30-mil-thick, flat, printed circuit board (PCB). The rectenna was placed in the exact location as the aperture of the Narda 640 calibration horn using a Teflon mounting fixture designed to place the rectenna at the correct distance and the correct orientation. Fig. 6 shows a photo of this setup.

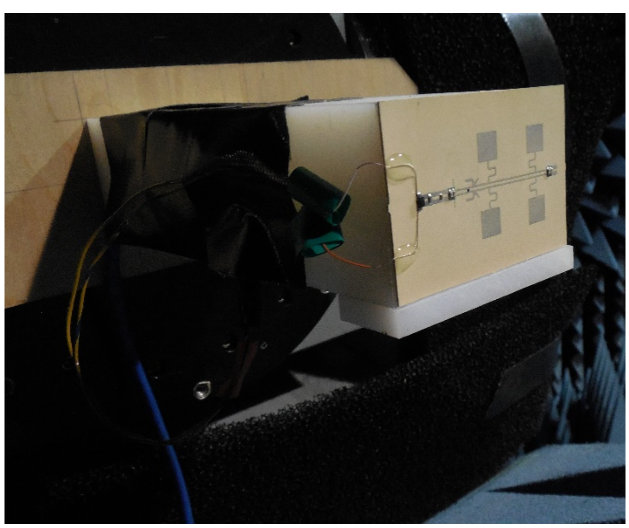

Fig. 2 - Rectenna under test (RUT) mounted for measurements

The DC output of the rectenna was connected to the analog input of the E8364B PNA, as shown in Fig. 1. The source antenna was set to vertical polarization. The polarization pattern shown in Fig. 3 was measured by fixing the RUT at broadside and rolling its face +/-180 degrees. The azimuthal rectenna pattern was acquired by setting the roll angle to 0 degrees and rotating the azimuth positioner +/- 45 degrees. The elevation rectenna pattern was measured in the same way, but with the roll angle set to -90 degrees. The output DC voltage of the rectenna and the magnitude of the RF source reference signal were collected at each measurement angle. These measurements were repeated for all prescribed power levels. An example of an azimuth data plot is shown in Fig. 4. RF-to-DC conversion efficiencies can also be calculated, after accounting for the 3-dB polarization loss in this particular setup.

This data established proof of concept. Larger rectenna apertures were also successfully characterized and measurements with an LHCP source antenna were also taken. These results will be documented in future reports.

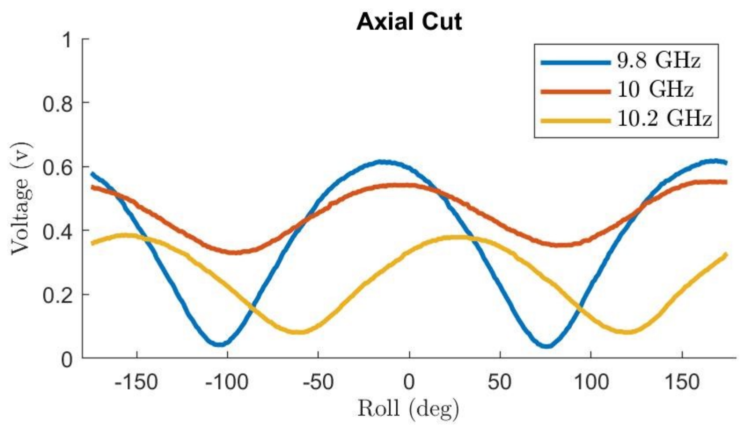

Fig. 3 – The polarization pattern of the RUT fixed at broadside while rolling its face +/- 180 degrees

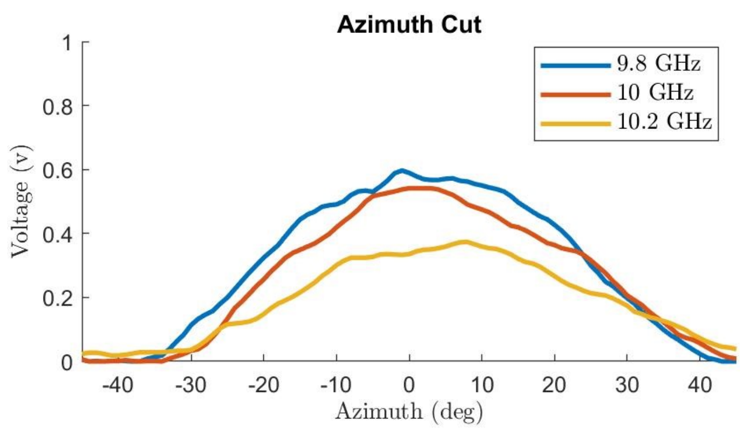

Fig. 4 – The measured DC output voltage for the RUT versus azimuthal angle

4. CONCLUSIONS

This report describes the successful development of a wireless power transfer test bed for rectenna characterization. The measurement procedures and calibration methods were validated through measurements. These techniques will allow the Code 5317 Antenna and RCS Measurement Facility to remain current with technological advancements in the field of wireless power transmission and capable of characterizing future rectifying antenna architectures.