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Remote Interrogation and Powering of a Spin Torque Nano-oscillator for Standoff Sensing

by Jesse Campbell, Theodore Anthony, Chris Fazi, and Alma E. Wickenden

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14. ABSTRACT

Passively powered devices are becoming more essential when designing centimeter-scale communication capable devices. Power components are often the majority of the weight in small robots, so eliminating the onboard power source will give engineers and scientists the ability to scale down devices. An X-band wafer level antenna on a 16- by 16-mm wafer that will harvest power from a base station with the intent of providing drive current to a low-power device such as a spin torque nano-oscillator (STNO) has been designed. A circuit that will rectify the propagating radio frequency (RF) waves and provide the STNO with a constant DC drive current was also designed. The STNO output radiation consists of an amplitude- and frequency-modulated signal that allows data to be transmitted from the STNO. Remotely powering the STNO will enable it to transmit data on the condition of a battlefield sensor back to the base station. This research was performed in the summer of 2009 as part of the Science Outreach for Army Research (SOAR) program.

15. SUBJECT TERMS

Frequency agile, RF communications, GHz, circuit, no-power communications, low-power communications, spin

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1. Objective

The spin torque nano-oscillator (STNO) is a magnetodynamic device in which coherent microwave precession at frequencies ranging from 1 to >100 GHz is induced under proper conditions of applied magnetic field and drive current (*1*). Although this is still an emerging technology, microwave transmission at approximately 9 GHz through air has been demonstrated using a discrete, antenna-coupled STNO, and the device has been demonstrated as an extremely low-power (0.25 mW input), broadband, amplitude- and frequency-modulated, high frequency radio frequency (RF) transmitter (*2*). The objective of this experiment is to design and evaluate the limits of a circuit that could passively power an STNO device to enable RF output at 10 GHz. The circuit is envisioned to extract its power from a propagating RF signal and use the harvested power to provide drive current to the STNO. The condition of a battlefield sensor could then be transmitted back to the base station by the STNO output.

2. Approach

The concept in figure 1 shows a base station (in this case, a small robotic platform) transmitting its radio frequency signal toward the conceptual non-powered, remotely interrogated sensing device.

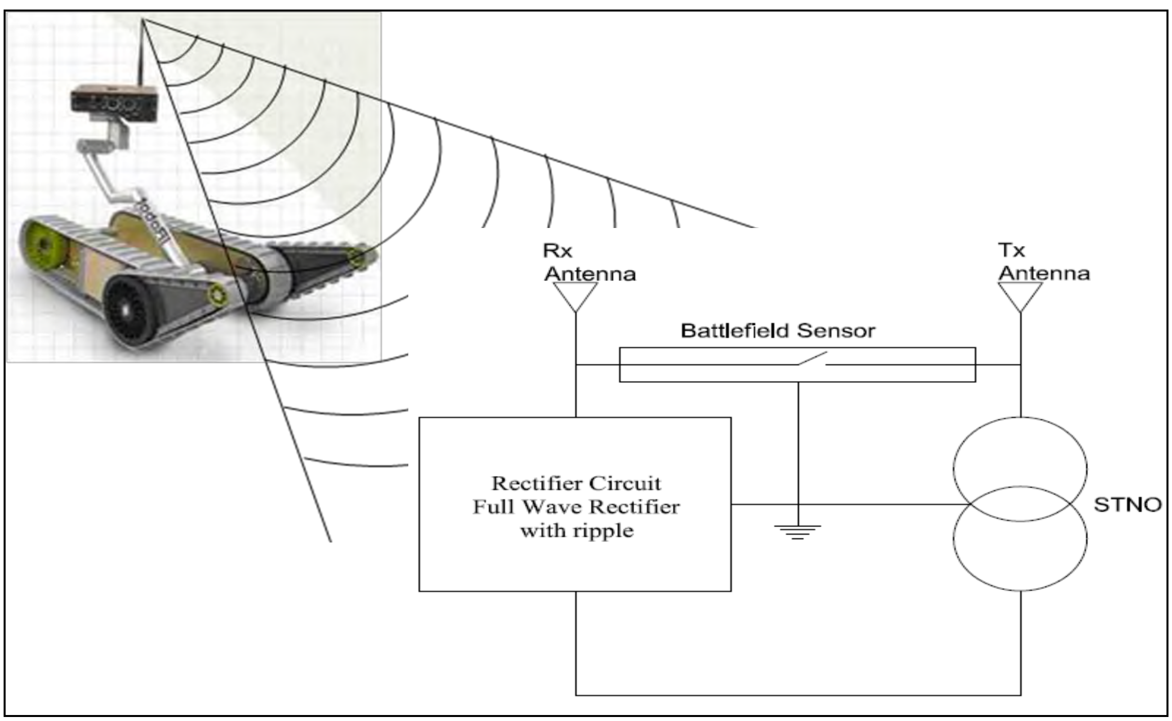

Figure1. Illustration of communication between a base station and the circuit.

Conceptually, the base station transmits a high-intensity RF signal wirelessly through free space toward the antennas embedded in the sensing circuit. Two antennas in this circuit function as a power receiver (RX) and a signal transmitter (TX) for the interrogated sensing circuit at 10 GHz. An alternative approach would be to implement one antenna to serve both functions, but would require a splitter right after the antenna in the circuit. The function of the splitter would be to keep the receive signal and transmit signal separate. The splitter also ensures that both signals are going through their designated route in the circuit. Without a splitter, the receive signal from the base station might go through a different path, instead of going to the rectifier circuit, as intended. The transmit signal might also go through a different path in the circuit, which would result in a loss of transmitted information. The single antenna approach could be implemented by designing a single antenna followed by a ferrite circulator. The disadvantages of this design are that the circulator is expensive and large, and would result in power loss. The preferred option is to create two different antennas, where one of the antennas would be used as a receiving antenna while the other would be used as the transmitting antenna. These two antennas would be designed to operate at different frequencies to ensure that only the receiving antenna is harvesting energy from the base station, not the transmitting antenna. The drawback of this design is that the two antennas take more space, but since an essential aspect of this device requirement is harvesting as much power as possible, this configuration is considered to be more suitable for this design.

In an RF energy harvesting system, a rectification circuit must be optimized to improve on the minimum power-threshold required for the system to operate (*4*). To overcome this power-threshold, the system requires a very efficient circuit and system level design (*5*). A low voltage rectifying circuit would assist in overcoming this problem.

The STNO DC output frequency is a function of its DC drive current. To attain a fixed output frequency, a constant DC drive current must be provided to the STNO. As shown in figure 2, moderate variation in the STNO drive current modulates the output frequency of the device. To enable frequency modulated STNO transmission, the output antenna must have a fairly wide bandwidth.

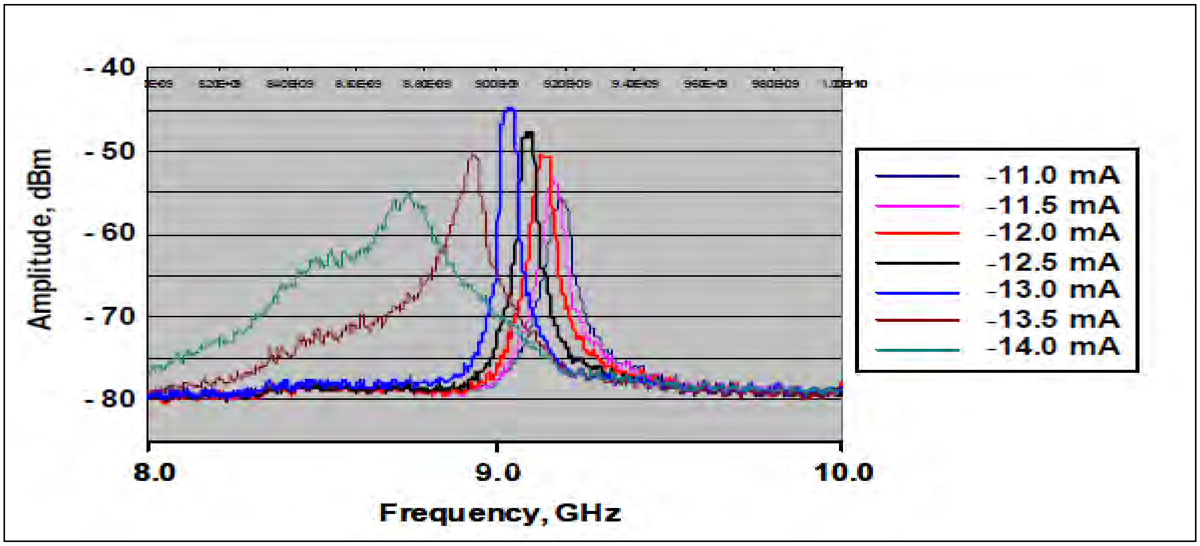

Figure 2. Frequency modulation of the STNO at a fixed applied magnetic field of ~0.3T; in this device geometry, frequency decreases with increasing applied drive current (*2*).

Since the X-band wafer level antenna has a narrow bandwidth, seven different antennas have been designed to meet the wide range of transmission possible with an STNO device. These antennas collectively have a frequency coverage from 9.65–10.35 GHZ. To also ensure that the STNO is able to transmit back to the base station while coupled with a battlefield sensor, the circuit is designed to feed a constant DC current to the STNO to enable a specific emission frequency.

3. X-band Antenna

A prototype antenna has been fabricated that receives power and transmits data for the interrogated sensing circuit at 10 GHz. The X-band antenna for the STNO was developed from a previously developed wafer level antenna designed to operate at 20 GHz. This antenna design has previously been demonstrated to be compact and efficient, and can be processed using microelectromechanical system (MEMS) technology. This prototype is a coplanar-fed, proximity-coupled patch antenna. Using Ansoft's High Frequency Structure Simulator (HFSS), frequency scaling was performed to produce a geometry capable of acquiring the desired 10-GHz frequency with a bandwidth of 120 MHz, as illustrated in figure 3. To convert a 20-GHz antenna to a 10-GHz antenna requires squaring some parameters of the antenna. The ground plane and the antenna were doubled, which quadrupled their areas. Due to this modification, the length of the signal line has to be increased for the 50-Ω matching requirement. After the frequency scaling, the following design parameters were acquired for 10-GHz operation: the antenna has substrate and ground plane dimensions of 16 by 16 mm, and the high resistivity silicon (Si) wafer is 0.5 mm thick with a dielectric constant of 11.9, a loss tangent of 0.015 and a conductivity of 0.025 S/m. The gap between the ground plate and the signal line is 0.355 mm, the signal line width is 0.56 mm, the signal line length is 10 mm, and the diameter of the antenna is 4.922 mm.

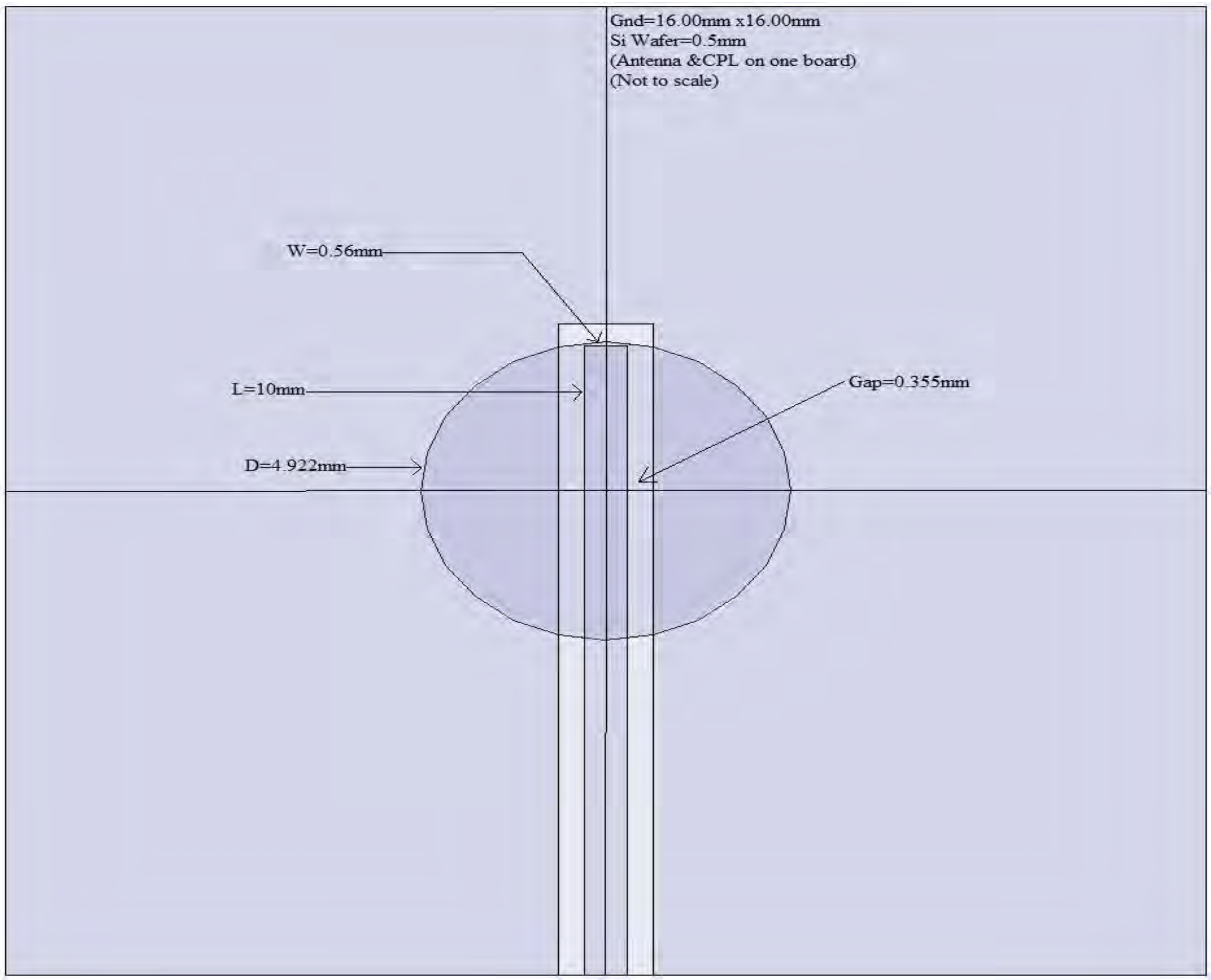

Figure 3. A three-dimensional (3-D) HFSS model, top view, of a coplanar-fed, proximity-coupled patch antenna with measurement.

To match the broadband output frequency of the STNO, six more antennas were designed and fabricated, as shown in figure 4. The additional antenna values were acquired by going 3% up and down relative to the 10-GHz center frequency. By doing this, the antenna retains its compact size but increases its bandwidth coverage. The new antennas were designed by adjusting the diameter of the 10-GHz antenna using the following equation:

$$D_{new} = (1 - [\text{New Antenna Percent}/100]) * 10\text{ GHz Diameter}. \quad (1)$$

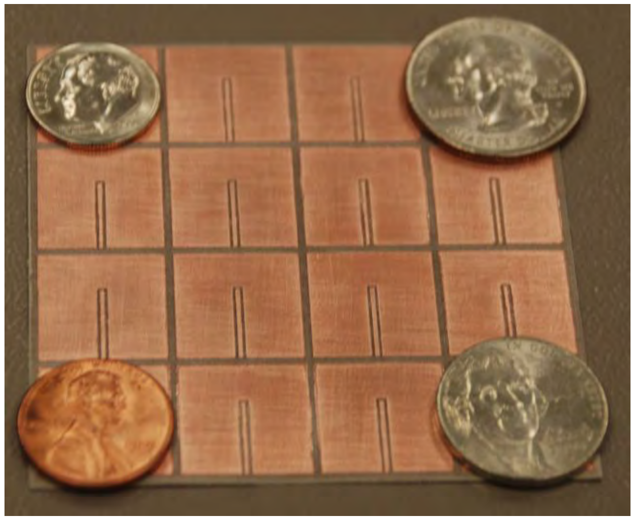

Figure 4. R03010 level antenna prototype, top view, with coins as a reference scale. The antenna has the same diameter as a U.S. dime.

Figure 5 shows the simulated radiation pattern of the coupled patch antenna, which describes the relative strength of the radiated field in various directions of the antenna. In general, the coupled patch antenna would be considered inefficient after –3 dB, relative to 0 dB. This standard convention is used because any power generated that is less than 50% shows that the system is inefficient.

$$10 \log10 (1/2) = -3.0103 \text{ dB} \qquad (2)$$

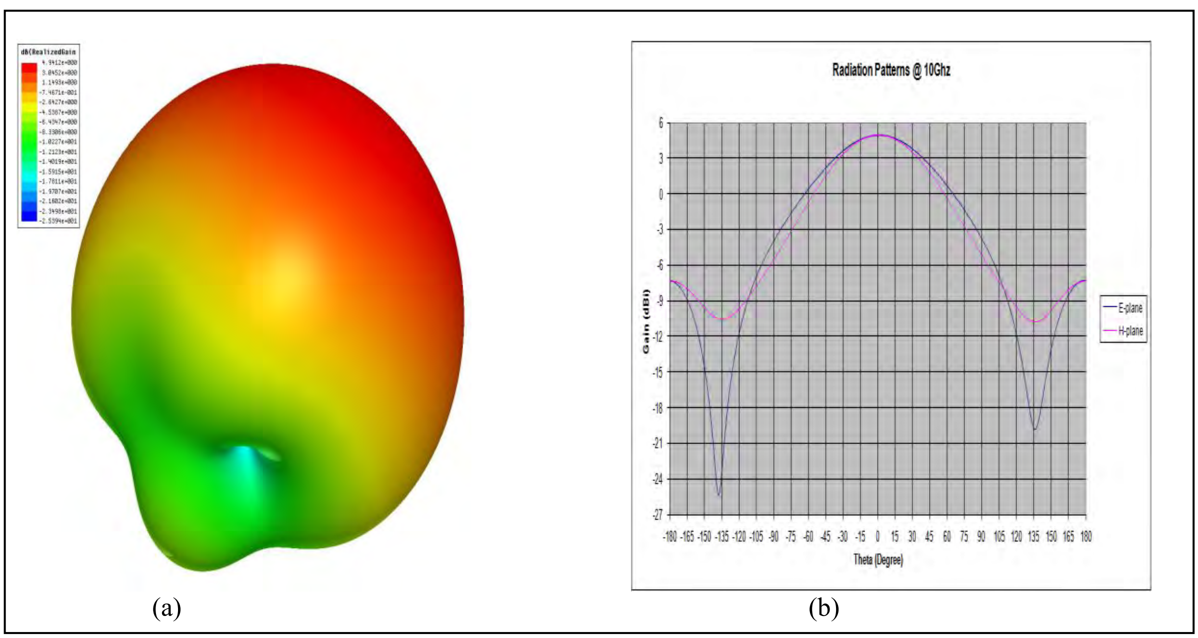

Figure 5. HFSS simulated radiation pattern for modeled wafer level antenna: (a) in a simulated 3-D radiation pattern, the red portion correspond to the antenna axis and (b) the angle 0 correspond to the antenna axis.

Given that the RF output of an STNO device is a sensitive function of its drive current, and that the coupled patch antenna has a narrow bandwidth, the STNO device is expected to be more sensitive to power loss at levels less than the conventional –3 dB. This is discussed further in a later section.

This antenna has been implemented on a printed circuit board (PCB) platform for the initial proof- of-concept, but was designed to use a Si wafer having a higher dielectric constant (ε_r), which would result in a smaller antenna.

Fabrication of the MEMS prototype antennas is planned using the U.S. Army Research Laboratory's (ARL) cleanroom facilities. Due to time constraints and cleanroom scheduling issues, quick prototype antennas were fabricated using the LPKF ProtoMat 93S mill/drill unit. The antennas fabricated using this method were less precise than the ones that will be created in the cleanroom on a Si wafer. The quick prototype antennas shown in figure 4 were designed on a R03010 material, which is a high frequency laminate. R03010 is a conventional RF stripline material that has a lower dielectric constant (ε_r) than Si; Si has ε_r of 11.9 while R03010 has ε_r of 10.2. The gain and radiation patterns of the prototype antennas were acquired in a tapered anechoic chamber. The return loss (S11) was measured on a HP8510 network analyzer.

The measured response of the quick prototype antennas that were designed using R03010 laminate is shown in figure 6. The frequency shift in the return loss graph is due to the fact that the antennas were originally designed to use a Si wafer and not a R03010.

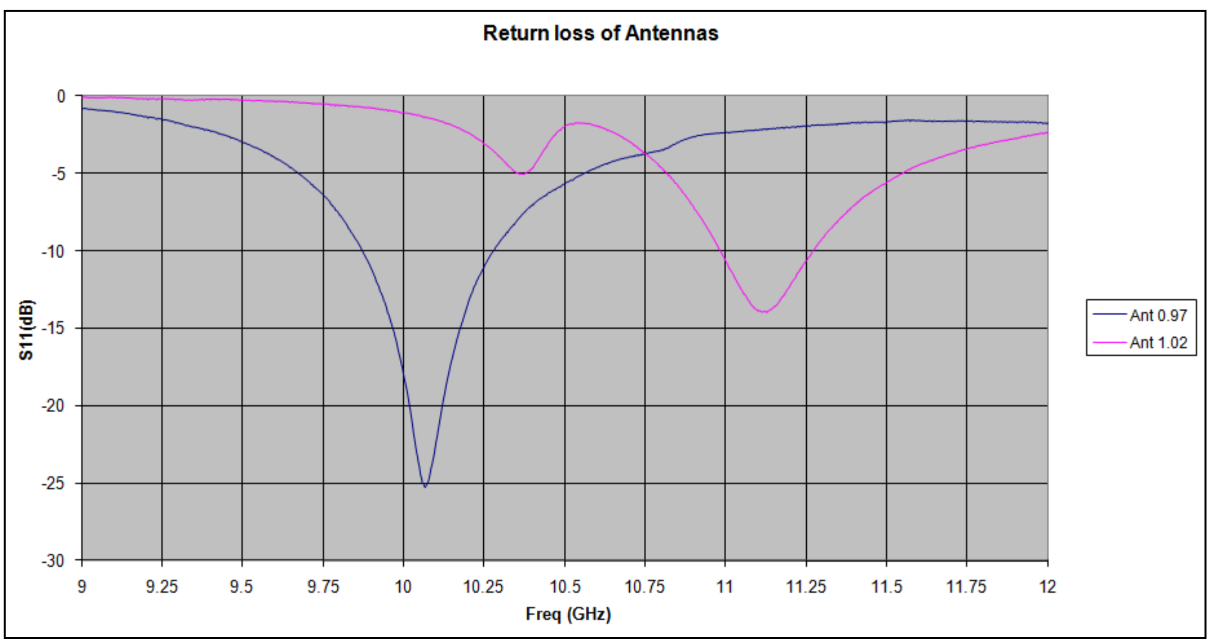

Figure 6. Simulated and measured return loss of the 97% and 102% prototype level antenna using a HP8510 network analyzer. These antennas are the quick prototype antennas that were designed using R03010 laminate and a ProtoMat 93S mill/drill unit.

4. Rectifier Circuit

A study of various rectifiers has been done and the full-wave rectifier with ripple has been determined to be the most suitable rectifier for this concept. A full-wave rectifier circuit, as shown in figure 7, is used to invert the negative portions of the sine wave so that a unipolar output signal is generated during both halves of the input sinusoid. A resistor–capacitor (RC) circuit is coupled with the full-wave rectifier circuit to filter out a large portion of the sinusoidal signal (*3*). The ripple voltage is defined as the difference between V_M (max voltage) and V_L (limit voltage). The ripple voltage was designed to be 1% in order to have a constant DC drive current input to the STNO. Having a constant DC drive current to the STNO determines the transmission frequency for a given device, enabling a more precise transmit antenna design with a narrow bandwidth to be used in the circuit.

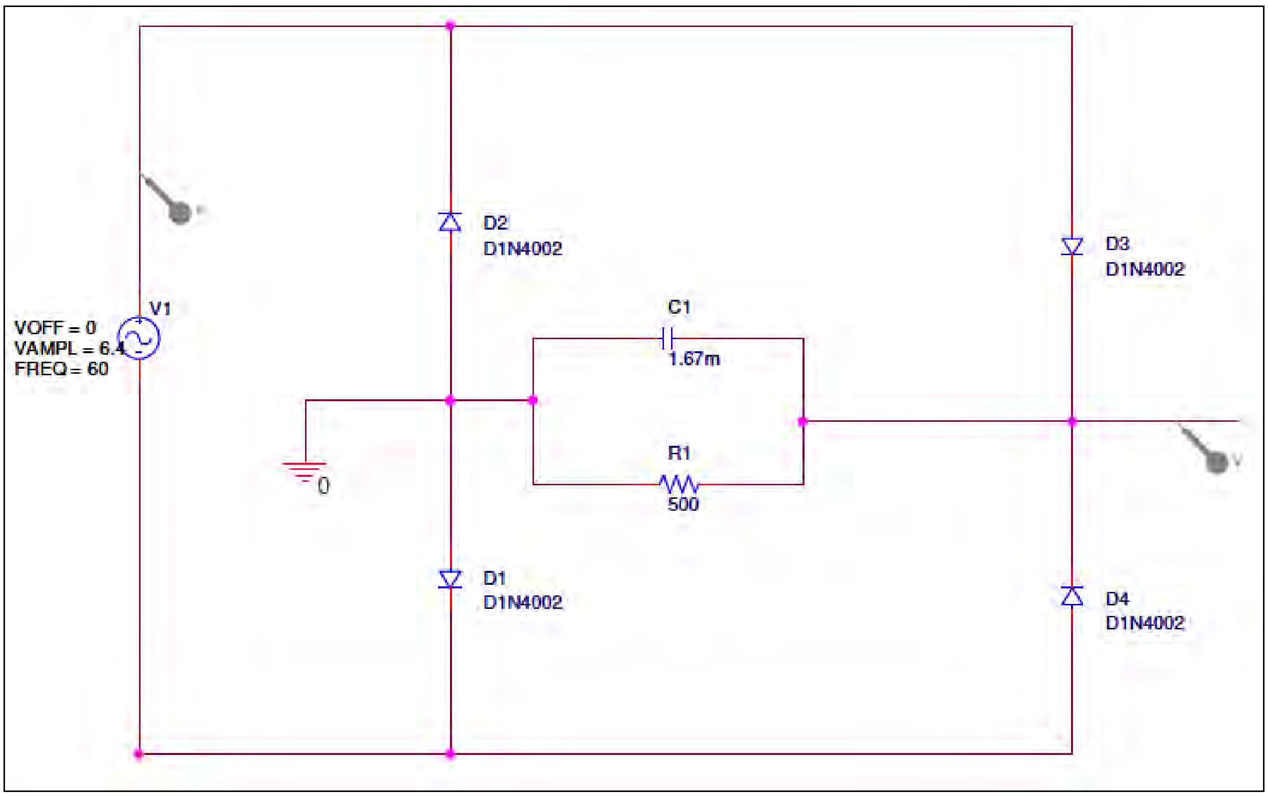

Figure 7. Schematic of a full-wave rectifying circuit with a ripple voltage.

The rectifying circuit shown consists of an output voltage of a sine wave which is the solid line shown in figure 8. After the sine wave is processed through a full-wave rectifier circuit with a 1% ripple, the sine wave output becomes a near-constant voltage, which is fed into the STNO. The ripple voltage is illustrated by the broken line.

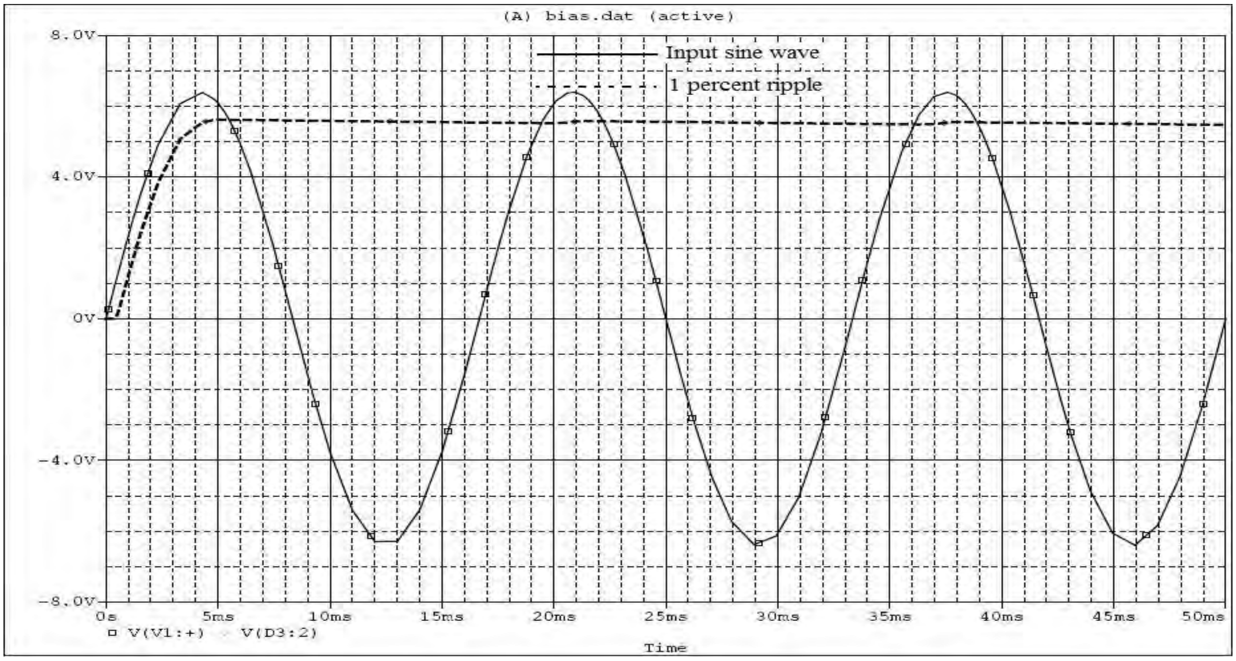

Figure 8. Output voltage of a sine wave and a full-wave rectifier coupled with a RC filter showing the ripple voltage.

The output voltage of the rectifying circuit illustrated in figure 8 is sensitive to the level of power captured by the receive antenna, which is, in turn, sensitive to angle of incidence, as shown in figure 5. Calculations were performed to analyze the DC current output of the rectifying circuit as a function of power loss, and are shown in figure 9. It is observed that a loss of approximately –1.5 dB results in an approximately 15% reduction in output current. For the STNO device response illustrated in figure 2, the bandwidth of frequency modulation resulting from this variation in drive current means that the device is expected to work effectively between a 0 and –1.4 dB loss, which corresponds to a beam range of –26° to +28° in the E plane of the antenna array.

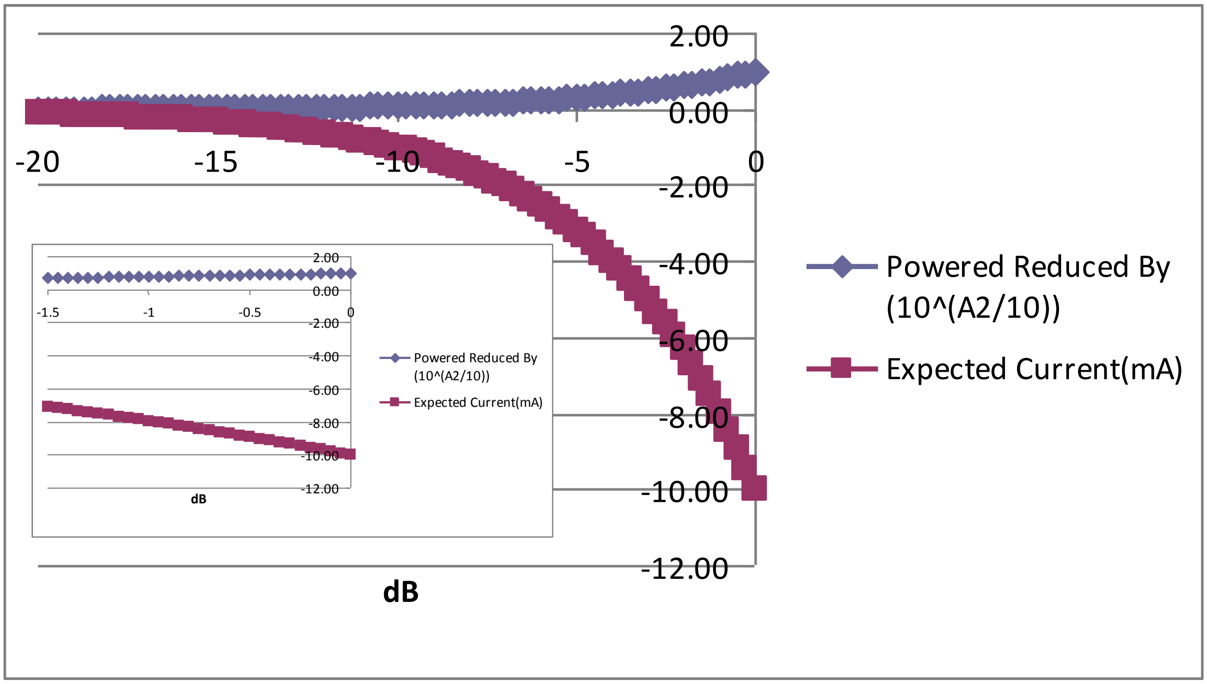

Figure 9. Simulation of current output.

5. Conclusions

A rectifier circuit was designed to transform the propagating RF signal into a constant DC drive current appropriate for a STNO device. Several coupled patch antennas were designed, fabricated, and tested around a frequency of 10 GHz, which is appropriate for the STNO. These antennas offer advantages such as reduced weight and cost, and increased performance. Future work with the antenna will entail analyzing the coupled antenna at different transmission angles to acquire the STNO response. Future work will also include designing an isotropic-type antenna to enable the same gain in all directions.

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List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
ARL	U.S. Army Research Laboratory
HFSS	High Frequency Structure Simulator
MEMS	microelectromechanical systems
PCB	printed circuit board
RC	resistor–capacitor
RF	radio frequency
RX	receive antenna
Si	silicon
STNO	spin torque nano-oscillators
TX	transmit antenna

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