WIRELESS POWER TRANSFER FOR A MICRO REMOTELY PILOTED VEHICLE

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ABSTRACT

A prototype rectifying antenna (rectenna) to provide wireless power transfer (WPT) to a micro-remotely piloted vehicle (MRPV) is developed. Microwave radiation at 1.3 GHz is converted into DC to drive a small motor and spin a mockup helicopter rotor blade. The rectenna serves a dual purpose as the antenna and outer body of the proposed vehicle and allows efficient reception of power over 360 degrees around the vehicle.

Wireless power transfer to the mockup MRPV has been demonstrated with less than 1 watt of transmitted power at near field ranges. Rectification efficiencies up to 30% were measured for two rectifier circuit configurations using 1.3 GHz continuous wave (CW) and pulse modulated transmitted signals.

1. INTRODUCTION

One important application of a micro-remotely piloted vehicle (MRPV) is the video surveillance of an area where people are not allowed or physically cannot go. Examples include the interior of buildings that may be controlled by unfriendly personnel, areas where environmental dangers are present or perhaps where it is more economical to use robotic surveillance.

A MRPV with the smallest possible size and greatest endurance is desired to meet the challenge of remote surveillance inside buildings. The chief aspect that prevents size reduction of a MRPV is the volume and weight devoted to carrying onboard fuel or batteries. Mission endurance requirements set onboard fuel/battery requirements, which in turn increase engine/motor and support structures requirements, all adding, size and weight. A remotely powered (via WPT) MRPV can reduce or eliminate onboard fuel or battery requirements and provide large-scale decreases in the size of the MRPV while permitting endurance to be independent of fuel storage requirements.

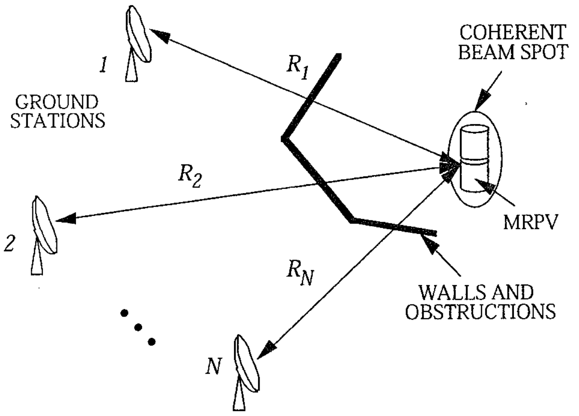

Figure 1: Proposed deployment of wireless powered micro-RPV

A proposed deployment of a MRPV system using beam tagging [1] to synchronize the signals from multiple ground stations is shown in Figure 1. Multiple transmitting sites provide signal diversity and maximize power density at the MRPV while reducing individual ground station power requirements and antenna size.

Previous WPT rectenna designs have concentrated on using either flat array antennas or flat rectangular or circular patch antennas [2-3]. Many of these designs have achieved a high RF-DC conversion efficiency (85%), however they are not suited to the current application because the antenna structures lack a uniform radiation pattern in azimuth and therefore restrict the orientation and maneuvers of the MRPV. For a wireless powered MRPV for use in the interior of a building, it is desired to eliminate these restrictions and therefore the development of a rectenna with uniform azimuth radiation pattern was undertaken. A rectenna of this type is shown in Figure 2. Previous research into the tradeoffs involved in frequency selection has led to the choice of 1-2 GHz region [4]. A frequency of 1.3 GHz was chosen for the demonstration model because it corresponds to the frequency of an exiting high power radar located at the Naval Postgraduate School.

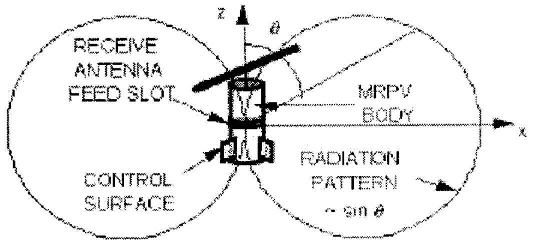

Figure 2: MRPV rectenna radiation pattern

2. MRPV RECTENNA DESIGN

The MPRV rectenna development consists of two parts: the antenna design and the development of the microwave rectifying circuitry.

The antenna structure was chosen to be a fat dipole with an offset slot feed. The radius of the dipole replicates a full scale MRPV prototype under development by Lutroics Corporation. Design parameters investigated include the overall dipole length, feedpoint, dipole arm separation and geometry of the region separating the arms. In an effort to reduce cost, commercially available off the shelf materials were used for the antenna. Since the prototype is non-flying, weight was not an issue and therefore copper plumbing pipe and endcaps were used. The copper pipe was easily cut to size on a lathe and thus reduced MRPV model development time. The antenna structures for functional flying MRPVs will use metal films or coatings layered over a lightweight composite structure.

Electromagnetic computer models of the MRPV rectenna were generated to determine an antenna structure with a driving point impedance close to that of the rectifier transmission line (50 ohms). Electromagnetic modeling was accomplished using the GNEC version of NECWINPRO. GNEC uses the Numerical Electromagnetic Code Version 4.1 engine (NEC 4.1) developed by Lawrence Livermore National Laboratory.

The full-scale body dimension of the Lutronics vehicle determined the length of the MRPV antenna. GNEC models that varied the feed position and separation of the dipole arms were generated and the impedance results analyzed until a VSWR of 1.55 was achieved at 1.3 GHz.

The rectifying circuit is a microstrip structure designed around a commercially available surface mount GaAs Schottky barrier diode manufactured by Hewlett Packard. The package is configured as an unconnected pair in a standard SOT-143 low profile package. Microstrip circuits using both one and two diodes connected in parallel were designed. A knowledge of the diode package scattering parameters (S-Parameters) at the operating frequency was required to design impedance matching circuitry for maximum power transfer. Low power (15 dBm) impedance characteristics of the HP GaAs Schottky diode package were determined from HP8510C vector network analyzer (VNA) measurements of the diode package surface mounted onto a 50 ohm microstrip test fixture fabricated from glass-epoxy (FR4) PC board material (Figure 3).

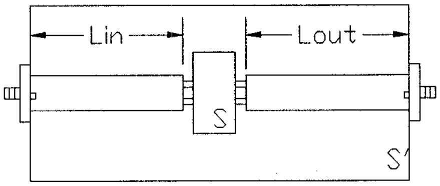

Figure 3: Microstrip test fixture for SOT-143 SMT Schottky barrier diode package

The diode scattering parameters were determined by shifting the reference planes of the microstrip test fixture VNA measurements using

$$[S]=\begin{bmatrix} e^{j2\theta_1}S'_{11} & e^{j(\theta_1+\theta_2)}S'_{12} \\ e^{j(\theta_1+\theta_2)}S'_{21} & e^{j2\theta_2}S'_{22} \end{bmatrix} \quad (1)$$

$$\theta_{1\,or\,2}=L_{in\,or\,out}\frac{2\pi}{\lambda_{guide}} \qquad \lambda_{guide}=\frac{\lambda_{free\ space}}{\sqrt{\varepsilon_{effective}}}$$

The effective dielectric constant of the microstrip substrate ($\varepsilon_{effective}$) is related to the relative dielectric constant (ε_r) of the dielectric substrate and the geometry of the microstrip transmission line by

$$\varepsilon_{effective}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+12\frac{d}{w}}}\right) \quad (2)$$

The relative permittivity of the substrate material and thickness (d) to width (w) ratio of the microstrip line are physical properties of the microstrip circuit. A microstrip thru line fixture was simulated using EEsof Touchstone. The relative permittivity (ε_r) was varied until the return loss (S_{11}) matched that measured on the VNA. Touchstone simulations provided the good agreement to VNA measurements when ε_r was 2.5.

A microstrip rectification circuit with a shorted microstrip stub for input impedance matching was designed using the scattering parameters determined from the VNA measurements. Two principal microstrip circuits were fabricated using this approach. One used two diodes of the HSMS-8525 diode package and the second only one of the diodes. Additional variations of these circuits were fabricated using a chip resistor (37 ohms) and a miniature DC motor as loads. The microstrip rectifier circuits with chip resistor loading were used to measure microwave rectification efficiency. The circuits with the DC motors were used to demonstrate MRPV operation. A sample microstrip rectifier circuit under test on the VNA is shown in Figure 4.

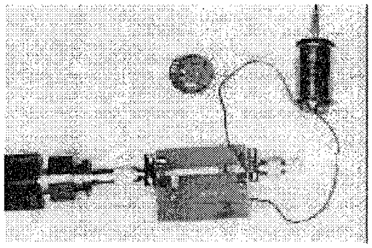

Figure 4: MRPV microstrip rectifier with DC motor

3. TESTING

3.1 Summary of Testing

MRPV testing consisted of rectifier efficiency measurements and of wireless powered motor operational testing. An objective is to provide transmitting power by the use of an available high power radar transmitter. The AN/SPS-58 air search radar transmitter was chosen as the transmitter due to its frequency (1.3 GHz) and high peak power (12 kW). Disadvantages of this transmitter include low pulse repetition frequency (PRF) of 3 kHz and low duty cycle (2.4%). However, due to the high peak power, the average power (290 watts) appeared to be great enough to encourage free space testing. Prior work [1-3] used CW signals, therefore measurements using pulse modulated microwave energy were required observe the effects of a pulsed radar signal on the rectifier efficiency. Efficiency measurements of simulated radar signals with characteristics of 7 µs pulse width at PRFs of 36 kHz, 13 kHz and 3 kHz. Signals were coupled directly into the MRPV rectifier circuit (no antenna attached). Average input power, average reflected power and DC voltage across the chip resistor load were measured. A block diagram of the test setup is shown in Figure 5.

3.2 Rectifier Efficiency Measurements

Measurements of DC power supplied to the chip resistor load as a function of absorbed power (input power less reflected power) were made and converted to rectification efficiency. Measurements were conducted for microstrip circuits containing a single diode and both diodes in the HP-8525 GaAs Schottky Barrier diode package. Efficiency measurements using 1.3 GHz CW as the input signal were also made for reference. Efficiency measurements were also made for pulse modulated (PM) signals to represent the effects of a high-powered search radar. The PM signals had a pulse width of 7 µs and pulse repetition rates of 36, 13 and 3 kHz. The 3 kHz PRF corresponded to the AN/SPS-58 Radar transmitter signal. Experimentation using various loading capacitances was conducted to determine if efficiency could be improved by storing energy for use while the pulse was off or during the negative half cycle of the received signal. Efficiency plots are shown in Figure 7 (single diode) and Figure 8 (dual diodes) for the various input signals. Solid lines indicate a 37-ohm chip resistor load and dashed lines the chip resistor with 11 µF capacitor in parallel.

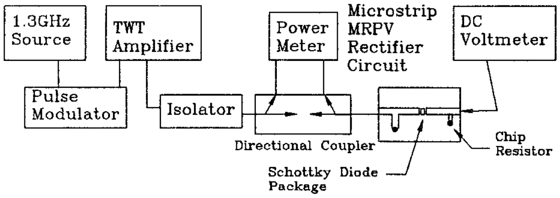

Figure 5: Block diagram of MRPV rectifier efficiency measurement using simulated radar signals

3.3 DC Motor Operation using Microwave Signals

A second set of rectifier circuits terminated with a miniature DC motor (replacing the chip resistor) were tested using the setup of Figure 5. DC voltage measurements were made for the same input signals as previously described and are shown in Figure 9 for the one diode configuration. Motor armature voltage (V_a) is a function of supplied current (I_a), motor rotor speed (ω_r) and permanent magnet DC machine flux constant (K_v) and is given by

$$Va = Ia \cdot Rdc + Kv \cdot \omega r \qquad (3)$$

K_v can be determined by open circuit voltage measurement when the machine is run as a generator at a known speed.

3.4 Wireless Powered Operation of Mockup MRPV

Wireless powered operation of the mockup MRPV was demonstrated using 1.3 GHz CW and 36 kHz PRF signals feeding a 16 dB horn antenna. Motor operation was demonstrated using WPT at a distance of 33 inches for CW and 3 inches for 36 kHz PRF. Average transmitting antenna power was 1.8 watts for CW and 0.44 watts for 36 kHz PRF. Both signals had field strength of approximately 0.4 mW/cm^2 at the MRPV.

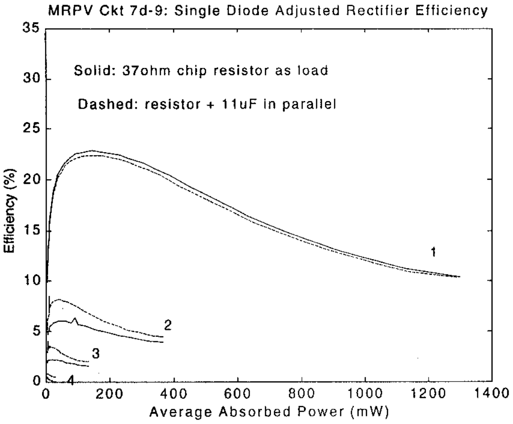

Figure 7: Microwave rectification efficiency for a single SMT RF Schottky barrier diode circuit. (1)-CW; (2)-prf=36 kHz; (3)-prf=13 kHz; (4)-prf=3 kHz

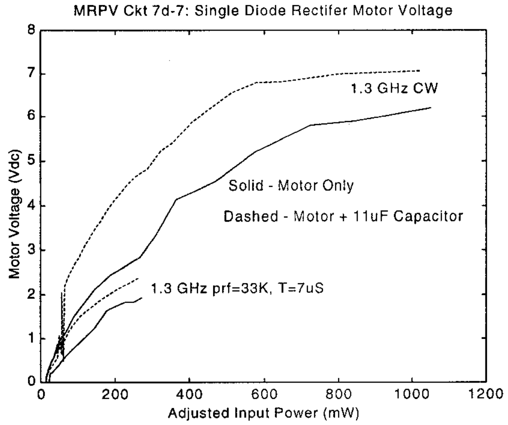

Figure 9: Motor Voltage using MRPV rectifier and microwave input signals, single diode configuration

4. CONCLUSIONS

Remote powering or fueling of a MRPV via wireless power transmission (WPT) has been demonstrated for a mockup MRPV. Transmitted microwave energy needed to be at least 0.4 mW/cm^2 at the MRPV location for operation.

Microwave rectifier efficiency tended to improve as incident power on the diode increased until the diode saturated. After saturation, efficiency decreased unless additional diodes were introduced in parallel to divide the current. As expected significant increases in rectifier efficiency were obtained when capacitance was placed in parallel with the load.

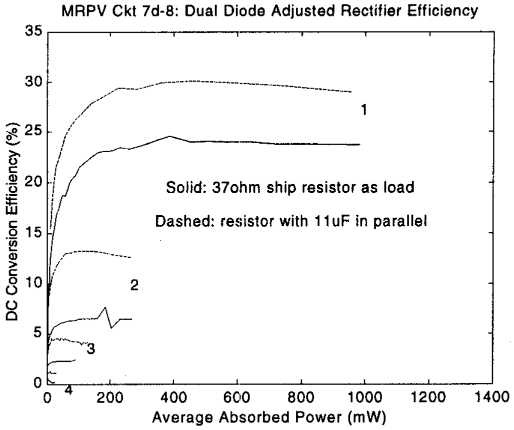

Figure 8: Microwave rectification efficiency for dual SMT RF Schottky barrier diode circuit. (1)-CW; (2)-prf=36 kHz; (3)-prf=13 kHz; (4)-prf=3 kHz

Rectification efficiency tended to decrease for pulse modulated (radar) signals and can be attributed to the low duty cycle of the signal. However as additional diodes are introduced along with some capacitance, efficiencies may approach that obtained using CW signals as indicated by the low power region of Figure 8.

Distances further away from the transmitting antenna require much greater transmitted power and/or multiple sources as previously discussed in [1]. Greater transmit power testing at longer ranges is planned using an air search radar. However, rectifier efficiency for the low PRF pulse modulated signals need to be improved.

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