2019 Student Design Competition Winners IMS

Backscatter Radio

A Winning Backscatter Modulator

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Wireless sensors have become commonplace in our daily lives for such tasks as tracking temperature, measuring humidity, and sensing light and gas. Many technologies capable of relaying sensor information are continually being refined, but the search for a robust and customizable technology to satisfy the exponentially increasing demand for large-scale and low-cost deployment of these wireless sensor nodes while minimizing power consumption has led to backscatter radio as a potential solution. Backscatter radio, first proposed in the 1940s as "communication by means of reflected power" [1], is a fairly mature technology that has been used in a variety of modern applications,

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especially those employing passive RFID technology in the ultrahigh-frequency band. The tags used in these applications are usually made up of just a transistor or switch and an antenna. These tags can be activated using only the RF power from an interrogating signal and, as a result, can be operated without any external energy source. Communication ranges of up to a few meters have been reported using this technology [2], [3].

In backscatter radio, an RF tag is illuminated by an interrogating signal, and the tag reflects the incident signal with a varying reflection coefficient determined by the load impedance presented to the antenna [4]. Typically, modulation between an open circuit and a short circuit that implements binary phase shift keying (BPSK) is used, although other modulation schemes have been suggested in the literature [5]. Due to the high monetary and power consumption costs of the components associated with conventional radios such as amplifiers, mixers and oscillators, the backscatter radio scheme presents a unique low-cost solution because it allows the sensor nodes to transmit data without generating their own signals, making it suitable for low-power sensing applications. In addition to the importance of having extremely low cost and power autonomous sensing nodes, it is desirable to build systems that have an environmentally friendly life cycle as well as being flexible and mountable.

With these requirements in mind, additive manufacturing technologies offer a unique combination of characteristics, providing an environmentally friendly waste-less approach, fast prototyping, and printing of a wide range of materials, such as conductors, semiconductors, and dielectrics, while also being compatible with both rigid and flexible substrates. Manufacturing techniques such as ink-jet and 3D printing have been used [6]–[8] for the realization of RF components and modules for Internet of Things and millimeter-wave applications. This article presents the work done on a design related to backscatter radio technology that won first place in the 2019 IEEE Microwave Theory and Techniques Society (MTT-S) International Microwave Symposium Student Design Competition sponsored by the MTT-S Technical Committee on RFID technologies.

Competition Design Goals and Metrics

For this competition, participants were asked to design, fabricate, and test a 1-MHz backscatter modulator operating at a carrier frequency of 915 MHz based on either binary amplitude shift keying or BPSK.

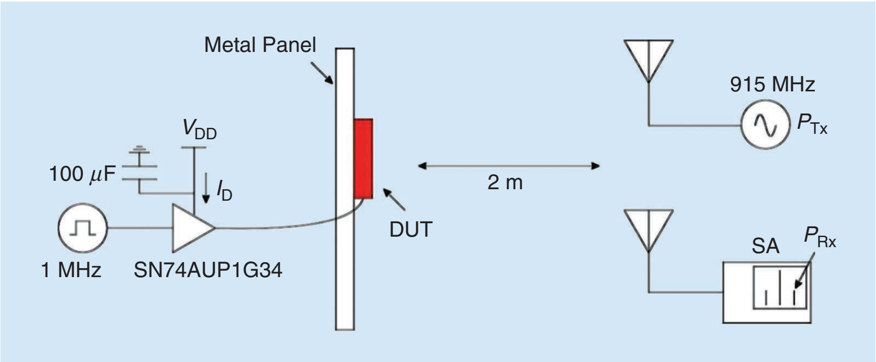

Figure 1. *A diagram showing the measurement setup. DUT: device under test; V_{DD}: voltage drain drain; I_D: drain current; SA: spectrum analyzer.*

The requirements called for a modulator optimized to achieve low power consumption and high sensitivity. The setup consisted of one reader and one tag. The reader comprised two linearly polarized antennas, one for the downlink and one for the uplink, in a bistatic configuration. The antennas were co-located and aligned with the center spot of a metal sheet on which the device was placed. The transmitting antenna was connected to a signal generator that produced a sinusoidal signal at 915 MHz, and the receiving antenna was connected to a spectrum analyzer. The equivalent isotopically radiated power considered in transmission was 25 dBm, which included both the gain of the transmitting antenna and the power out of the signal generator. The tag was placed 2 m from the reader and was composed of the backscatter modulator, a waveform generator used to produce the 1-MHz modulation signal, and a driver to interface the modulation signal to the backscatter modulator (Figure 1).

The teams were afforded a high degree of freedom to carry out the design using any technology, and the use of commercial components was permitted for the purposes of the competition. However, to encourage innovative, sensitive, and low-power designs, neither on-board batteries nor energy-harvesting systems were permitted. The device, including both the substrate and any soldered components, could be no larger than 5 × 5 × 2 cm, with a total allowable volume of no more than 50 cm^3. The device was also specified to weigh no more than 10 g. The measurement setup considered for the validation of the design involved the mounting of the device on a vertical metal plane having dimensions of 1 × 1 m, with measurements taken with the device mounted and centered at three different locations on the metal plane (Figure 2). The metal plane was realized with a dielectric covered by aluminum foil.

The performance of the device was evaluated as a tradeoff between the various design geometries, the sensitivity, and the total power consumption in the given transmitted power scenario. The evaluating criterium was the figure of merit (FOM) given by

$$\text{FOM} = \frac{P_{RX1}(nW) + P_{RX2}(nW) + P_{RX3}(nW)}{P_{C1}(\mu W) + P_{C2}(\mu W) + P_{C3}(\mu W)} * \frac{50}{D1(\text{cm}) * D2(\text{cm}) * D3(\text{cm})} * \frac{10}{\text{weight (g)}}, \quad (1)$$

where P_{RXi} (nW) is the received power associated with the first sideband signal measured by the spectrum analyzer (power at 916 MHz) and P_{Ci} (μW) is the measured power consumption of the driver corresponding to the transmitted power and the device position, $i = 1, 2, 3$.

The overall power consumption of the device (P_c) was evaluated by measuring the power consumption of the driver [voltage drain drain (V_{DD}) times drain current (I_D): $Pc = V_{DD} I_D$]. The current consumption of the driver was calculated as the average current consumption during a continuous modulation operation. The driver is the single buffer SN74AUP1G34.

Selected Design and Manufacturing Process

In observing the FOM, it is clear that the optimal design is a small, low-power, lightweight, and highly sensitive backscatter modulator. To come up with the best design, we had to analyze the various parameters involved in the calculation of the FOM. The received power at the reader ($PRXi$) is given by

$$P_{RXi} = \frac{P_{Tx} G_{Tx} G_{Rx} G_{\text{tag}}^2 \lambda^2}{(4\pi)^3 d^4}. \quad (2)$$

This equation shows an interesting property of backscatter modulation in that the gain of the front end is squared because it contributes in both the reception of the interrogating signal from the reader and the retransmission back toward the reader. Thus, we see that, in selecting an antenna, we want to ensure that this property is as high as possible because any additional increase in gain in decibels relative to isotropic results in twice that amount added to the received power. So, in our design process, we assigned the highest priority to the design of a high-gain antenna.

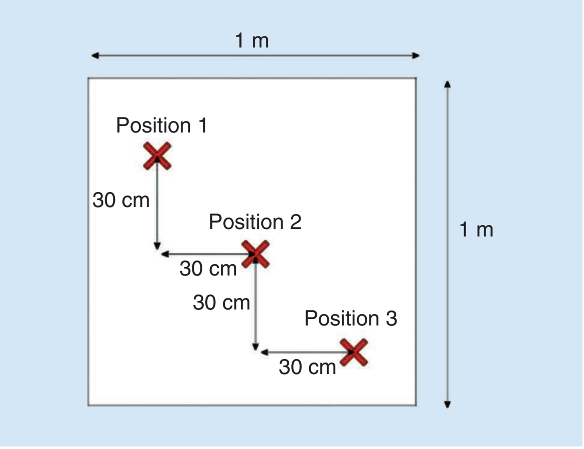

Figure 2. *A diagram showing device positions for measurement.*

In selecting the antenna, a very important requirement to consider is that the device must be mounted on a metal sheet. The metal sheet acts as a short circuit and reflects incident waves with the phase reversed so that, if the antenna is too close to the sheet, the radiation destructively interferes, leading to low sensitivity and received power. However, we are limited by the dimensional constraints of the device. As a result, we cannot place any designed antenna far enough or choose a thick enough substrate to avoid some amount of destructive interference while preserving the high gain of the antenna.

The antenna chosen for the backscatter modulator was a microstrip-based Yagi-Uda antenna because we can take advantage of its architecture to actually use the metal sheet as a parasitic element of the antenna structure and make it act like the reflector of the antenna array. A Yagi-Uda antenna array conventionally comprises a number of linear dipole antenna elements where only one of the elements is driven while all of the others act as parasitic elements having currents induced via mutual coupling [9]. In the proposed scenario, we can orient the device so that it is orthogonal to the metal plane and is in the appropriate configuration for a Yagi-Uda array having one driven element and one reflector.

After the antenna was selected, the next parameter to consider was the substrate on which it would be manufactured. From (1), we saw that weight and thickness are both important parameters, so we wanted to choose a substrate that would help maximize the impact of these parameters on the FOM. For this device, we chose the extremely thin (50-μm thick) XT/duroid 8000 from Rogers Corporation, with permittivity $\varepsilon_r = 3.23$ and loss tangent $\tan\delta = 0.0035$. This material proved to be low loss and very light due to its thinness. The substrate, clad in half-ounce copper with a thickness of 18 μm, was especially lightweight, thus helping to keep the weight of the fabricated device very low.

Finally, an appropriate switching mechanism to enable the modulation had to be identified and selected. This was done using a low-noise field-effect transistor (FET). The CE3521M4 RF low-noise FET from California Eastern Laboratories was chosen because its many desirable features help further the goal of maximizing the FOM. The transistor has a very low input-gate capacitance and gate-to-source leakage current, so that the power consumption due to the switching characteristics and current leakage of the transistor is low; thus, the overall power consumption of the backscatter modulator is also reduced. The power consumption of the switch is estimated to be a meager 0.416 uW due to contributions from the static transistor current leakage and the 1-MHz switching. The transistor chosen also features an extremely low profile, being only about

60 μm thick [10]. In the topology selected, the transistor drain and source pins are connected across the arms of the antenna such that the load seen by the antenna switches from open to short as it is biased.

Once the desired antenna and all required components to create the backscatter modulator were selected, the next step was to design the antenna on the chosen substrate and assemble the components. The antenna design was done using CST Microwave Studio 3D electromagnetic simulation software (Figure 3). The driven element of the Yagi-Uda array was chosen to be a meandered dipole with total electrical length of roughly a half wavelength. The horizontal sections were set to be as far as possible from the metal sheet to maximize radiation in the boresight direction; thus, the maximum allowable dimension of 5 cm in the horizontal and vertical direction was used, and the antenna was designed to resonate at a center frequency of 915 MHz while being constrained to fit within the 25 cm^2 of area available. Since virtually all of the available area was used, it was of utmost importance to minimize as much as possible the weight and overall thickness of the device so that a high FOM could be obtained.

Included in the design of the backscatter modulator are biasing pads so that the voltage from the waveform generator can be easily applied to the transistor. Also included are soldering pads for the transistor package as well as a pair of pads to solder on 0603 format surface-mount inductors to aid RF–dc isolation due to the biasing across the transistor and antenna. Figure 4 shows the assembled backscatter modulator with the soldered-on transistor, RF–dc isolation inductors, and biasing pads. The components were attached by applying a small amount of solder paste to the pads. The paste was then melted using a heat gun to complete the process.

The final step was the manufacturing of the device. This was done via an ink-jet masking procedure where Microchem SU8 is ink-jet printed onto the copper-clad surface of the XT/duroid substrate. The SU8 solution behaves as a positive photoresist in which the areas of the copper that are masked by the solution are insoluble while the rest of the copper is etched away using an iron-chloride solution. Due to the use of an extremely thin substrate (50 μm) the ink-jet masking procedure is an ideal solution that enables the selected design to be easily manufactured on the substrate using a very simple and inexpensive procedure.

The manufactured device has dimensions of 5 × 5 × 0.013 cm and weighs a miniscule 0.25 g. Once the device was manufactured and assembled, it was validated in a lab setting similar to the setup described in the competition rules. The backscatter modulator was mounted perpendicular to the metal sheet, which acts as a reflector in the Yagi-Uda antenna configuration; two pieces of adhesive tape were used to secure the device onto the metal plane. The 1-MHz modulation signal from the waveform generator was fed onto the device's biasing pads, and the signal re-emitted from the backscatter modulator was measured using a

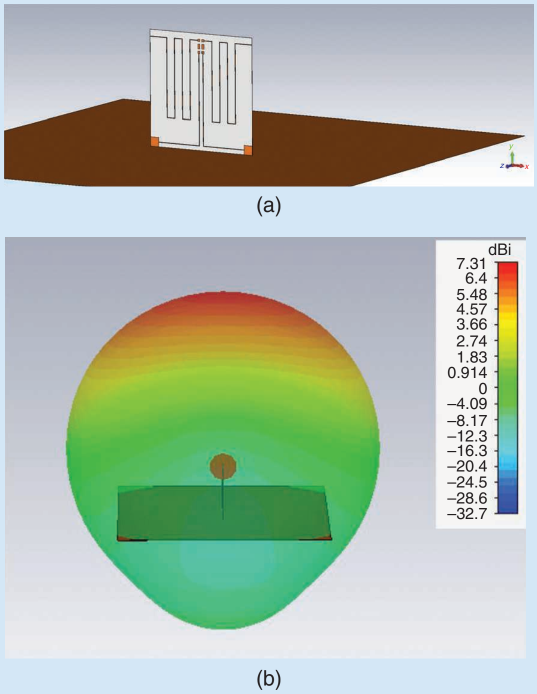

Figure 3. *(a) An illustration showing a simulation model (using CST Microwave Studio 3D electromagnetic simulation software) of an antenna perpendicular to a metal sheet. (b) A simulated radiation pattern (gain: 7.313 dBi).*

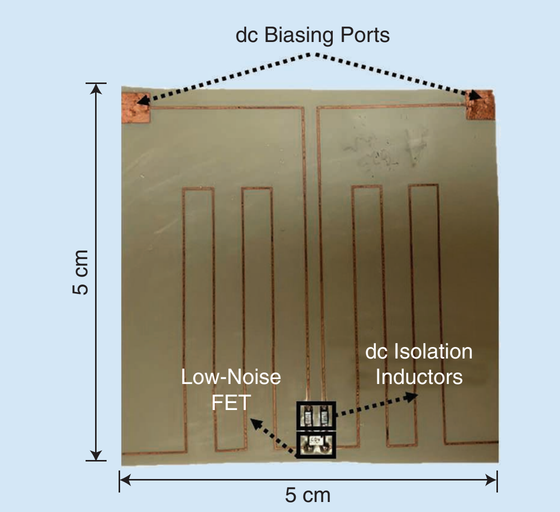

Figure 4. *The assembled backscatter modulator.*

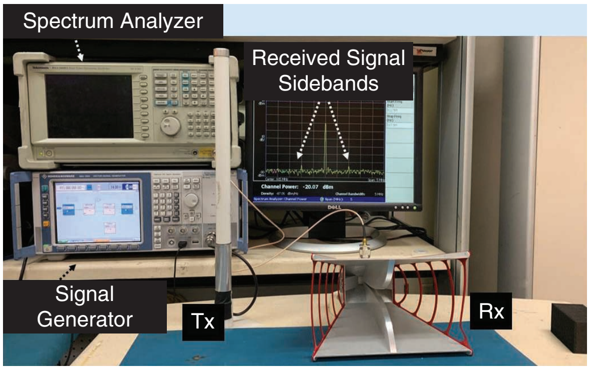

Figure 5. *The laboratory setup. Tx: transmitter; Rx: receiver.*

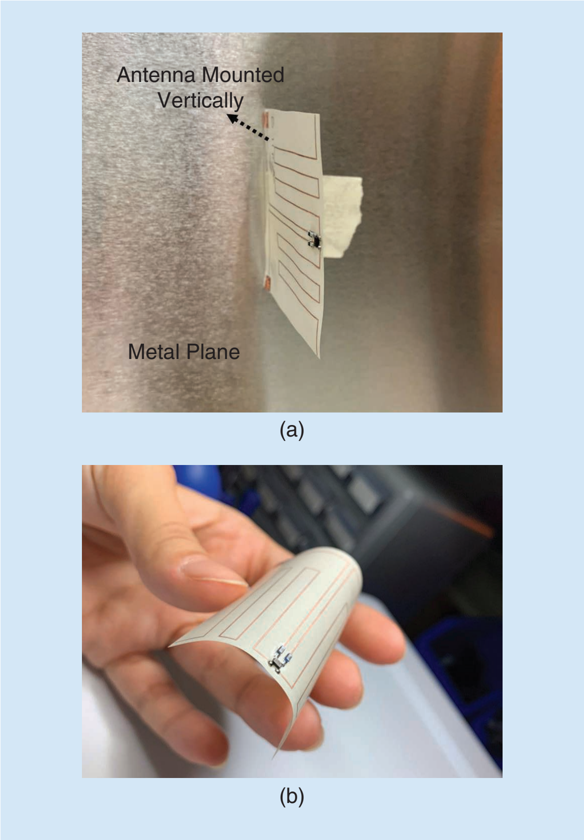

Figure 6. *(a) The mounted backscatter modulator. (b) A profile of the assembled backscatter modulator showing its flexibility.*

Tektronix RSA 3408A real-time spectrum analyzer. Figure 5 shows the experimental setup used for evaluating and testing the backscatter modulator as well as the received sideband signals at 914 and 916 MHz, respectively, for the setup where the device was placed at the center of the metal sheet. The transmitting antenna is a 915-MHz omnidirectional dipole while the receiver is a double-ridged horn antenna. Figure 6 shows the vertically mounted backscatter modulator and a side profile view of the fabricated device.

Conclusions

The design presented here shows an innovative solution to an interesting problem in backscatter communications. We have successfully demonstrated the viability of a simple, lightweight, and ultralow-power backscatter modulator operating at 915 MHz and able to function near a metal surface while meeting the stipulated dimensional constraints. The device is capable of delivering −67 dBm of received power at a distance of 1 m while mounted on the metal sheet. The tag's thinness, extreme lightness, and large radar cross section contribute to a very high FOM, beating out other designs by several orders of magnitude.

Acknowledgment

We acknowledge the efforts of the organizers of the 2019 International Microwave Symposium, without which the competition would not have been possible. We also express our gratitude to the members of the IEEE Microwave Theory and Techniques Society committee on RFID technologies who put together this competition. Finally, we appreciate the support of Rhode & Schwarz for providing measurement equipment on the day of the competition.

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