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Transponder Utilizing the Modulated Re-Scattering Communication Principle

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Abstract

In this work, the performance of a re-scatter transponder is investigated. The transponder is based on a 90° hybrid coupler, and it provides independent amplitude and phase modulation as a function of the bias voltage. The structure operates at a frequency of 3.42 GHz, and the performance of the transponder is investigated using simulations and measurements. The results show that the proposed approach is a viable candidate to implement wireless connectivity for simple, passive and low-cost devices.

1 Introduction

Wirelessly connected devices and things are expected to enable the next industrial revolution. In proposed paradigms such as Internet of Things (IoT), the number of devices connected to the Internet is foreseen to increase by several billions from today. In the first phase, relatively complex and expensive devices and things, such as cars and household appliances will be wirelessly connected by equipping the devices with active radio transceivers powered from a battery or other energy source.

However, there is a huge number of things that would benefit from even a simple wireless connection, but are too small, inexpensive, or lack a power supply, and cannot therefore be equipped with an active transceiver. It is proposed that such devices could harvest power for their operation from ambient radio waves and also use the ambient radio waves for communications using the modulated re-scattering principle [1]–[3]. In this communications principle, the device captures an ambient radio wave, attaches its own message to it by modulating the signal, and then redirects the signal to the receiver. This way, the whole network could operate parasitically within an active radio network.

We aim to study the concept further by designing a transponder capable of using the modulated re-scattering principle. In particular, we design a transponder that can independently phase and amplitude modulate a signal at 3.42 GHz. Modulation is binary in both cases.

2 Transponder Design Process

In the current work, the designed transponder is intended to operate at a frequency of 3.42 GHz. The transponder is based on a reflection-type phase modulator and reflection-type amplitude modulator. The reflection-type phase modulator is realized using a 90° hybrid coupler with identical loads connected to two of its ports.The load impedance is made tunable using a varactor diode.

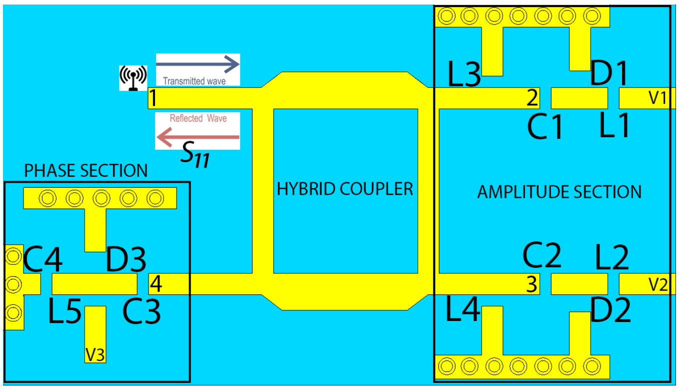

Figure 1. Schematic illustration of the transponder model used in the simulator.

The amplitude modulator is a load whose impedance can be modulated with a diode. Many designs and implementations for a 90° hybrid coupler have been presented in the literature, e.g., in [4]–[6]. For the 90° hybrid coupler, the required power splitting ratio and output phase difference can be achieved by adjusting the length and width of the coupling section.

Individual parts of transponder are designed using the electromagnetic simulation software CST Microwave Studio, and circuit simulations are carried out in AWR Design Environment. Figure 1 shows the CST layout of complete transponder.

2.1 Reflection-type Amplitude Modulator

The amplitude modulator has been designed as a simple RLC resonator circuit as shown in Figure 1. The desired operation of an ideally matched hybrid quadrature coupler at the required frequency shows no reflections at port 1 (input) and no output at port 4 (isolation).

The signals at the output ports 2 and 3 have a phase shift of 90° and 180°, respectively, with respect to the input and therefore the phase difference between these two branches is 90° (quadrature coupler). When the hybrid coupler is excited at Port 1, the signal splits in half and will propagate to ports 2 and 3. These ports have been extended with an additional circuit to reflect the incident signal. An HSMS-2860 diode with SOT-23 packaging has been used as tunable resistor to create an impedance mismatch.

In the amplitude modulator, the signal amplitude can be changed until a signifcant phase shift begins to appear. In our proposed design, an amplitude modulation of up to 3 dB can be utilized, and this is implemented by forward-biasing diodes D1 and D2 at the same time with a bias voltage. In addition to the diodes, a 6-pF capacitor and a 3.9-nH inductor are used to implement the required amplitude modulation with a constant phase at a given bias voltage. This topology is similar to an RLC circuit.

The signals reflected from ports 2 and 3 propagate to port 4 (isolation port). The reason for this is that the reflected signal has a different phase with respect to the input signal and also due to the fact that destructive interference between the input signal and reflected signals will cancel out the signal going back towards port 1. Therefore, the reflected signal will not travel to port 1. Instead, it will propagate only to the isolated port 4 (constructive interference). When the reflected signal reaches port 4, the same phenomenon willhappen again in reverse. Port 4 now becomes the input port and the backscattered signal will propagate to ports 2 and 3 again. Due to impedance mismatching in these ports, the signal is reflected again, and it will eventually reach port 1. We can then measure the magnitude and phase of the signal at port 1.

2.2 Reflection-Type Phase Modulator

Next, the operation of the hybrid-coupler based reflection-type phase modulator is explained. The input signal at port 1 divides equally among ports 2 and 3. Waves reflected from these two ports will add in-phase at port 4. At this point, we are using a varactor diode to change the phase according to our requirement, namely to achieve a 180° phase shift. Varactor diodes provide a capacitance that varies with the bias voltage, and thus they operate as electrically adjustable reactive circuit elements.

By reverse biasing the varactor diode we can choose two distinct voltage points where we get the desired phase shift while keeping the amplitude constant. The phase modulator uses an SMV-1247 varactor diode as a tunable capacitance. This particular varactor diode is chosen because it gives a sufficient capacitance tuning range as a function of voltage compared to other available varactor diodes.

2.3 Transponder Prototype

Previously, the schematic of the transponder model used in simulations was shown in Figure 1. A photograph of the manufactured transponder prototype is shown in Figure 2 along with the length and width of the printed circuit board (PCB) and the microstip lines. The overall design is implemented on a 0.8-mm thick FR-4 substrate, whose details are given in Table 1.

Table 1. Parameters of the transponder used in simulations and measurements.

Parameter	Value
Operating frequency	3.42 GHz
Relative permittivity	4.43
Loss tangent	0.027
Substrate height	0.8 mm
Microstrip thickness	0.035 mm
Substrate	FR4

Table 2. Details of the lumped components and diodes used in the transponder.

Component	Value
L1,L2,L5	100 nH
C1,C2	6 pF
L3,L4	3.9 nH
C3	100 pF
C4	0.5 pF
Diode1,Diode2	HSMS-2860
Diode3	SMV-1247

In the final design, actual components (RLC circuits, dc-block capacitors, and RF-block chokes) from Murata are used, and the transponder is implemented using GQM18 and LQW18 series capacitors and inductors (component size 1608), respectively. Component values and diode types used are given in Table 2.

Physical implementations for placing the lumped components in the design are subsequently created in CST with the help of suitable pads, which are shown in Figure 1. All the previously discussed individual parts are connected together in the prototype, and the performance of the complete transponder is verified with measurements.

3 Performance of the Designed Transponder

Measurements were performed using an Agilent vector network analyzer (VNA) and an external voltage supply to provide the necessary bias voltage for the amplitude modulators. Figure 3 shows the simulated and measured performance of the amplitude modulator. When the diode is not biased, the initial amplitude value is –3.3 dB and –7.7 dB in simulations and measurements, respectively. To achieve a desired amplitude modulation of 3 dB, a bias voltage of 0.2 V is required in simulations and 0.19 V in measurements. According to simulations, this results in an amplitude value of –6.4 dB, and the corresponding measured amplitude is –10.3 dB.

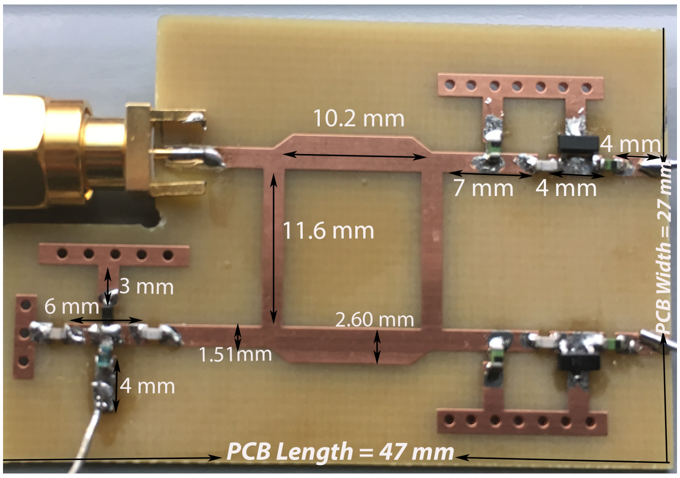

Figure 2. Illustration of the transponder prototype with dimensions. All dimensions are in millimeters.

Changing the bias voltage from 0 to around 0.2 V does not cause a significant change in the phase. The resulting phase shift is 1.674° in simulations and –3.33° in measurements, which means that our amplitude modulator is able to provide the necessary modulation in the amplitude while essentially maintaining a constant phase.

Figure 4 shows the simulated and measured response of the phase modulator. In simulations, we are getting almost a 180° phase shift at bias voltages 2.7 V and 3.3 V for the varactor diodes. At these bias points, the signal amplitude remains more or less the same at –6.5 dB. Measurement results show that we are getting the 180° phase shift at bias voltage points 1 V and 2.5 V with similar amplitude levels around –9 dB. Here, normalized phase values are used. All simulation and measurement results are also summarized in Tables 3–4.

It is interesting to notice that with a value of the bias voltage of the phase modulator that results in an amplitude value as close to 0 dB as possible, we can keep the phase modulator at constant bias. Then, we can start to change the amplitude to meet our requirements with a constant phase. This approach allows achieving the maximum reflected power, thereby increasing the overall signal modulation and transponder performance.

When comparing the simulated and measured performance of the designed transponder, including the amplitude and phase modulators, the obtained results show similar characteristics. Some of the differences, e.g., not achieving exactly 180° phase modulation can be attributed to inaccuracies in the manufacturing process, slight variations in the diode and lumped component values, as well as additional losses in the structure. One possible way of improving the performance of the design could be to use a substrate material with lower losses, or by more conservative use of soldering tin, as it can also provide some small losses.

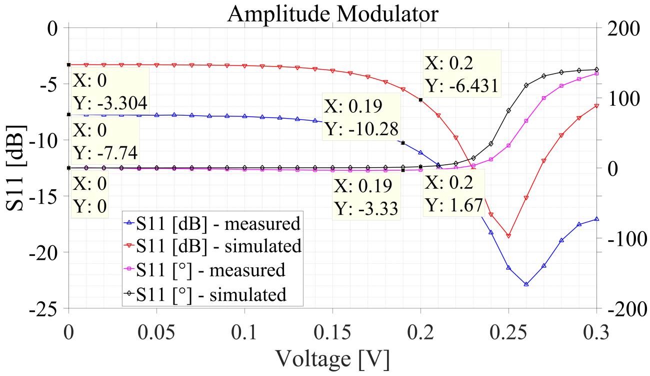

Figure 3. Simulated and measured performance of the amplitude modulator.

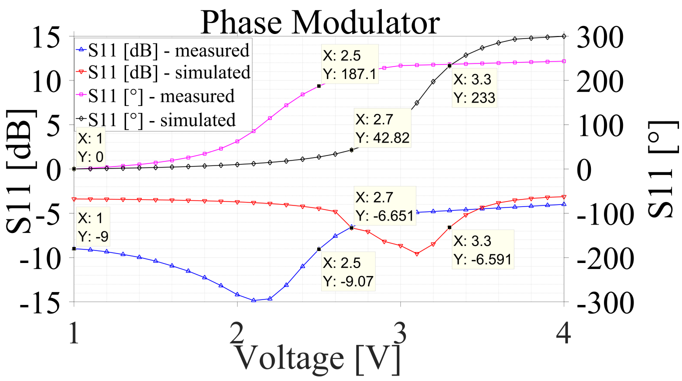

Figure 4. Simulated and measured performance of the phase modulator.

Table 3. Simulated and measured signal at port 1 of the amplitude modulator.

V_{bias} (V)	$\lvert S_{11}\rvert$ (dB)	$\angle S_{11}$ (°)	Comments
0	–3.3	0	Simulation
0.20	–6.4	1.67	result
0	–7.7	0	Measurement
0.19	–10.3	-3.33	result

Table 4. Simulated and measured signal at port 1 of the phase modulator.

V_{bias} (V)	$\lvert S_{11}\rvert$ (dB)	$\angle S_{11}$ (°)	Comments
2.7	–6.551	42.82	Simulation
3.3	–6.591	233	result
1	–9	0	Measurement
2.5	–9.07	187.1	result

4 Conclusion

This work has presented the design of a transponder based on the modulated re-scattering principle. In the proposed design, the amplitude and phase characteristics of the backscattered signal can be modified by applying a suitable bias voltage to the diodes in the amplitude and phase modulators. In simulations and measurements, the amplitude and phase can be modulated independently, and the transponder can provide more than 3 dB of amplitude modulation and a phase modulation of 180°. Future and ongoing work in this field includes using the proposed transponder concept for testing and characterizing software-defined radio based IoT networks.

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