Tunnel Diodes for Backscattering Communications

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Abstract

The authors want to give an overview about the research progresses done in the latest years to enhance ranges of microwave backscattering communications with RFIDs exploiting the tunneling effect of tunnel diodes. The first prototype of a Tunneling RFID Tag built using a tunnel diode outperformed semi-passive tags by at least a factor of 5 in range. Tests on the 5.8 GHz backscattering link reached 1.5 km of ranges and demonstrated that a DC power of only 20.4 μW and 2.9 $\frac{pJ}{bit}$ are required to operate the Tunneling Tag.

1 Introduction

Japanese researcher Reona (Leo) Esaki won the Nobel Prize in 1958 for inventing the tunnel (or Esaki) diode [1], the first proven electronic device that employed quantum tunneling. In subsequent years, the device never saw much commercial success, but it is nowadays experiencing its renaissance. Tunnel diodes operate at exceptionally high frequencies and have been used to transmit uncompressed videos in real time at 6 Gbit/s in the THz frequency range [2]. Their particular IV-characteristic made them suitable for RF energy harvesting applications [3] and for long-range 5.8 GHz backscattering links [4].

This paper focuses on how a tunnel diode can be used to develop a microwave Tunneling RFID Tag to achieve backscattering links that go beyond the typical ranges of this technology. After a look at the properties of its core component (the Tunneling Reflector), the experimental results obtained with the first Tunneling Tag ever manufuctured are showed in terms of achieved ranges and gains; these data are also compared against those of an ideal RFID tag not equipped with tunnel diodes.

2 The Tunneling RFID Tag

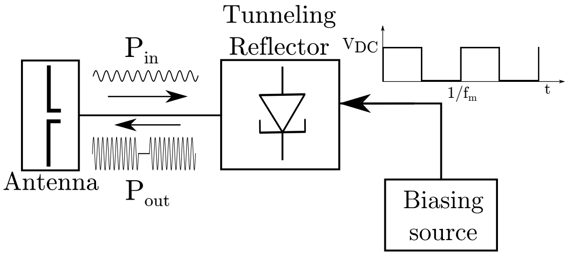

Figure 1. Block diagram of a Tunneling RFID Tag.

For a long-range backscattering link involving an RFID tag and a bistatic transceiver with co-located antennas, the received power P_r can be defined as:

$$P_r = P_T G_T G_R G_t^2 \left(\frac{\lambda}{4\pi r}\right)^4 G_{TR}; \qquad (1)$$

its strength depends on the transmitted signal P_T; the transmitting and receiving antenna gains (G_T and G_R); the tag antenna gain G_t; the frequency of operation; and the distance r between the tag and the transceiver nodes. A communication engineer can design a Tunneling RFID Tag (Fig. 1) so that its tunneling gain G_{TR} is can be greater than one. A Tunneling Tag is obtained by equipping its circuitry with a properly biased tunnel diode. Typically, such a solution can be detrimental for backscattering links since RFID tags are usually not equipped with any battery. Nevertheless, tunnel diodes require extremely low biasing powers to operate that is converted, through the *injection locking effect*, into RF and added, upon reflection, to the impinging RF signal. A Tunneling Tag provides a significant improvement to the achievable ranges at the cost of very low biasing power. Moreover, the modulation of the applied voltages adds data on the amplified backscattered signals.

A Tunneling Tag consists of a Tunneling Reflector and an antenna transponder. The tested prototype was realized to work at 5.8 GHz. Despite the challenges of operating a long-range low-powered backscattering link at this frequency, experimental results demonstrated the capability of the Tunneling Tag to go beyond the hundred-meter ranges. The Tunneling Reflector is the core component; it consists of a microstrip line on FR408 substrate[1] mounting a tunnel

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[1] ε_r = 3.66 and $\tan\delta$ = 0.0127 at 5 GHz.

Table 1. S-parameters amplitudes of Tunneling Reflector at 5.8 GHz for different biasing levels and RF input power P_{in} = -55 dBm.

Bias (mV)	$\|S_{11}\|$ (dB)
0	-1.87
90	27.24
130	7.47
180	-12.78
270	20.31

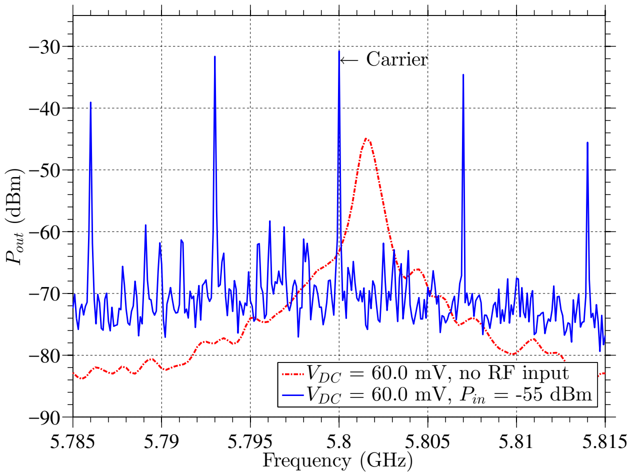

Figure 2. Locking of the Tunneling Reflector for f_{in} = 5.8 GHz, P_{in} = -55 dBm, f_m = 7 MHz and V_{DC} = 60.0 mV. Signal Analyzer Settings: 3 kHz RBW; 100 kHz VBW; 100 MHz span; 1001 points. An early version of this plot appeared in [5].

diode that, through proper biasing, amplifies and modulates the impinging RF signal. The one port S-parameter data, $|S_{11}|$, collected by connecting the Tunneling Reflector both to a vector analyzer and a biasing source, suggest the possibility of implementing amplitude modulation of the Tunneling Tag by turning on and off the biasing source. In fact, as shown in Tab. 1, amplifications occur only when a proper biasing voltage is applied.

Amplitude modulation was demonstrated by injecting, into the Tunneling Reflector, a 5.8 GHz input RF carrier P_{in} = -55 dBm while a modulating square wave of amplitude V_{DC} = 60.0 mV and frequencies f_m at 250 kHz, 1 MHz and 7 MHz were applied. The observed output at 7 MHz is shown in Fig. 2; In the same Figure, the modulated output signal, P_{out}, is compared with the output generated by the device when a constant 60.0 mV bias and no RF input are applied; in this case, the absence of an RF input does not trigger any injection locking and no modulation nor amplification take place. At 60.0 mV, the modulating square wave drives a current of 340 μA (20.4 μW) corresponding, at 7 MHz, to a total energy consumed per bit of 2.9 $\frac{pJ}{bit}$; much lower than the energy consumption of a Bluetooth Low Energy (BLE) module that is usually of the order of tens of nJ.

3 Backscattering with the Tunneling Tag

To demonstrate the wireless capabilities of the Tunneling Tag, successful field tests were conducted extensively by varying the distances r of the tag from the RF transceiver [4]. For each distance, a biasing voltage V_{DC} of 60.0 mV and a modulation frequency f_m of 250 kHz were applied. Since the Tunneling Tag demonstrated a very high sensitivity, a measurement setup characterized by a transmitting power P_T of only 0 dBm, a total Equivalent Isotropic Radiated Power (EIRP) of only 6 dBm[2], and a receiving antenna gain of G_r = 24 dBi was used to test the prototype communication capabilities up to 160 m. The wireless experiments allowed to measure the average received powers P_r (Fig. 3) and were compared against those expected by an ideal semi-passive RFID tag (G_{TR} = 0 dB) when using the same measuring setup. Lower RF impinging RF powers P_{in} trigger higher gains in the Tunneling Tag when a proper bias is applied, allowing a substantial extension of the backscattering link range. Assuming free-space propagation, the gains G_{TR} added by the Tunneling Reflector were also estimated and plotted in Fig. 3 as function of the distance r from the transceiver. A maximum backscattering range of 1.5 km was also demonstrated by increasing the EIRP of the transceiver up to 28 dBm and using more directing tag (G_t = 24 dBi) and receiving (G_T = 24 dBi) antennas.

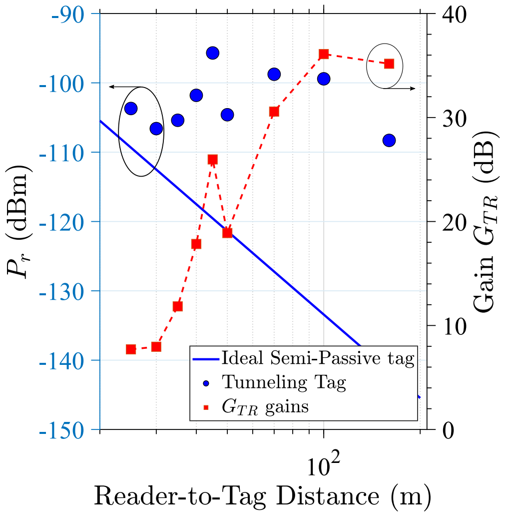

Figure 3. *Left Axis*: received signal strengths P_r in free-space as function of distances r (from 25 to 160 meters); results are compared against an ideal semi-passive tag (M = 1 without Tunneling Reflector). *Right Axis*: measured Tunneling Reflector gains, G_{TR}. Setup: biasing voltages V_{DC} = 60.0 mV, , modulation frequency f_m = 250 kHz, P_T = 0 dBm, G_T = G_t = 6 dBi, G_R = 24 dBi.

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[2] FCC regulations allow EIRPs up to 36 dBm

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