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An Optical to Wireless Data Link Using Radio Frequency Backscatter

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Abstract—The changes in the impedance of an antenna-coupled photo-detector under optical illumination are used to encode data on a backscattered wireless signal similarly to the standard techniques used for radio frequency identification and tagging. The effect is strong enough to allow retrieval of the information without requiring a dc supply at the optical to wireless interface.

Index Terms—Backscatter, homodyne systems, on-off keying.

I. INTRODUCTION

Radio frequency identification technology (RFID) devices and schemes have traditionally exploited the principle of modulated backscatter produced by impedance changes of a transponder or tag in order to encode binary information on microwave frequency carriers [1]. Optically modulated backscatter has been used as a tool to map out radiation patterns from antennas [2] but not to transfer data. In this study, we investigate a variation of the RFID technique, where the impedance changes are produced by on-off switching of an unbiased photo-detector subjected to optical illumination and demonstrate its capability as a very low power data link.

We employ a pseudo-random bit sequence (PRBS) to switch the impedance of an antenna coupled photo-detector between two different values in a similar way to the popular on-off keying modulation scheme [3]. The modulated impedance is then used to produce a backscatter signal that can be read by an interrogator circuit at microwave frequencies. The system is implemented at a carrier frequency of 1 GHz and a bit rate of 5 Mbit/s. In this study the data rate has been limited by the power and frequency resolution of the arbitrary waveform generator required to produce the optical switching, and not by the intrinsic principle of operation of the system. The optical part of the link is powered by the optical signal with typically 1 mW average power.

The microwave interrogator works as a monostatic, homodyne transceiver with a single radio frequency source that is used to carry the modulated backscatter information. Under proper conditions, the modulation can also be used to obtain phase information from the carrier to assist antenna steering towards the interface [4]. The optical part of this system operates at a center wavelength of 1550 nm and is implemented with a laser diode (LD) and photo-detector (PD) coupled to a radio frequency (RF) antenna.

II. PD VARACTOR EFFECT

The RF output port of a commercial photo-detector is plugged directly to an omnidirectional 0 dB gain microwave antenna that has been tuned for operation at 1 GHz [5]. The optical input of the PD is connected to a 1550 nm semi-conductor laser source. The change of the PD RF output impedance is shown in Fig. 1 for the cases when the laser source power changes between off and on with a power of 0 dBm. The light source modulation is accomplished by means of an LD which has its electrodes connected to the output of an arbitrary waveform generator (AWG). The LD light is coupled to the PD using a lens fiber aligned to its beam with a micro-positioner.

Fig. 1(a) shows the PD output impedance change between frequencies of 800 MHz and 1.2 GHz. Fig. 1(b) shows the magnitude change of $S_{11}$ in the same frequency range. This change translates as a difference on the reflection coefficient of 13 dB at 1 GHz. An incident RF carrier to the PD will suffer a reflection twenty times higher under the illuminated state, which is equivalent to an increased radar cross section (RCS) seen from a wireless transceiver [6]. In this study, we exploit that change to encode binary information and transmit it from the optical to the wireless domain.

A circuit schematic of the PD RF model is shown in Fig. 2(a). The device can be represented as a varactor with equivalent capacitance values varying between the PD diode junction capacitance under darkness ($C_{dark}$) and illumination ($C_{ill}$) conditions. The model is completed with an inductance $L$ (due to packaging of the PD), the bulk resistance $R$ of the PD substrate material (due to low-doped semiconductor buffer layers), the RF input impedance $Z_{in}$ ($\sim 50 \Omega$), and the interconnecting transmission line ($Z_0 = 50 \Omega$) [7]. A comparison between the simulated and measured values of $S_{11}$ is shown in Fig. 1 for the cases of darkness ($C_{dark} = 0.65 \text{ pF}$ ) and illumination ($C_{ill} = 3 \text{ pF}$) of the PD. A good agreement with the measured $S_{11}$ is obtained at the carrier frequency of 1 GHz. In the dark state, the difference between measurement and simulation is kept below a 3 dB variation in the magnitude of $S_{11}$ for a bandwidth of 400 MHz between carrier frequencies of 800 MHz and 1.2 GHz [Fig. 1(b)]. For the illuminated state, the experimental and simulated $S_{11}$ curves are indistinguishable.

The commercial PD used in these experiments has been designed to detect an optical signal with a power level that does...
not affect the broadband impedance matching of the RF output. In order to produce a substantial impedance change (10% of the impedance magnitude), the optical power has to be increased to a level above $-5 \text{ dBm}$. The changes, however, are important for the application proposed in this study and are required to modulate the wireless backscatter.

The capacity to retrieve the information contained in the backscatter modulation is a function of the RF power received and the radar cross-section of the antenna-PD interface [6]. The backscattered RF power is inversely proportional to the distance $d$ from the RF source ($\sim 1/d^6$). In this study, however, it is demonstrated that even with such low received power levels, the binary information can be retrieved wirelessly using off-the-shelf components commonly available for mobile communications systems.

Fig. 2(b) shows the measured spectrum of a 1 GHz carrier signal backscattered from the antenna-PD interface optically modulated with a 5 MHz square waveform. The measurement was obtained at a distance $(d)$ of 4 cm and co-located with the RF signal source using a microwave circulator. The RF power level used from the source was 5 dBm.

The PD used in these experiments is a packaged commercial 50 GHz bandwidth device with 0.65 A/W dc responsivity at 1550 nm ($u^2t$ Photonics XPDV2020R). The LD is a Fabry-Pérot, InGaAsP buried hetero-structure device, with $\sim 6 \text{ mW}$ threshold current, 0.25 W/A slope efficiency, 12 GHz modulation bandwidth, and a 50 $\Omega$ matched input (CST GLOBAL Ltd.). The lens fiber used for coupling the light from the LD output facet to the PD has a spot diameter of 5 $\mu$m and a working distance of 26 $\mu$m.

III. EXPERIMENTAL SETUP

Fig. 3 shows the different components required to assemble the optically modulated backscatter interface. The antenna-PD, and modulated light source are represented in Fig. 3(a). An auxiliary antenna is used to monitor the RF spectrum of the backscatter and co-located with the interface [Fig. 3(b)]. The wireless homodyne transceiver or interrogator is placed at a distance $d$ from the interface and illustrated in the diagram of Fig. 3.

The signal generator in Fig. 3(c) is tuned to the frequency of 1 GHz with a power output of 5 dBm. The signal is divided and sent to the transmitter antenna and the interrogator de-modulator local oscillator port. The received modulated backscatter is coupled to the de-modulator by a microwave circulator that is also tuned to the carrier frequency of 1 GHz. The de-modulator consists of an off-the-shelf commercial circuit AD8347 and differential receiver AD8130 commonly used for radio communication links. The AD8347 circuit includes automatic gain control

![Fig. 1. Radio frequency response of photo-detector under darkness and illumination with 1550 nm optical fiber power of 0 dBm (Z$_0 = 50$ $\Omega$). (a) $S_{11}$ measured (continuous) and simulated (dashed) (b) magnitude of $S_{11}$ measured (continuous) and simulated (dashed).](image1)

![Fig. 2. (a) Electrical model of PD for the case of darkness ($C_{vak}$) and illumination ($C_{an}$). (b) Spectral components of backscattered radio frequency signal.](image2)

![Fig. 3. Experimental setup of optical-wireless interface showing (a) modulated backscatter interface photo-detector and antenna, (b) auxiliary monitor antenna, and (c) wireless interrogator.](image3)
capable of a total RF and baseband gain of around 70 dB. The high gain allows an increase of the backscatter power spectrum sidebands observed in Fig. 2(b) to a level closer to the nominal power required for waveform demodulation (−10 dBm).

A low-noise amplifier was inserted between the RF reception of the circulator and the input of the demodulator circuit. The LNA allows further enhancement of the baseband spectral components. A maximum LNA gain of 20 dB at 1 GHz was used in the experiments reported in this study.

The demodulated waveform is monitored by an oscilloscope as shown in Fig. 3(c). The oscilloscope is triggered by the same arbitrary waveform generator that was used to modulate the 1550 nm LD source in Fig. 3(a). This allows synchronization between the data used at the interface, and the data received by the interrogator.

IV. DATA TRANSMISSION

A PRBS word of 100 b at a data rate of 5 Mbit/s was used to modulate the LD source illustrated in Fig. 3(a). The pattern was implemented as a non-return to zero (NRZ) sequence with a peak-to-peak voltage of 3.5 V that switches the laser diode output between on and off states. The backscatter produced by the modulation is received by the interrogator and the oscilloscope in Fig. 3(c), which recover the RF transmitted bit word.

The eye diagram obtained from the oscilloscope 100 b waveform acquisition is shown in Fig. 4. An estimation of the eye diagram quality factor ($Q_{factor}$) can be obtained from information of the received voltage levels at the top ($P_{top}$) and base ($P_{base}$), as well as the standard deviation of the measured voltage levels ($\sigma_{top}, \sigma_{base}$)

$$Q_{factor} = \frac{P_{top} - P_{base}}{\sigma_{top} + \sigma_{base}}.$$ (1)

This equation can be used under the assumption that the amplitude noise has a Gaussian distribution [8]. The values of $P_{top}$ and $P_{base}$ were obtained by averaging the received and measured voltage levels of $10^6$ b for the cases of high (> 0 V) and low (< 0 V) states, respectively. Using this technique the values obtained were $P_{top} = 107$ mV and $P_{base} = -104$ mV. Similarly, the standard deviation was calculated using the same sample size of measured bits and the calculated average levels $P_{top}$ and $P_{base}$. The obtained values were $\sigma_{top} = 24$ mV, and $\sigma_{base} = 23$ mV. Substitution of these values in (1) gives $Q_{factor} = 4.45$. An estimation of the bit error rate (BER) can be obtained from these parameters if the $Q_{factor}$ from (1) is considered as the minimum possible value allowed at a given rate [8]

$$BER = \frac{1}{2} e^{-\frac{Q_{factor}}{\sqrt{2}}}.$$ (2)

The value of BER calculated from the backscattered data transmission in the system of Fig. 3 was $4.3 \times 10^{-6}$. A direct measurement of BER was also performed by capturing a total number of $10^6$ b ($10^4$ waveforms) and comparing the value of each integrated symbol with the original bit pattern supplied to the arbitrary waveform generator. A sampling frequency of 50 Msps was used in those experiments. No errors were found on the total number of bits transmitted, which implies that BER values below $10^{-6}$ can be achieved.

V. CONCLUSION

In this study, an optically powered wireless interface demonstrator has been presented. The principle of modulated backscatter due to impedance changes has been exploited as a mechanism for data transmission from optical to wireless domains. The optical part of the interface does not require power originated from electrical mains, and with average optical power of 0 dBm and RF power of 5 dBm has been shown capable of operating wirelessly at 5 Mbit/s with BER values below $10^{-6}$. Neither filtering nor amplification has been necessary at the interface in order to demonstrate the operation of the system. A wireless interrogator based on off-the-shelf components was successfully implemented for extraction of the binary information. The interrogator works as a homodyne transceiver with a simplified topology that does not require carrier frequency tuning in order to download data from the optical to wireless interface.

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