An Optical Wireless Temperature Sensor

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Abstract—This paper presents a wireless temperature sensor that uses GaAs as a wireless transmitter of information. Transmission of information with a solar cell is possible by modulating the luminescent radiation emitted by the solar cell. This technique, dubbed Optical Frequency Identification or OFID, was recently reported in the literature and in this work is used to transmit temperature measurements wirelessly. The hardware design of an OFID temperature sensor tag and its corresponding reader is described. A prototype of the proposed sensor was built as a proof of concept. Experimental results demonstrate wireless data transmission at a distance of 1 m distance and at a bit rate of 1200 bps. The wireless temperature sensor has a maximum error of 0.39 $^{\circ}$C (after calibration) with respect to a high-precision temperature meter.

Index Terms—wireless sensors, photo-luminescence, energy harvesting, optical communications

I. Introduction

Radio communications has been the dominant wireless technology for a growing number of interconnected Internetof-Things (IoT) devices. It has been predicted that the number of deployed IoT devices will reach 24 billion by 2020 [1]. Such a large number of IoT devices is expected to increase electro-magnetic (EM) interference in radio bands degrading communication throughputs. Moreover, in some scenarios, such as hospitals and airplanes, radio transmissions are altogether discouraged to minimize EM interference with sensitive equipment.

Visible light communications (VLC) is a wireless alternative for IoT devices that is not affected by EM interference and that enjoys unlicensed access worldwide [2]. A VLC scheme dubbed Optical Frequency Identification or OFID, in which a solar cell is used as an optical wireless transceiver, was proposed in [3]–[5]. In OFID, the luminescent radiation of a solar cell is modulated to transmit information optically and wirelessly. Furthermore, by exploiting the photo-transduction property of a solar cell, it can also be used to receive information encoded optically. In this work, a wireless temperature sensor tag based on the OFID concept is presented.

Fig. 1 depicts a conceptual diagram of the proposed OFID temperature sensing system. The system comprises an OFID temperature sensor tag and a reader. The main components of the sensor tag are a GaAs solar cell, a PL modulator, an energy harvester, a data receiver, a microcontroller (MCU) and a temperature sensor. The tag also includes a super-capacitor (SC) to store harvested energy. The OFID sensor tag uses its solar cell for three different functions: data transmission, data reception and conversion of radiant energy into electricity. On the reader side the main components are an LED driver, a data receiver, an LED and a photo-diode. The reader also includes the necessary optics to focus the light emitted by the LED and the solar cell. An MCU controls all the reader functions and presents data to a user via an LCD display.

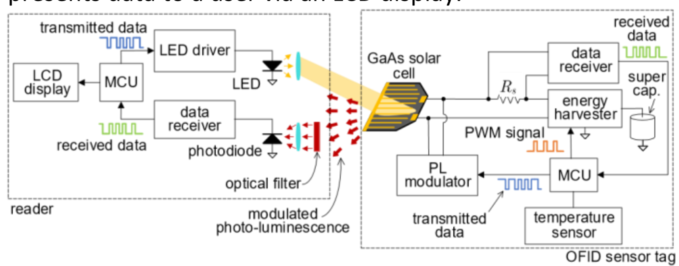

Fig. 1. Conceptual diagram of the OFID temperature sensing system. The system consists of an OFID sensor tag and a reader.

The reader shown in Fig. 1 is an active reader as it actively illuminates the solar cell to stimulate the generation of PL radiation. Unlike silicon, GaAs has a direct bandgap electronic structure, which results in strong luminescent emissions. For GaAs, these emissions are in the near infrared region of the EM spectrum (∼880 nm). The luminescent radiant flux of a solar cell is a function of the voltage across its terminals [4]. Hence, it can be modulated by varying the load connected to the solar cell. In this work On-Off Keying (OOK) modulation is achieved by connecting and disconnecting the solar cell to a switched inductor DC-DC converter. The DC-DC converter works as an energy harvester by moving packets of charge from the solar cell to a SC and in this process boosts the relatively low voltage generated by the solar cell (∼0.8 V to 1.0 V) to a voltage that is more suitable to power electronic circuits.

II. OFID Sensory System Hardware Design

This section describes the OFID sensor tag and the reader hardware. The tag and the reader are built using commerciallyavailable components. Best efforts at the hardware and software levels have been made to reduce the power consumption of the tag while keeping it flexible enough to test different communication and energy harvesting strategies.

A. OFID Temperature Sensor Tag

Fig. 2 shows a schematic diagram of the OFID temperature sensor tag. The solar cell employed in the tag is a singlejunction GaAs solar cell from Alta Devices [6]. This cell has a record efficiency of 28.8% and exhibits a strong luminescence response. The energy harvester is a traditional switchedinductor boost DC-DC converter. When the NMOS transistor, M_1, in this converter is closed, the inductor charges from the solar cell and when M_1 opens, the inductor discharges into the SC. The input capacitor, C_d, stabilizes the voltage across the solar cell during charging and discharging of the inductor and helps to reduce the ripple noise introduced by the switching action of M_1. Selecting the value of C_d involves a tradeoff between ripple noise, bandwidth and DCDC conversion efficiency [7]. In this work, C_d is set to 10 μF. The MCU (Atmel SAML21J17B) generates the clock signal φ that drives M_1. The MCU executes an algorithm that sets the duty cycle of φ such that, maximum power is transfered from the solar cell to the SC. When maximum power is transferred to the SC, the solar cell is said to be operating at its Maximum Power Point (MPP). An MPP tracking algorithm known as fractional open circuit (OC) voltage tracking algorithm is implemented in the MCU.

The data receiver consists of current-sense resistor R_s, instrumentation amplifier A_1 (Texas Instruments INA122), a second-order bandpass filter (constituted by amplifiers A_2 and A_3 and their corresponding resistor-capacitor networks) and voltage comparator COMP (Texas Instruments LMV7239). The bandpass filter removes DC offset due to ambient light and ripple noise due to the switching action of the energy harvester.

The PL modulator consists of a CMOS analog switch S_1 (Texas Instruments TS3A4751) and a voltage buffer. Modulation of the PL radiation is carried out by opening and closing S_1. When S_1 is open, the solar cell is left in OC condition. When S_1 is closed, the solar cell is forced to work at the MPP by the energy harvester circuit. When the solar cell is in OC, its PL emission is maximum as the photo-generated charges inside the solar cell cannot leave the cell, which results in maximum radiative recombination. When the solar cell gets connected to the energy harvester, most of the photo-generated charges are able to leave the cell resulting in a significant drop in internal radiative recombination and, therefore, in the emission of infrared photons.

An analog temperature sensor (STMicroelectronics STLM20) is employed to measure temperature. The MCU's internal ADC digitizes the output of the temperature sensor and a scaled version of the SC voltage V_{SC}. Using the PL modulator, the MCU transmits a seven-byte packet of information when requested by the reader. Each packet contains a header byte, a payload-type byte, two bytes encoding temperature, two bytes encoding V_{SC} and a checksum byte.

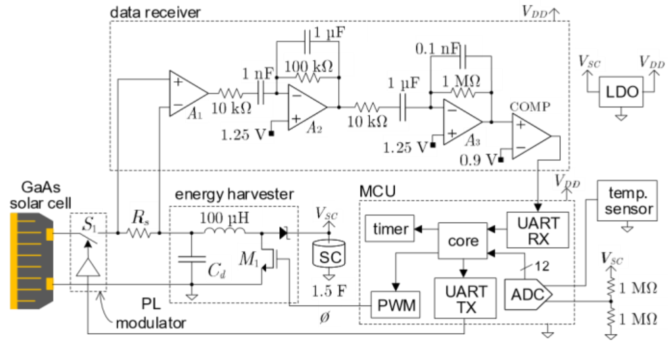

Fig. 2. Schematic diagram of the OFID temperature sensor tag.

B. Reader

A schematic diagram of the reader is shown in Fig. 3. The reader includes a high-power LED (Cree XPEBRD) with center wavelength of 625 nm and an LED driver circuit built around a DC-DC buck-boost converter (Maxim Integrated MAX16833). The dimming input of the LED driver is connected to the MCU's UART data transmission (TX) output. When the MCU is not transmitting data, its UART TX output remains high resulting in maximum LED brightness. The LED is kept inside a focusable flashlight to take advantage of the focusing optics. Data is transmitted from the reader to the sensor tag using four-byte packets. Each packet contains a header byte, a payload-type byte, a data byte and a checksum byte. These packets are used to transmit commands to the sensor tag. The commands that are currently implemented are: 1) data retrieval, which requests the transmission of temperature and SC voltage and 2) blink, which commands the sensor tag to blink its solar cell for few seconds. This command is used to verify basic functionality.

To receive data from the sensor tag, the reader employs a photo-diode (Vishay BPW34), a trans-impedance amplifier (TIA), a bandpass filter and a voltage comparator. The photodiode is housed inside a second focusable flashlight to allow the user to adjust the focus. An 850 nm long-pass optical filter is placed in front of the photo-diode optics to remove interference due to ambient light.

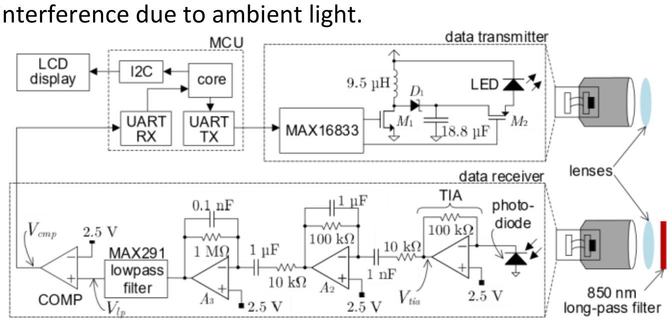

Fig. 3. Schematic diagram of the reader.

The MCU in the reader (Atmega328p) decodes received data packets. If the checksum of a received data packet matches a locally-computed checksum, the temperature and the SC voltage are calculated based on the corresponding packet bytes. A user interface, composed of an LCD display and two pushbuttons, allows the user to visualize received data as well as to send commands to the sensor tag.

III. Results

The proposed OFID-based temperature sensor system was built and tested to verify its functionality in terms of wireless communication, temperature sensing and energy harvesting. To verify optical data transmission from the sensor tag to the reader, selected waveforms from the tag and the reader were recorded. These waveforms are V_{mod} from the sensor tag and V_{tia}, V_{lp} and V_{cmp} from the reader and are shown in Fig. 4. For these recordings, the distance between the sensor tag and the reader was set to 1 m and the bit rate was set to 1200 bps. As it can be seen, the waveform received by the reader (V_{cmp}) matches very well with the waveform transmitted by the sensor tag (V_{mod}).

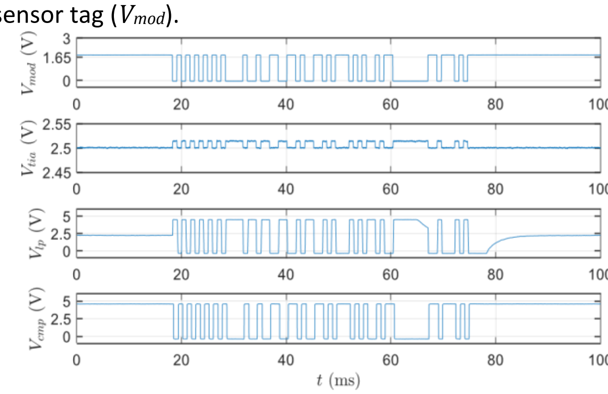

Fig. 4. Recorded waveforms V_{mod} from the sensor tag and V_{tia}, V_{lp} and V_{cmp} from the reader.

To evaluate the capacity of the sensor tag to harvest radiant energy while transmitting information, the sensor tag was programmed to transmit a data packet every five seconds. The sensor tag was illuminated by the reader at a distance of 1 m and the voltage across the SC (V_{SC}) was recorded. This voltage was also recorded when the sensor tag transmitted no information. The recorded waveforms are shown in Fig. 5. The inset in the figure shows the transmission events. From this figure we can see that when the sensor tag transmits data (data transmission on), the SC gets charged 111.7 mV above its initial value of 3.506 V after 10 min as opposed to 127.7 mV above its initial value when the sensor tag does not transmit data (data transmission off). This experiment reveals an important tradeoff in OFID-based communications, namely, wireless transmission with a solar cell comes at the cost of lowered harvested energy. This is due to the fact that, in order to modulate PL, the solar cell is left in OC for some periods of time. During this time the sensor tag cannot harvest energy.

Lastly, an experiment to demonstrate wireless temperature sensing was carried out. Fig. 6 (right) shows the setup for this experiment. The sensor tag was placed on top of a regulated heated plate. For reference, a high-precision temperature

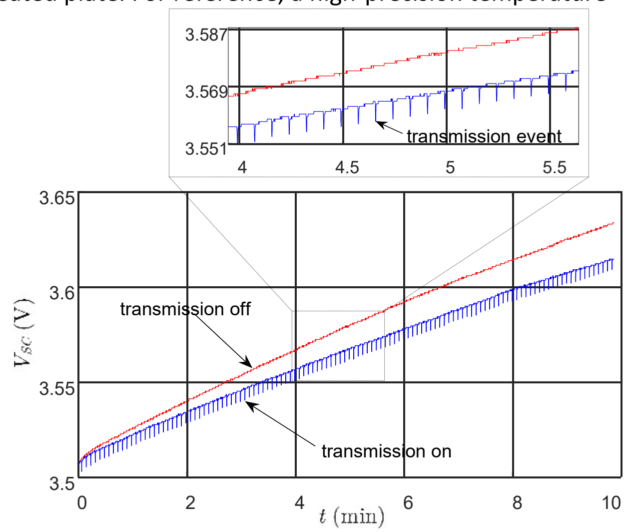

Fig. 5. Recorded SC charging profiles with and without data transmission

meter (Omega Engineering HH804) was used to measure the temperature of the sensor tag. Using the heated plate, the sensor tag was heated to about 30°C and its temperature was progressively brought down to room temperature (~22°C). Fig. 6 (left) shows the recorded temperature values. An offset of about 1.8°C was observed between the sensor tag and the HH804 meter. After this offset was removed (calibrated), the sensor tag achieved a maximum error of 0.39°C with respect to the HH804.

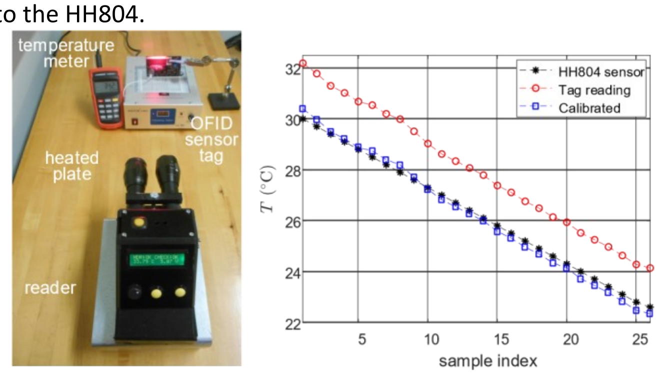

Fig. 6. Experimental setup demonstrating wireless temperature sensing.

IV. Conclusion

The design and implementation of an OFID wireless temperature sensor was presented. The sensor's on-board GaAs solar cell was used as an optical wireless transmitter and receiver. The photo-luminescence of the solar cell was digitally modulated to transmit temperature and the state of charge of the sensor's energy reservoir (a super-capacitor). Experimental results demonstrating the functionality of the temperature sensor were presented and discussed.

Acknowledgment

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