MEMS-BASED NEAR-ZERO POWER INFRARED WIRELESS SENSOR NODE

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ABSTRACT

This paper reports on the first demonstration of an infrared (IR) wireless sensor node (WSN) with near-zero standby power consumption. The prototype presented here employs a plasmonically-enhanced micromechanical photoswitch (PMP) that exploits the energy contained in the impinging IR spectral band of interest itself, to perform passive sensing and digitizing functions. The palm-sized IR WSN demonstrated in this work comprises a vacuum-packaged PMP (IR power threshold ~284 nW, lithographically-defined IR absorptance: ~89% at 4.6 µm, 0.75 µm bandwidth) connected to a CMOS load-switch which wakes up a coin battery-powered sub 1-GHz wireless microcontroller to transmit data when the IR signal of interest is detected. The standby power consumption for the IR WSN was measured to be just ~2.6 nW: a >1900X improvement over state-of-the-art pyroelectric IR WSNs, while offering integrated spectral-selectivity. This work represents the first demonstration of an OFF-but-alert WSN that awakens only in the presence of a signal of interest, resulting in near-unlimited battery-life when deployed to detect infrequent but time-critical events.

INTRODUCTION

Due to the emerging IoT revolution, there has been a rising demand for greater numbers and densities of remotely-deployed sensor nodes. However, state-of-the-art sensors use active electronics (for signal conditioning and processing) to monitor the environment and consume electrical power continuously even when the targeted signals of interest are not present (i.e. at standby). In most of the IoT applications (i.e. indoor/outdoor environmental monitoring) the target of interest appears infrequently leaving the sensor in standby for the great majority of its lifetime. Therefore, most of the battery's energy is wasted to process irrelevant data while waiting for the signal of interest [1,2]. This fundamentally limits the number of wireless sensors that can be deployed in an IoT network due to the unsustainable costs associated with battery replacements.

Recently, device concepts that fundamentally break the paradigm of using active electronics for sensing have been proposed—sensors that remain dormant with near-zero power consumption until awakened by a specific target of interest [3-6]. In essence, these sensors harvest various forms of energy (e.g. vibrations, sound and electromagnetic radiation) emitted from a target of interest and use them to trigger a switch. The emissions themselves can act as specific signatures of the target. For example, a car emits vibration at certain frequencies from its engine and IR radiation at specific wavelengths from its hot exhaust. By designing sensors that only respond to a certain signature of interest, "event-driven" sensors with near-zero standby power consumption can be realized.

To this end, near-zero power IR digitizing sensors based on PMPs have been demonstrated previously on a device level, showing spectrally-selective IR detection thresholds down to 500 nW for detecting and discriminating infrared sources such as hot gas plumes [3,8]. In this work, a vacuum-packaged PMP with ~2X improved threshold is exploited for the first time at a system-level, resulting in the first experimental demonstration of a complete battery-powered, event-driven IR WSN with near-zero standby power consumption. Thanks to the nearly-complete elimination of unnecessary standby power consumption, the lifetime of IR WSNs is expected to extend by more than an order of magnitude (limited only by the self-discharge of the battery itself), enabling the realization of a new class of long-lasting "deploy-and-forget" remote IR sensing systems for massively scalable remote sensor networks.

DESIGN

The key component of the near-zero standby power IR WSN shown in this work is a PMP [3,8,9], which comprises a pair of symmetric bimaterial-based micromechanical cantilevers facing each other as shown in Fig. 1(a), with a pair of platinum (Pt) contacts attached to either side (Fig. 1(b)). Each cantilever has a square "head" which either absorbs or reflects IR radiation. The IR absorbing head incorporates a plasmonic IR absorber, implemented by a 2D periodic array of metal-insulator-metal structures [10], while the reflector head is made of a plain metal layer (Au). The plasmonic absorber features complete lithographic tunability of the spectral absorption band providing the ability to target any desired IR wavelength [10].

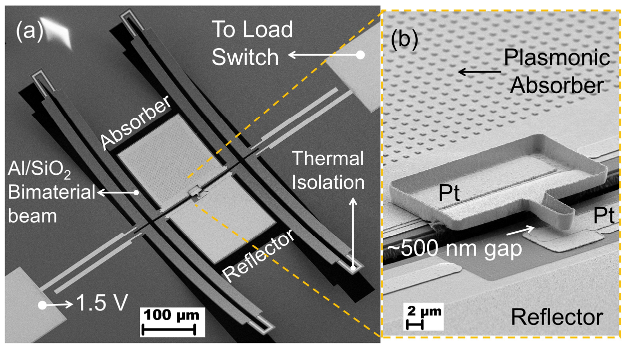


Figure 1: (a) Scanning electron microscope image of the PMP showing the temperature-compensated symmetric structure [3]. (b) Close-up of the bowl-shaped top contact and the bottom contact showing their physical gap, which guarantees near-zero subthreshold current and thus near-zero standby power consumption.

When IR radiation from a target matching the spectral absorption band of the plasmonic absorber impinges on the absorber head, a plasmonically-enhanced thermomechanical coupling occurs which heats up the adjacent Al/SiO_2 bimaterial beams causing them to bend down due to differential thermal expansion [3,9]. When the absorbed IR power exceeds the designed threshold, the bowl-shaped contact on the absorber head moves down and traverses the gap touching the other contact on the reflector head, thereby mechanically completing a low-resistance electrical path across the PMP. Differently from conventional IR motion detectors (pyroelectric, photodiode, etc.) that require active electronics (i.e. amplifiers and comparators) to digitize their output, the PMP relies on a pair of contacts separated by a design-defined gap to passively perform the comparator function while eliminating subthreshold leakage currents (<5 fA) [3], resulting in zero standby power consumption.

The PMP is designed to turn ON an active system (in this case a wireless transmitter) when a targeted IR signal is detected (such as the IR spectral emission bands from the gases in a vehicular exhaust plume), while keeping it completely disconnected from the power supply at all other times. To achieve this, the PMP ideally needs to be placed in series between the battery and the power supply terminal of the transmitter. However, this implementation requires the PMP to handle all the current drawn by the transmitter when turned ON. Due to thin metal routing layers used in the PMP's thermal isolation regions to maximize thermal sensitivity, the maximum current the PMP can handle is limited to ~200 μA, which is insufficient for the ~10's milliamps bursts of current required during wireless data transmissions. To overcome this limitation, the PMP is interfaced to the input of a low-leakage CMOS load switch as shown in Fig 2(a)– essentially a common-gate transistor whose gate is controlled by the PMP while the supply current flows through its source and drain (~200 mA limit) [11].

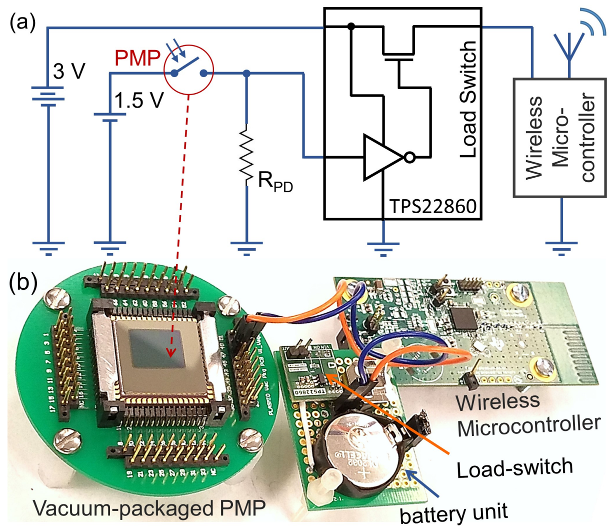
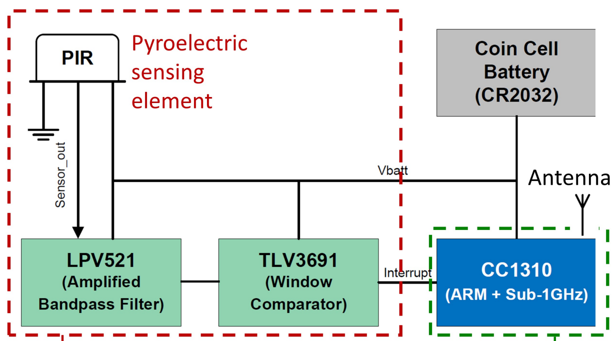


Figure 2: (a) Near-zero power IR WSN circuit schematic: the IR-activated PMP controls the load-switch, which connects the 3 V battery to the wireless microcontroller. (b) Image of the palm-sized IR WSN prototype demonstrated in this work.

In this configuration, the PMP is isolated from the supply current (from a 3 V coin cell), and can have a smaller independent applied voltage bias (supplied here by a 1.5 V button cell) for ON/OFF control of the load switch gate. The bias voltage of 1.5 V was chosen because it is larger than the load-switch's minimum turn-ON voltage but low enough to avoid electrostatic stiction issues. This scheme also allows biasing of the PMP for potential electrostatic threshold scaling [12]. A pull-down resistor (R_{PD}~330 kΩ) is employed to ground the load-switch gate in standby and to limit the current when the PMP is ON (PMP ON resistance~3 kΩ). Due to the near-infinite subthreshold slope of the PMP [3], the gate voltage of the load-switch is maintained well below the conduction threshold even upon exposure to large subthreshold IR power, resulting in a very low leakage current in standby. This PMP-load-switch implementation also makes it compatible with a variety of load electronics such as alarms, cameras and other more sophisticated sensors.

It is worth noting that the zero-power IR WSN prototype demonstrated here was designed based on the state-of-the-art low power PIR (passive IR) motion detector demonstrated in [2]. The microcontroller (CC1310), its clock circuit and its auxiliary RF antenna components for data transmission were implemented on the wireless microcontroller PCB shown in Fig. 2b without any layout modifications with respect to [2]. A block diagram of the original PIR sensor is shown in Fig. 3 with the reported standby current consumption– ~95% of which is drawn by the sensing element and its supporting signal processing electronics while the remaining ~5% is drawn by the microcontroller itself, resulting into a total standby current of ~1.65 μA. Therefore ~5 μW (3 V supply) of power is always consumed by the state-of-the-art PIR motion detector to process irrelevant data (even when leakage currents from high subthreshold IR signals is not considered).



Component	Standby Current
Sensor/Amplifier/filter	1.534 μA
Microcontroller	120 nA
Total	1.654 μA

Figure 3: Block diagram of the low power PIR WSN on which the prototype is based on (source: [2]). The sensing element (pyroelectric detector) requires active signal processing to provide a signal to the microcontroller when there is an above-threshold IR signal. The table shows the standby current drawn by the sensor and microcontroller. By replacing the components in the red dashed box with the PMP, this can be improved by orders of magnitude.

In this work, the pyroelectric sensing element of [2] and all its supporting active circuitry was replaced by the PMP-load switch circuit connected to the supply pin of the wireless microcontroller PCB (as shown in Fig. 2b), which drastically reduces the standby power consumption to a near-zero value. The PMP was vacuum-packaged (<1 mTorr) in a ceramic header with an IR-transparent germanium window using a low temperature (175°C) activated getter [13]. Since the need for processing an interrupt signal is completely eliminated in the proposed zero-power implementation, the program executed by the wireless microcontroller was greatly simplified to only output data to the pin connected to the RF antenna circuit whenever the power supply is connected (i.e. the PMP is ON) as depicted in Fig. 4.

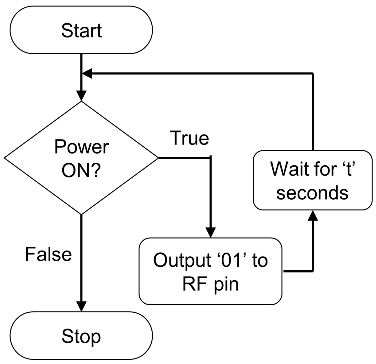


Figure 4: Flowchart of wireless module for the modified microcontroller program used in this work. The microcontroller module keeps transmitting the data packet at regular intervals of time (set by 't') until the power to the microcontroller is shut off. Note: during operation, there is no "if" logic processing in the microcontroller; there is only an infinite loop with a delay of 't' in each loop.

Experiment setup

The IR WSN was tested by placing the vacuum-packaged PMP in a lab environment under a calibrated blackbody source (CI Systems SR-200). The package was exposed to different IR wavelengths by rotating a filter wheel placed underneath the blackbody source while manually chopping the radiation. Seven different filters from 3 to 6 µm were used, each having ~500 nm bandwidth. A source-meter (Keithley 2450) set at 3 V was connected across the IR WSN's supply terminals to emulate the CR2032 coin-battery and was used to measure the standby leakage (when the radiation was chopped OFF) and the ON current (when triggered ON by IR) of the IR WSN. Since the standby leakage was extremely low, the standby current measurement was done by placing the IR WSN in a shielded chamber and using shielded triaxial cables to connect to the PCB boards. A USB wireless receiver dongle (Fig. 5b) was connected to a laptop to capture and display the IR-triggered RF transmissions and demonstrate the wireless functionality [2]. The Texas Instruments "SmartRF Packet Sniffer" software was used to parse and display the captured data on the computer. The laptop was placed about 10 m away from the IR WSN (limited by lab space, extendable to >220 m [2]).

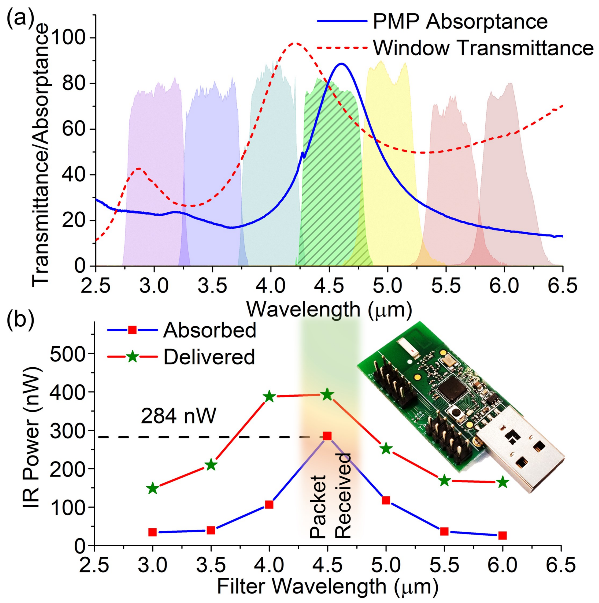


Figure 5: (a) Graph of the FT-IR measured PMP absorptance and the transmittance of the vacuum package's window and of the filters. (b) Graph of delivered and absorbed IR power for each filter (±5% uncertainty). The inset shows a USB receiver dongle (CC1111) which was used to capture the wireless data.

RESULTS

The PMP absorptance was measured using a FTIR microscope and found to be ~89% at 4.6 µm with a bandwidth of ~0.75 µm (Fig. 5a). It is worth noting that the transmission spectrum of the AR-coated Ge window (optimized for 8-12 µm) used in the PMP vacuum package is reasonably transparent within the PMP's absorption band (Fig. 5a). To find the device threshold, a 4.5 µm filter (closely matching the PMP absorption band) was employed while increasing the blackbody temperature until the PMP turned ON (IR ON current in Fig. 6a) and a packet was captured by the USB receiver. Using the method described in [3] based on IR power density measurements, a threshold of ~284 nW was estimated (Fig. 5b)– the best threshold achieved so far without voltage bias [3,8,9,12]. For reference, this translates into a possible detection range of ~7 m if the absorber was designed to detect a plume of NO_2 gas as described in [12]. Fig. 6a shows the response of the PMP to above-threshold chopped IR radiation at 4.5 µm. Using the filter wheel, the IR WSN was exposed to different IR wavelengths, and as expected, data was received only upon exposure to IR through the 4.5 µm filter (shown in shaded green in Fig. 5a). There was no response to IR exposure with any other filter even though the delivered power was similar (with 4 µm filter) as shown in Fig. 5b, thus demonstrating spectral selectivity of the IR WSN.

In order to measure the ON current and the standby leakage current (OFF current) of the IR WSN, the source meter was connected across the battery terminals (with battery disconnected) and the current was monitored as the IR radiation was chopped. Fig. 6b shows the measured current drawn by the IR WSN for a supply voltage of 3 V when the packaged PMP was exposed to chopped IR radiation. On exposure to above-threshold IR radiation at

4.5 µm, an average current of ~2 mA with spikes of ~30 mA is seen: these spikes correspond to the instances when a data packet was sent. Each transmission was captured by the USB dongle and displayed on the laptop with 0% misses (a screenshot of the received data, circled in red, is shown in Fig. 6d). Since the spikes lasted <10 ms, the source meter measurement speed was increased to observe them. But this increases noise due to reduced integration time in the source meter. A larger range setting (in this case 100 mA), and lack of any shielding also increases noise (seen in the IR OFF state which has a noise floor of ~5 µA with ~µA level of peak-peak noise).

To measure the actual standby current however, the same connections as for Fig. 6b were used but using triax cables in a shielded metal chamber. The source meter was set to a slower (5x) integration time and a smaller measurement range (10 nA). In this situation, as shown in Fig 6c, a current of just ~0.86 nA was measured (noise floor was ~5 pA, measured by disconnecting the supply). This translates to a standby power of just 2.6 nW: >1900x lower than the state-of-the-art sensor demonstrated in [2].

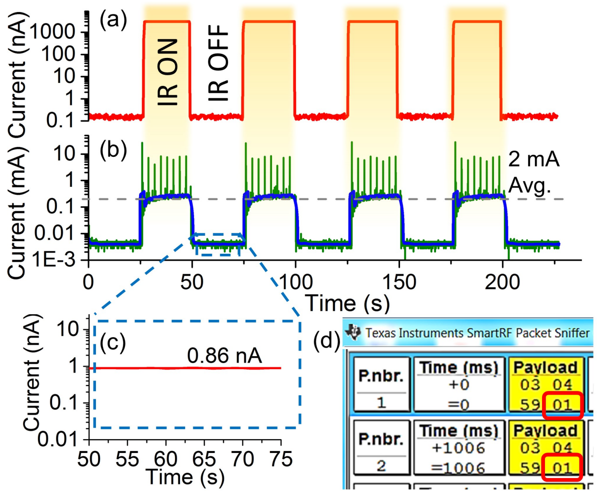


Figure 6: (a) Measured response of the PMP to chopped IR radiation. The source meter was connected across the PMP's terminals using jumper cables and a bias of 10 mV was applied while the current was monitored. (b) Measurement of the current drawn by the entire IR WSN in response to chopped triggering IR radiation. (c) Low-noise measurement of the standby supply current. (d) Software screenshot sample from laptop showing received packets. A wait time 't' of 1000 ms was used in the microcontroller program as seen in the timestamps.

CONCLUSION

In this work, for the first time, we designed and experimentally demonstrated a zero-power IR WSN prototype based on a PMP, a load switch and a wireless microcontroller. In addition to the near-zero standby power consumption (2.6 nW) and spectral selectivity, this IR wake-up system provides the capability to interface with and drive all kinds of commercial-off-the-shelf (COTS) electronics. Future work will involve more sophisticated PMP interconnection schemes that passively perform logic functions [8] to detect and discriminate between various IR signatures such as that of humans, vehicular exhaust, fires, etc. Through this technology we aim to usher a new era of "asleep-yet-aware", maintenance-free remote sensors with extremely long field lifetimes with applications in sensing, communication and security.

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