Poster Abstract: Enabling Non-contact, Low-Power Sensing using Tunnel Diodes

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ABSTRACT

Tracking movements in the environment of macroscopic objects enables numerous applications, from monitoring vital signs through body movements to inferring hand gestures. However, current systems overwhelmingly rely on contact-based sensors or energy-consuming radio frequency mechanisms that necessitate complex radio transceivers for receptions. We present ongoing research on a novel low-power sensor that leverages the unique characteristics of tunnel diodes. This sensor can detect minute changes in its vicinity and communicate these changes over radio waves, all while consuming under 150 microwatts of power consumption. Notably, the transmitted radio waves are processed using low-cost, off-the-shelf radio transceivers, resulting in low cost and power consumption. The sensor's functionality stems from the sensitivity of the resonant frequency of the tunnel diode oscillators to changes in their electromagnetic surroundings. Our early work exhibits its potential for detecting a person's breathing patterns, and hand gestures.

1 INTRODUCTION

The past decades has seen a growing interest in designing systems that track movements in the environment. They employ contact-based mechanisms, such as accelerometers, or observe changes in radio frequency (RF) signals to infer motion. Applications include tracking breathing rate [1], emotions [10], and gestures [5]. However, these sensing systems face challenges. Contact-based systems limit application scenarios where wearable devices are impractical. On the other hand, RF-based systems suffer from high complexity and power consumption. They typically require a dedicated device to generate high-frequency radio waves, which interact with the human body and produce reflected signals indicative of movement. Detecting minute variations in these reflections necessitates significant processing, including self-interference cancellation circuits and complex algorithms. Consequently, most systems rely on software-defined radios as receivers, resulting in high energy consumption, cost and complexity that hinder real-world applicability.

We present a novel sensing modality that can track minute changes in its vicinity in a non-contact manner, with a sensing range of tens of centimeters. The sensor itself is low-power, consuming less than 150 microwatts. By leveraging off-the-shelf radio transceivers, movements can be processed and inferred at distances of up to tens of meters from the sensor. Thus, the system enables low-power, low-cost, and low-complexity tracking of macroscopic object movements in the physical environment.

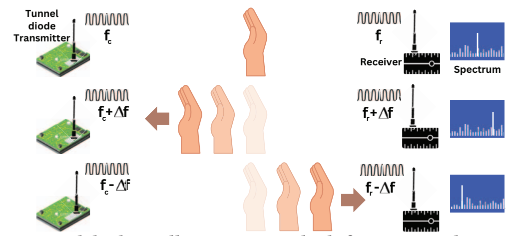

Figure 1: Tunnel diode oscillators generate high-frequency radio waves with a power consumption of under 150 microwatts. Movements near a tunnel diode oscillator alter the electromagnetic environment in its vicinity, leading to changes in the oscillator's resonant frequency and, consequently, the frequency of the generated radio waves. These frequency variations can be detected using a commodity radio transceiver. We demonstrate a variation in the resonant frequency caused by hand gestures performed in its proximity.

The system is enabled by the unique properties of tunnel diodes, which are semiconductor devices that exhibit negative resistance at low voltages and current consumptions. This characteristic allows for the design of oscillators [7, 8], reflection amplifiers [2, 3], and sensors [4] at microwatts. Building on TunnelScatter [7], we design a low-power tunnel diode oscillator (TDO) that generates radio waves in the FM broadcast [6] and 868 MHz frequency bands, consuming under 150 microwatts of power. This low power consumption enables prolonged operation on small batteries or energy harvested from ambient environment and stored in a capacitor.

Tunnel diode oscillators are highly sensitive to minute changes in their surrounding electromagnetic environment. These changes can cause variations in the oscillator's resonant frequency. We demonstrate that hand gestures or the presence of a person near the TDO can induce such frequency changes in radio waves.

Beyond the sensor's low power consumption, it also reduces processing cost and complexity. The movements are replicated as frequency changes in the radio waves, eliminating the need for the radio receiver to isolate reflected signals from stronger incident signals. This simplifies receiver design and allows commodity radio transceivers to track resonant frequency changes and infer motion. This system has numerous potential applications. We demonstrate its ability to detect human breathing and hand gestures. Figure 1 presents a high-level overview of the proposed sensing system.

2 DESIGN

Our system comprises a low-power platform designed using a TDO and a receiver employing commodity transceivers. The platform can operate on a small battery or harvest energy from ambient sources,

*Co-primary authors contributed equally to this work. Yuvraj Singh Bhadauria conducted this work when he was visiting National University of Singapore.

979-8-3503-6201-5/24/$31.00 ©2024 IEEE
DOI 10.1109/IPSN61024.2024.00056

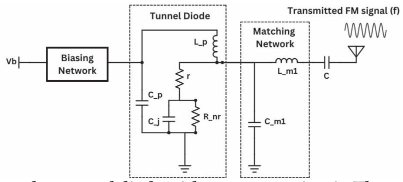

Figure 2: We couple a tunnel diode with a resonant circuit. The resonant circuit dictates the oscillator's frequency, and thus the frequency of the generated radio waves. Changes in the surrounding electromagnetic environment (such as macroscopic movements) can cause drifts in the tunnel diode oscillator's frequency, which serves as the basis for our sensing mechanism.

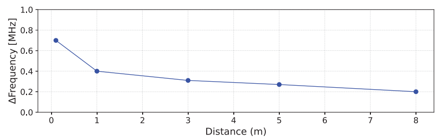

Figure 3: The drift in TDO frequency decreases with the increased separation between the TDO and the person making movements in the environment.

like light or radio waves, storing it on a capacitor. This stored energy powers a TDO, which generates carrier signals. Notably, the TDO resonant frequency shifts based on the movement in its vicinity, for example, hand gestures or a person's breathing. The radio transceiver, which may be built into a commodity device, then captures such variations and interprets these shifts to support end-user applications such as gesture detection or human vitals.

Generating radio-waves. Tunnel diodes exhibit negative resistance characteristics at low voltages and currents. This unique property, coupled with their low power consumption, makes them ideal for designing RF circuits such as amplifiers [2, 3] and oscillators [7, 8]. We employ a 3I306E tunnel diode to generate a carrier signal. As depicted in Figure 2, we couple the tunnel diode with a resonant circuit configured to generate a 96 MHz carrier signal with a strength of -12 dBm while maintaining a power consumption of approximately 150 microwatts. We have also tuned the circuit to generate a carrier in the 868 MHz frequency band.

Tracking radio-waves. The TDO encodes the movement information in the frequency variations of the radio waves it generates. This allows us to simplify the design of the receiver. In particular, we can employ commodity radio transceivers to track frequency variations. Most radio transceivers support the capability to track frequency variations of the radio waves. Furthermore, in this work, we also leverage an FM radio transceiver. It enables us to capture a raw audio stream, which we can then process using signal processing techniques [9]. In particular, the variations in the frequency of the TDO lead to changes in the amplitude of the acoustic signal, which can be used to infer the movement. For controlled experiments, we have also used a spectrum analyzer.

3 EARLY RESULTS

We present early results to demonstrate the ability of our system to track hand movements and breathing of the end-user.

Setup. We perform experiments by placing the platform on a desk powered by a regulated power supply. We perform hand gestures near the TDO (around 0.5 meters), and for breathing detection the person was sitting at a distance of 0.3 meters from the TDO. The receiver comprises a spectrum analyzer (Signalhound BB60c) or a software defined radio (ADALM-PLUTO).

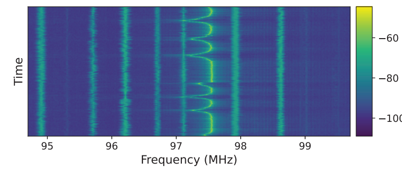

Figure 4: We observe drifts in the TDO frequency with the performance of hand gestures. The baseline resonant frequency of the TDO is 97.3 MHz.

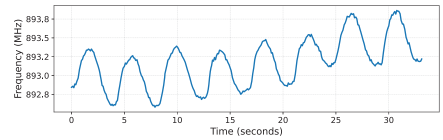

Figure 5: A person breathing close to the TDO causes changes in the resonant frequency of the oscillator, and thus the generated radio-waves. The magnitude of the change depends on the person's location from the TDO.

Frequency drift and distance. We investigate the impact of the distance between the person and the TDO. The person sits at different distances from the TDO, and we observe the frequency drift. As the distance between TDO and the person increases, the magnitude of drift from the baseline decreases, as shown in Figure 3.

Hand gesture sensing. We move the hand near the TDO to represent different gestures. We first establish a baseline, which is the frequency of TDO without any movement. Next, we observe the frequency drifts in TDO in the FM band as the gestures are performed. We demonstrate the variations in the TDO frequency in the waterfall plot in Figure 4.

Breathing sensing. We investigate our platform's ability to track the person's breathing. The person sits at a distance of 0.3 meters from the TDO. As the person breathes, the chest moves, corresponding to the breathing of the person. This results in changes in the frequency of the TDO. We capture these changes using a spectrum analyzer, and we show these results in Figure 5.

ACKNOWLEDGMENTS

We thank the reviewers for their comments. This work is funded through a grant from Advanced Research and Technology Innovation Centre (ARTIC) (A-8000976-00-00), a startup grant (A-8000277-00-00), and MoE Tier 1 Grant (A-8001661-00-00) hosted at the National University of Singapore.

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