Demo Abstract: Microwatt Microwave (M²) Oscillator: Enabling 105 µW, Stable and Standalone Transceivers

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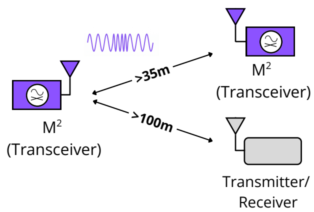
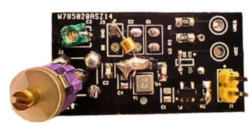
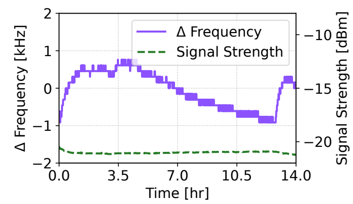


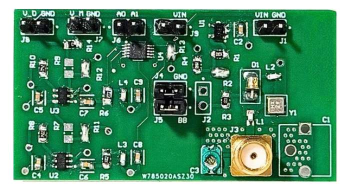
(a) Overview of M²



(b) M² oscillator prototype



(c) Long-term stability over 14 hours



(d) M² transmitter prototype

Figure 1: (a), (b) M² generates stable microwave signals through an oscillator that breaks the power-stability tradeoff, enabling standalone transceivers. (c) M² achieves a 2.10 ppm **frequency stability at** 434.22 MHz **over** 14 hours**, with a maximum drift of only** 916 Hz **under** 105 µW**. (d) Transmitter board instantiated using M².**

Abstract

Stable carrier generation at low power has long been a contradictory goal in communication. We demonstrate M², which challenges this assumption by coupling a tunnel diode with a SAW resonator to generate a microwave carrier at 105 µW with 2.10 ppm stability over extended durations. M² also exhibits self-oscillating mixing and autodyning, enabling standalone microwatt radio transceivers.

CCS Concepts

• **Hardware** → **Sensor devices and platforms**; **Wireless devices**; *Networking hardware*; • **Computer systems organization** → **Sensor networks**.

Keywords

Embedded systems, Wireless transceivers, Tunnel diodes

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1 Introduction

Radio transceivers remain the most power-consuming component in embedded systems. Despite rapid efficiency gains in microcontrollers and sensors, transceiver power is dominated by analog components such as oscillators, mixers, and amplifiers, which have not benefited from Moore's Law to the same degree as digital logic. Microwave oscillators are central to this challenge, since commodity wireless standards demand both high frequency precision and stability, historically achievable only at milliwatt-scale power.

This tension led to the delegation architecture, where carrier generation is offloaded to externally powered infrastructure [1, 2]. Backscatter is a prominent example: an emitter device (ED) generates the carrier while the tag modulates its reflection. While this lowers tag power, the resulting three-device topology (ED, transmitter, receiver) has hindered adoption beyond RFID applications. Returning to a true two-device architecture on a microwatt budget was considered impossible: phase-locked loops draw milliwatts, and microwatt tunnel diode oscillators (TDOs) lack the required stability at UHF frequencies [3]. M² challenges the assumption that low power and frequency stability are fundamentally incompatible.

We demonstrate M², a microwave oscillator that breaks this power-stability tradeoff by coupling a tunnel diode with a high-Q SAW resonator. Consuming 105 µW, M² generates a stable carrier in the 433 MHz ISM band with 2.10 ppm stability over 14 hours (Figures 1(b) and 1(c)). We show that M² maintains stability despite environmental changes including motion, voltage, and temperature variations, representing at least an order of magnitude improvement over related systems [3, 5], and that its self-oscillating mixing (SoM) property enables transmission. M² also exhibits autodyning, enabling the same circuit to serve as a complete receiver, thus enabling transceiver design (Figure 1(a)). We verify low power operation via a precision voltage supply. M² takes a major step toward a new class of standalone microwatt microwave transceivers [4].

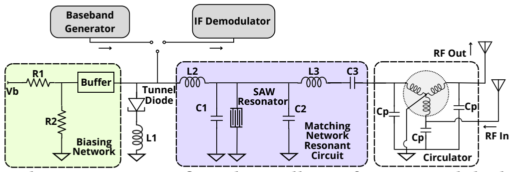

Figure 2: The SAW resonator fixes the oscillation frequency while the tunnel diode provides negative resistance to sustain oscillation. SoM and autodyning enable transceiver operation without discrete mixer stages.

2 Design and Evaluation

Stability. The quality factor (Q) of an oscillator's resonant circuit governs frequency stability, phase noise, and consequently link quality. Classical TDOs operating at UHF rely on LC tanks built from discrete inductors and capacitors. Parasitic resistance, skin-effect losses, and substrate dielectric losses limit Q to typically below 100, and because these parasitics are environmentally coupled, the oscillation frequency drifts with temperature, humidity, and antenna loading. Recent efforts such as SharpPeak [3] and AudioCast [5] avoid injection locking through careful bias control and shielding, but do not resolve the underlying low-Q stability problem. SharpPeak [3] reports MHz-range drifts under bias-voltage and temperature changes, making the design of transceivers adhering to commodity wireless standards challenging if not impossible.

A SAW resonator confines energy in a mechanical standing wave on a piezoelectric substrate, with the resonant frequency set lithographically by electrode pitch. The acoustic wavelength at UHF is micrometer-scale, concentrating energy with minimal radiative loss and yielding Q-factors exceeding 1000, an order of magnitude above lumped LC tanks. This higher Q directly attenuates the frequency shift caused by a given perturbation, ensuring superior stability.

Circuit design. M² couples a 1N3712 germanium tunnel diode to a 433.92 MHz SAW resonator through a custom matching and biasing network as shown in Figure 2. The SAW resonator fixes the oscillation frequency through its lithographically defined acoustic resonance, while the tunnel diode, biased in its negative differential resistance (NDR) region, supplies the negative conductance that sustains oscillation. The matching network (C_1, C_2, L_2, L_3) transforms the diode's impedance to SAW's motional impedance at its resonant frequency (f_0) and cancels the total circuit reactance within the SAW's narrow inductive window. A variable capacitor aligns the reactance cancellation point to this window; without it, fabrication tolerances prevent oscillation. An inductor L_1 in series with the diode compensates parasitic lead inductance and junction capacitance, isolating the matching design from device-level parasitics. The bias network uses a resistive divider (R_1, R_2) followed by a buffer to provide a stable bias point in the NDR region.

Transceiver. Beyond oscillation, the matching network preserves the tunnel diode's nonlinear I-V characteristic, enabling the same circuit to function as a transceiver. In transmission, this nonlinearity enables SoM: a low-frequency baseband signal is injected through the bias node, and the diode upconverts it to sidebands at $f_0 \pm f_{\text{baseband}}$ without a separate mixer (Figure 1(d)). In reception, the same nonlinearity enables autodyning [2], where an incoming RF signal near f_0 mixes with the self-generated carrier to produce an IF signal extracted by the demodulator. A single antenna and circulator route RF energy bidirectionally: the circulator directs the diode's outgoing carrier to the antenna for transmission and directs incoming RF to the diode for autodyne downconversion,

System	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz
Classical Inj.-locked TDO	−81.56	−88.94	−98.88	−116.90	−118.49
USRP B210 SDR	−87.07	−92.43	−99.05	−117.38	−118.75
M² (over the air)	−80.83	−92.30	−99.01	−109.93	−108.89
M²	**−83.08**	**−92.25**	**−99.29**	**−119.02**	**−118.82**

Table 1: M² exhibits phase-noise performance comparable to a commercial SDR and a classical injection-locked TDO, indicating high spectral purity.

while isolating the two paths. Small parasitic capacitances C_p at the circulator ports decouple the RF stage from external DC bias paths. This consolidates carrier generation and mixing into a single circuit, eliminating discrete oscillator and mixer stages.

Power consumption. We measure the power using a precision voltage source. The tunnel diode is biased at 156 mV, and the complete frontend including the SAW resonator consumes 105 µW. Without the SAW resonator, consumption is 70 µW, indicating that the resonator adds only 35 µW. M² does not require active temperature compensation, as ambient temperature variations in real-world deployments do not significantly impact frequency stability.

Phase noise performance. We evaluate M²'s phase noise against an injection-locked TDO and a commercial SDR. M² is connected to a BB60C spectrum analyzer via coaxial cable in an isolated room, and phase noise is measured at offsets from 1 kHz to 10 MHz using the analyzer's built-in function. As shown in Table 1, M²'s phase noise closely matches both references across all measured offsets, achieving SDR-like spectral purity at practically relevant offsets. It also remains significantly better than recent TDO systems [3, 5].

3 Demonstration

We demonstrate M²'s stability in the indoor conference environment. The setup comprises an M² transmitter, a classical TDO reference board, an SDR, a precision source measurement unit (SMU), and a laptop. The SMU powers the M² frontend and reports its power consumption. The SDR continuously tracks the center frequency and amplitude of the carrier generated by M². A classical TDO is cabled to the same SDR through a switched path, ensuring identical characterization conditions. We also transmit and receive through the same oscillator, demonstrating M²'s transceiver capability. Visitors observe that M² maintains its carrier frequency while the classical TDO drifts visibly, confirming at least two orders of magnitude stability advantage at a microwatt power budget.

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References

[1] A. Varshney et al. 2017. LoRea: A Backscatter Architecture That Achieves a Long Communication Range. In *ACM SenSys 2017*.
[2] P. Medaranga et al. 2025. Unraveling the Missing Link in Low-power Communication: An Autodyning Receiver Architecture that Achieves a Long Range. In *ACM MobiSys 2025*.
[3] M. Padmal et al. 2026. SharpPeak: Unlocking the True Potential of Tunnel Diodes for Low-Power Long-Range Communication. In *ACM SenSys 2026*.
[4] P. Sooriya Patabandige, D. Shah, et al. 2026. Microwatt Microwave (M²) Oscillator: Going Beyond the Delegation Architecture of Low-power Wireless Communication. In *ACM MobiSys 2026*.
[5] C. R. Reddy et al. 2025. AudioCast: Enabling Ubiquitous Connectivity for Embedded Systems through Audio-broadcasting Low-power Tags. *ACM IMWUT* (2025).