

A Compact Multimode Wearable Antenna With Polarization and Frequency Agility for Future Advanced Internet of Things Applications

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Abstract—We present a compact substrate-integrated wearable antenna that simultaneously provides continuous frequency tuning and selectable orthogonal linear polarizations to improve communication reliability in dense and dynamic IoT environments. The proposed design merges two quarter-mode substrate-integrated waveguide (QMSIW) structures into a single aperture-shared radiating patch and uses PIN switches and varactor tuning to realize mode selection and continuous frequency agility. A PIFA mode extends the lower band coverage while sharing the same feed. Measurements on fabricated prototypes validate a 34% tuning range (1.83–2.58 GHz) and polarization switching at $\pm 45^\circ$ in the QMSIW states. Its compact form (70 mm $\times$ 70 mm $\times$ 1.57 mm) and substrate-integrated packaging make it a practical option for wearable IoT modules.

Keywords—Communication reliability, interference, Internet of Things (IoT), substrate integrated antennas, wearable antennas.

I. INTRODUCTION

The Internet of Things (IoT) has grown rapidly, with connected devices projected to reach 37.5 billion by 2030 [1]. As device density increases, two critical challenges emerge: maintaining stable communication links and minimizing channel interference [2]–[4].

Wearable antennas are essential for IoT-based Wireless Body Area Networks (IoT-WBAN) systems [5]–[8]. However, conventional designs often lack adaptability in both frequency and polarization. Frequency agility allows devices to avoid congested channels [8]–[11], while polarization adaptability mitigates multipath fading and unpredictable channel conditions [12]. Although frequency-reconfigurable antennas [13] and polarization-reconfigurable antennas [14], [15] have been extensively investigated, the integration of both capabilities into a single design has received relatively little attention. In this work, a substrate-integrated wearable antenna is introduced, offering continuous frequency tuning and dual orthogonal polarization within a compact aperture-shared geometry that is well suited for wearable applications.

II. METHODOLOGY

Fig. 1 shows the evolution from a metallic rectangular cavity to the proposed aperture-shared wearable antenna. By exploiting the symmetric field distribution of a conventional cavity, the structure is divided along virtual magnetic walls, forming a compact quarter-mode SIW (QMSIW) antenna [16]. Two orthogonally oriented QMSIW modes are then combined into a single radiating aperture using two groups of PIN diodes and capacitors integrated along the top slot. This configuration

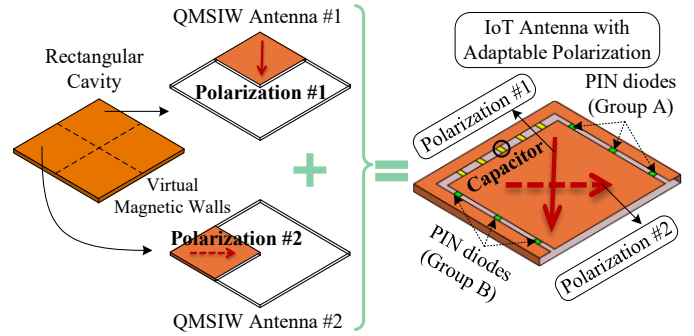


Fig. 1. Design evolution from a fundamental metallic rectangular cavity toward the proposed IoT antenna capable of adaptable polarization.

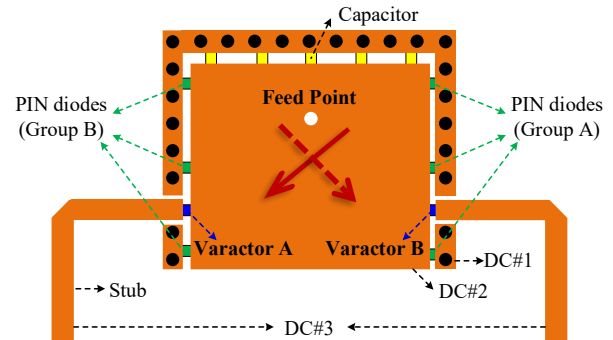


Fig. 2. Proposed frequency agility scheme for continuous tuning.

enables switchable dual-polarization operation with significant size reduction compared to conventional designs.

To realize continuous frequency tuning, Fig. 2 introduces two varactor diodes and stub extensions placed near the side walls. The shorting walls are implemented using arrays of metallic vias, and three DC bias lines (DC#1–DC#3) configure the antenna states. Activating Group-A or Group-B PIN diodes selects $\pm 45^\circ$ slant linear polarizations, with the corresponding varactors serving as the main tuning elements. When all PIN diodes are off, the antenna transitions to a PIFA mode sharing the same feed.

III. ANTENNA CONFIGURATION

Fig. 3 shows the configuration of the proposed antenna, symmetric about the y-axis. The radiating layer (Fig. 3(a)) is implemented on Rogers 5880 ($\epsilon_r = 2.2$, $\tan\delta = 0.0009$, $h = 1.57$ mm), while a DC bias board beneath it (Fig. 3(c)) is etched on FR4 ($\epsilon_r = 4.4$, $\tan\delta = 0.02$, $h = 1.57$ mm). The two boards are interconnected through two ground pins.

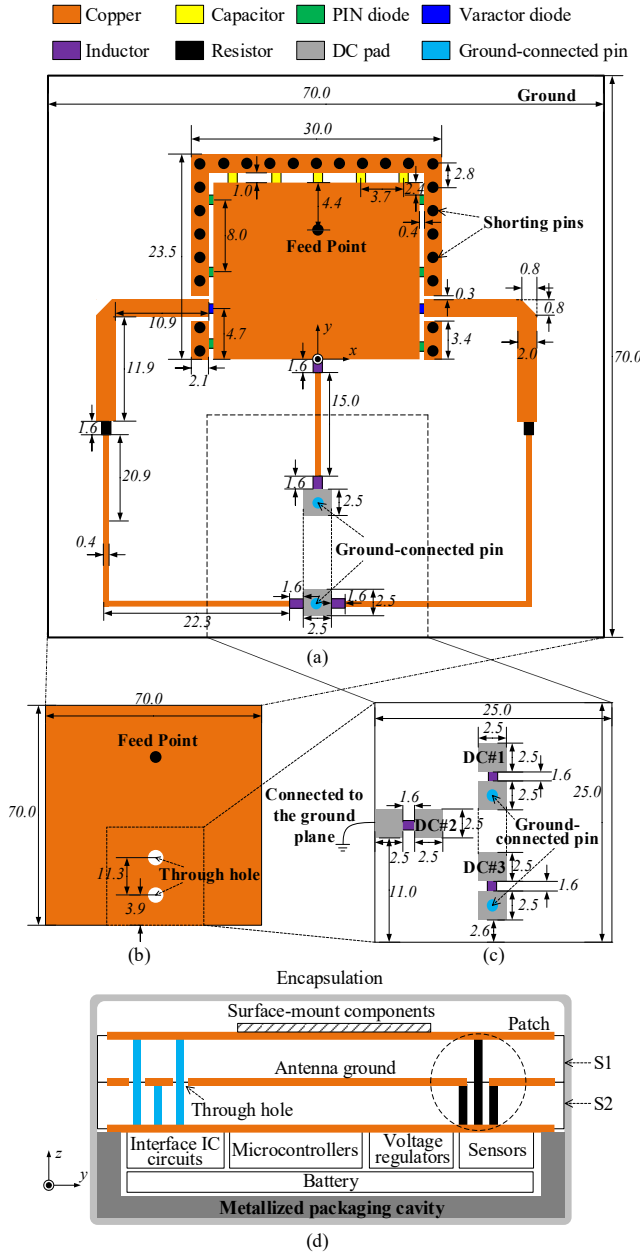


Fig. 3. Antenna system configuration (dimensions in mm): (a) top patch layout, (b) ground plane, (c) DC bias board, and (d) encapsulation scheme illustrating integration into wearable devices.

Three edges of the top patch are loaded with closely spaced 1-mm shunting vias to form effective shunting walls. An open-ended slot with two 90° bends accommodates five 10-pF capacitors, two varactor diodes, and six PIN diodes. The capacitors provide an RF path while isolating DC. The varactors are inserted between the inner patch and the open-end stubs, and two PIN-diode groups (A/B) enable polarization switching via DC#1 and DC#2. 1-M Ω resistors isolate the bias network, and 100-nH inductors act as RF chokes connecting the DC pads.

The DC board includes through-holes for the ground pins and three additional RF-choke inductors for bias routing. Three DC pads supply DC#1–DC#3 voltages, with the pad near DC#2 referenced to ground. In the ON state, the PIN diode is represented by a series 0.4-nH inductance and 2- Ω resistance. In the OFF state, it is modeled as a 0.08-pF capacitor in parallel with a 5-k Ω resistance, followed by the

TABLE I
DIFFERENT OPERATING MODES

	QMSIW Mode #1	QMSIW Mode #2	PIFA mode
(DC#1, DC#2)	(1.5 V, 0 V)	(0 V, 1.5 V)	(0 V, 0 V)
Polarization	+ 45° slant	− 45° slant	y-direction
Frequency	Higher band		Lower band

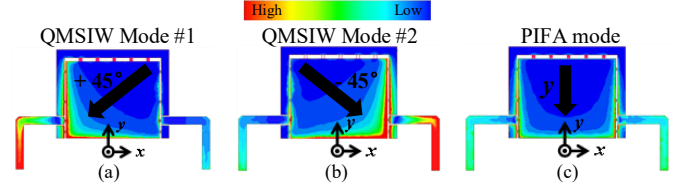


Fig. 4. Simulated current distributions on the antenna top patch: (a) QMSIW mode 1, (b) QMSIW mode 2, and (c) PIFA mode.

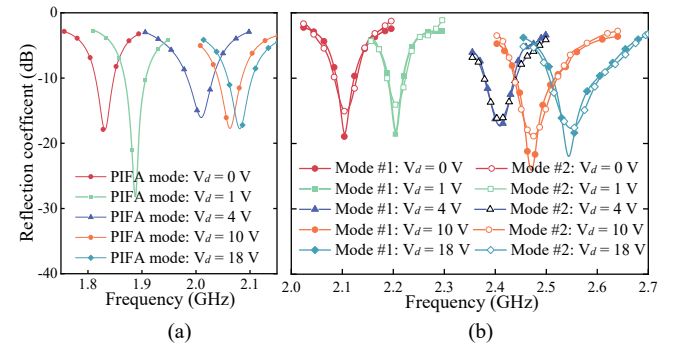


Fig. 5. Measured reflection coefficients under varying bias voltages (V_d) applied to DC#3, illustrating frequency tuning: (a) PIFA mode in the lower band, (b) QMSIW modes #1 and #2.

same 0.4-nH series inductance. The final antenna size is 70 mm $\times$ 70 mm $\times$ 1.57 mm.

Fig. 3(d) illustrates a conceptual integration scheme for wearable devices, using two stacked PCB substrates. S1 hosts the substrate-integrated antenna, while S2 accommodates the DC bias circuitry and optional electronics. The large SIW ground plane provides inherent EMI suppression, which can be further improved using metallized shielding.

IV. RESULTS

The antenna supports three bias-configurable modes controlled by DC#1 and DC#2. Table I summarizes the modes, and Fig. 4 shows the corresponding surface current distributions. In QMSIW Modes #1 and #2, dual orthogonal $\pm 45^\circ$ linear polarizations are enabled, improving link robustness in wearable IoT environments. The PIFA mode provides frequency tuning in a lower band, extending the overall tuning range, though without polarization agility.

Measured reflection coefficients, as shown in Fig. 5, indicate that increasing the tuning voltage V_d from 0 to 18 V shifts the QMSIW resonances from approximately 2.10–2.58 GHz, and the PIFA resonance from about 1.83–2.08 GHz, resulting in an overall tunable range of 1.83–2.58 GHz ($\sim 34\%$). Simulated results are not shown for brevity, as they closely agree with measurement.

The fabricated prototype is shown in Fig. 6(a) and (b), while Fig. 6(c) and (d) illustrate the antenna assembly and the

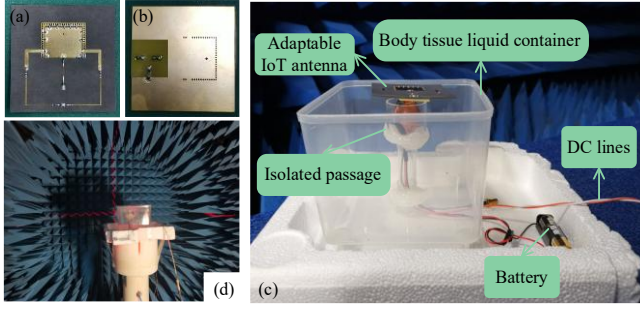


Fig. 6. Fabricated antenna prototypes: (a) top view, (b) bottom view with DC bias board, (c) assembled system, and (d) measurement setup in an anechoic chamber.

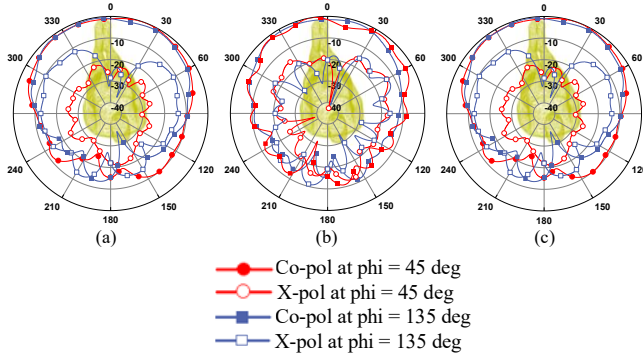


Fig. 7. Measured radiation patterns. (a) QMSIW Mode #1 at 2.43 GHz, (b) QMSIW Mode #2 at 2.43 GHz, (c) PIFA mode at 2 GHz.

measurement setup in the anechoic chamber. For wearable evaluation, a plastic container filled with tissue-equivalent liquid ($\epsilon_r \approx 49$, $\sigma \approx 1.7$ S/m at 2.2 GHz) was used. Measurements were performed under controlled conditions (18 °C, 52% humidity).

Fig. 7 presents the radiation patterns for both QMSIW and PIFA modes at a tuning voltage of $V_d = 4$ V. The antenna exhibits excellent polarization purity, with cross-polarization discrimination exceeding 10 dB in the broadside direction. The measured gain is approximately 2 dBi, confirming efficient radiation in both modes.

V. CONCLUSIONS

A compact substrate integrated wearable antenna with adaptable frequency and polarization has been demonstrated. The aperture-shared design achieves wide tunability and dual orthogonal polarizations without increasing footprint. This approach enhances IoT communication reliability in dynamic environments such as WBANs and smart health systems.

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