Supplementary Material

Simulation of the integrated sensor design (without meandering)

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Miniaturization Simulation of a Coaxially-Fed Microstrip Antenna

Preliminary simulation of the patch antenna was conducted using HFSS software. The radiating element has a thickness of 0.035 mm, and alumina ceramic is selected as the dielectric layer of the sensor with a thickness of 1 mm. Coaxial line feeding is adopted for excitation. The first patch antenna is responsible for measuring strain in the 0° (horizontal) direction, and its simulation results and return loss are shown in Figure 1(a) and 1(b), respectively. The second patch is used to measure strain in the 45° and 135° directions, with its simulation results and return loss presented in Figure 1(c) and 1(d). The third patch is dedicated to temperature measurement, and its simulation results and return loss are illustrated in Figure 1(e) and 1(f). These figures indicate that the simulated resonant frequencies of the three patch antennas (2.23/2.53/2.83/3.30 GHz) are in good agreement with the designed resonant frequencies. The return loss at all four resonant frequencies is less than -12 dB, and the separation between each resonant point is no less than 0.3 GHz, satisfying the requirement of return loss below -10 dB.

Wireless Simulation Verification of the Integrated Sensor

The three individual coaxial feeds for each patch antenna were removed, and a stepped configuration was adopted to integrate the three patch antennas onto a single alumina substrate, spatially offsetting their radiating edges to avoid direct overlap of the electric field distribution and thereby reduce mutual coupling effects. The integrated sensor is shown in Figure 2(a), with its specific parameters detailed in Figure 2(b). To validate the feasibility of wireless transmission for the integrated sensor, a standard rectangular waveguide WR430 was used as the interrogating antenna. The sensor model was placed directly beneath the rectangular waveguide for simulation. Figure 2(d) shows the 3D gain pattern of the rectangular waveguide, indicating a maximum gain of 4.05 dBi at θ = 180°, i.e., along the negative z-axis. Therefore, when the sensor is positioned directly facing the rectangular waveguide, the transmission and reception of electromagnetic signals are strongest, achieving optimal coupling performance. Wireless transmission between the sensor and the interrogating antenna was simulated, with the simulation model shown in Figure 2(c). The four resonant frequencies are 2.20 GHz, 2.52 GHz, 2.83 GHz, and 3.31 GHz, all meeting the requirement of return loss below -10 dB. Figure 2(f) presents the Smith chart of the wireless passive sensor, demonstrating good impedance matching.

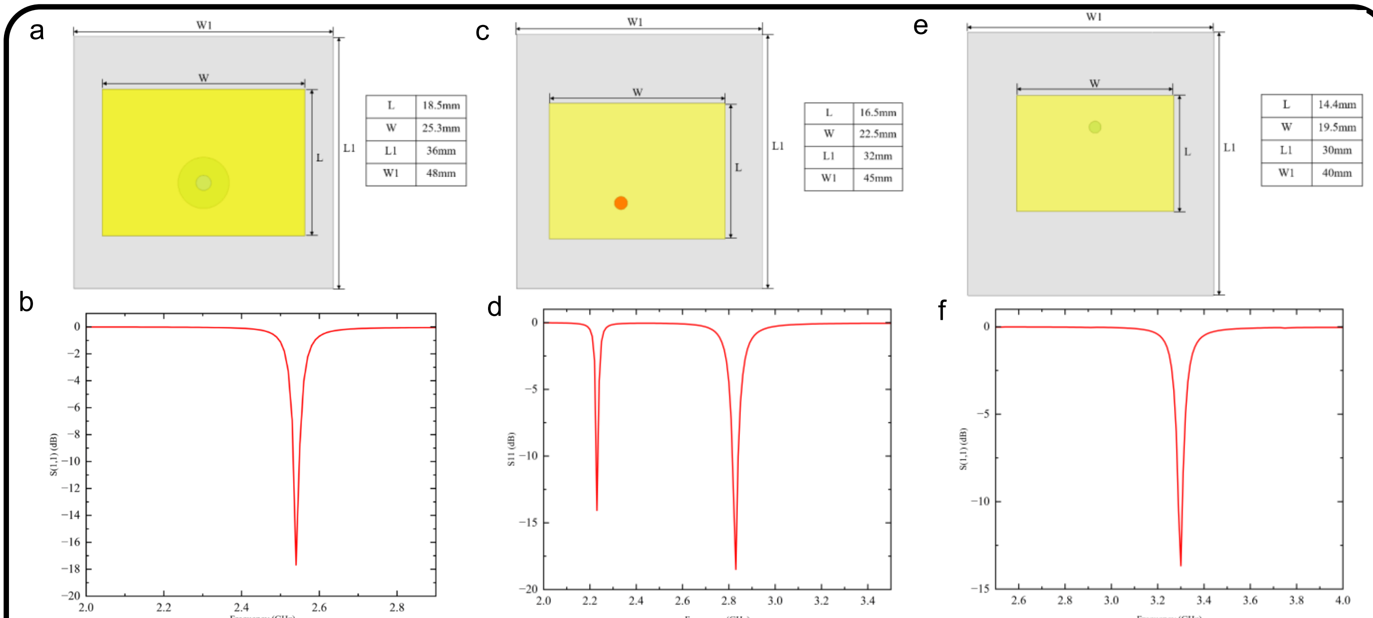
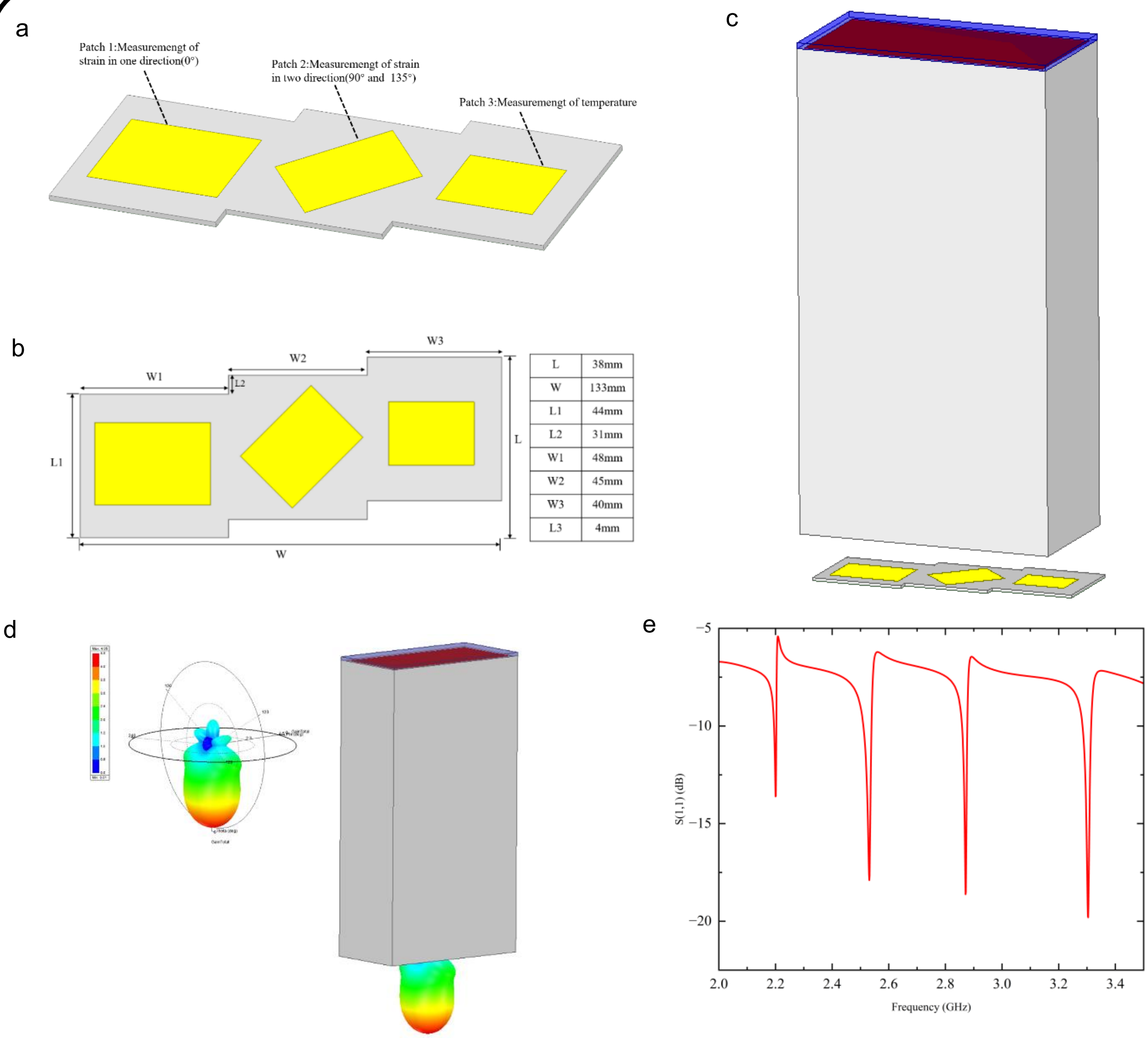


Fig. 1 Miniaturization simulation of wired patch antenna (without meandering) **a** Simulation diagram of patch No.1. **b** Return loss diagram of patch No.1. **c** Simulation diagram of patch No.2. **d** Return loss diagram of patch No.2. **e** Simulation diagram of patch No.3. **f** Return loss diagram of patch



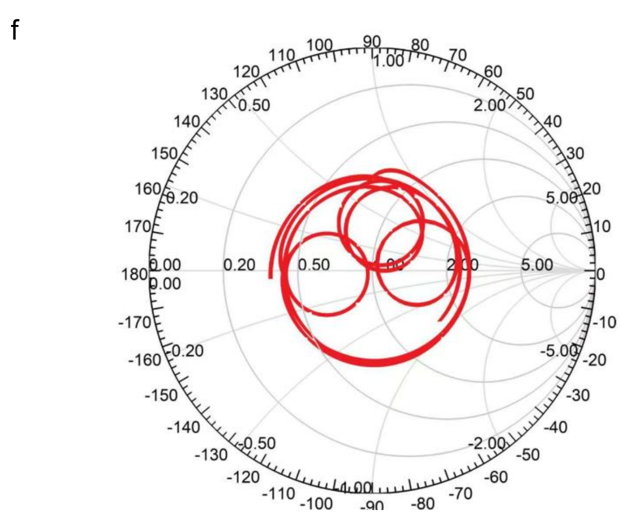


Fig. 2 Integrated Sensor Wireless Simulation (without slotting) **a** Schematic diagram of integrated sensor. **b** Integrated sensor physical dimensions diagram. **c** Wireless simulation verification of integrated sensors. **d** 3D gain diagram of rectangular waveguide. **e** Wireless Transmission S11 Diagram. **f** Smith Circle Diagram (after slotting).