

Supplementary Information for Integrated Digital Metasurface-Enabled Agile Wireless Power Transfer System

**Hao Zhang¹, Zhenyuan Li¹, Yuxuan Deng¹, Yuhua Chen¹, Xilong Lu¹, Zhenfei Li²,
Yue Yin^{1,*}, Li Sun^{1,*}, and Xudong Bai^{1,*}**

¹ School of Integrated Circuit, Northwestern Polytechnical University, Xi'an, 710129, China

² School of Physical Science and Technology, Northwestern Polytechnical University, Xi'an 710129, China

* baixudong@nwpu.edu.cn

* yinyue@nwpu.edu.cn

* lisun@nwpu.edu.cn

Note S1 : Structural parameters of each layer of the meta-atom and the current distributions of the meta-atom under two operating states.

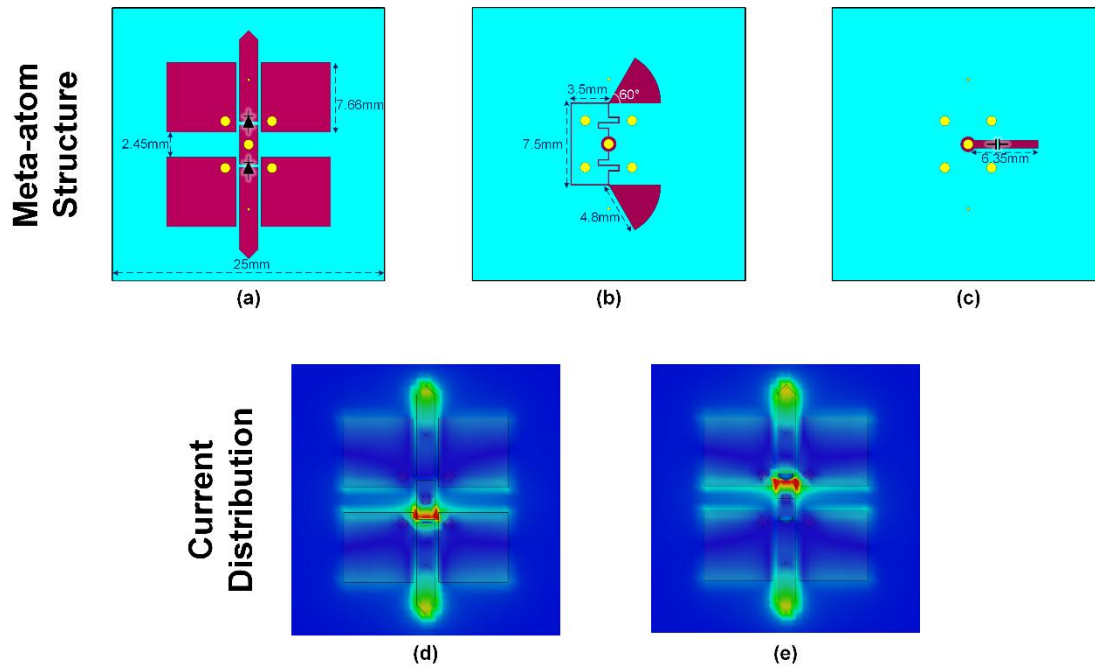


Figure S1 Structure of the meta-atom and current distributions under two states. a, radiation patch layer. **b,** bias network layer. **c,** feed network layer. **d,** current distribution of the meta-atom in the “0” state. **e,** current distribution in the “1” state.

The proposed meta-atom consists of four metallic layers: the radiation patch layer, bias network layer, metallic ground layer, and feed network layer. The detailed configurations and corresponding parameters of the radiation patch, bias network, and feed network layers are illustrated in Fig. S1a–c. The current distributions of the meta-atom under two distinct states are shown in Fig. S1d and Fig. S1e.

In the “0” state, the lower PIN diode behaves as a forward-biased resistor, while the upper PIN diode acts as a reverse-biased capacitor. Conversely, in the “1” state, the lower PIN diode functions as a capacitor (off state) and the upper PIN diode as a resistor (on state), thereby achieving an approximately 180° phase difference between the two states. By applying positive or negative bias voltages through the FPGA control circuit, the meta-atom can realize 1-bit dual-phase modulation.

Note S2 : Two-dimensional gain radiation patterns and one-dimensional polar plots of the metasurface under single-beam, dual-beam, and quad-beam configurations with different coding schemes.

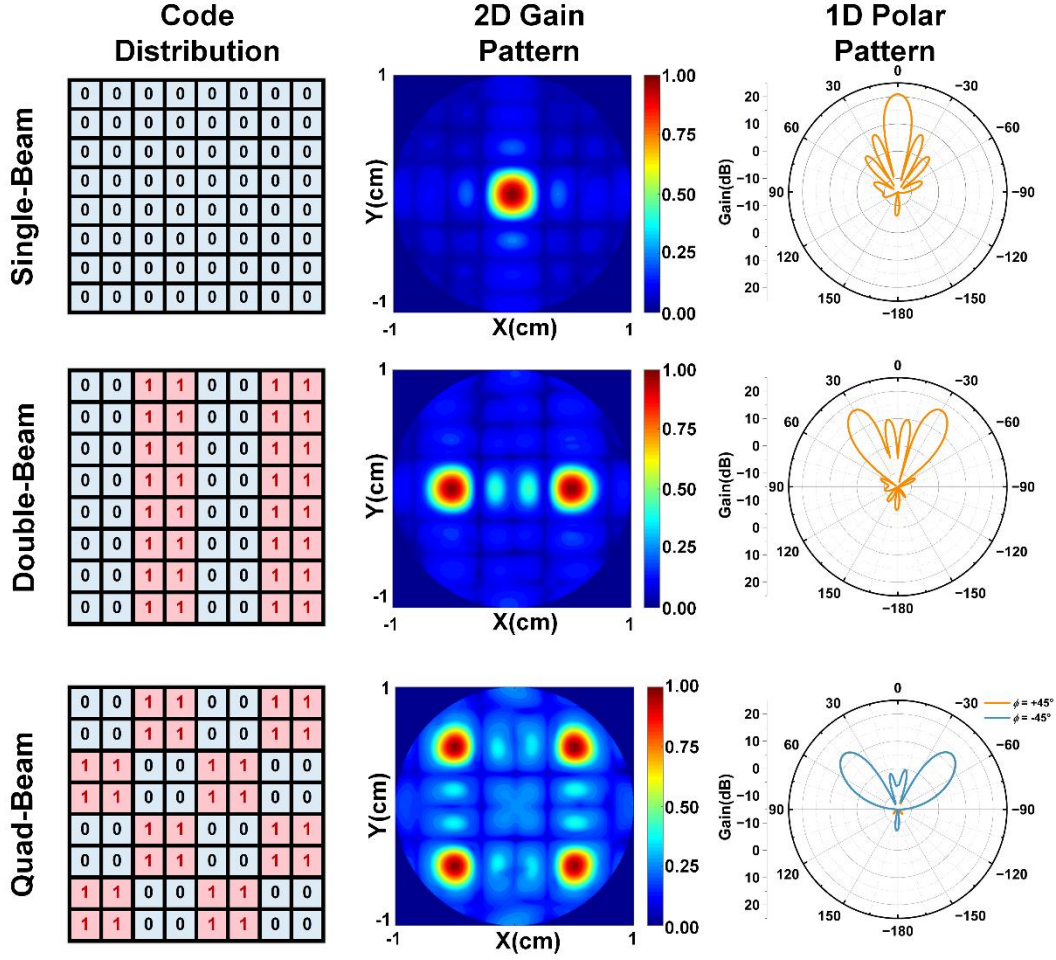


Figure S2 Two-dimensional radiation patterns and one-dimensional polar plots of the metasurface array under single-, dual-, and quad-beam configurations with different coding schemes.

By applying different coding schemes to the metasurface array, highly directive pencil beams with good isolation can be achieved. Under the single-beam configuration, the metasurface exhibits a high-directive pencil beam with a peak gain of 20.8 dBi. In the dual-beam case, two main lobes are symmetrically steered toward -30° and $+30^\circ$, with the actual gains of the two beams being 17.20 dBi and 17.21 dBi, respectively. For the quad-beam configuration, four main lobes of nearly equal gain are directed toward $\pm 45^\circ$, indicating effective beamforming performance. The gains of the four beams are 13.20 dBi, 13.26 dBi, 13.2 dBi, and 13.16 dBi, respectively. As the number of beams increases, a slight reduction in both beam gain and sidelobe suppression is observed, which is consistent with the fundamental antenna theory.

Note S3 : Performance characterization of the metasurface conducted in an anechoic chamber environment.

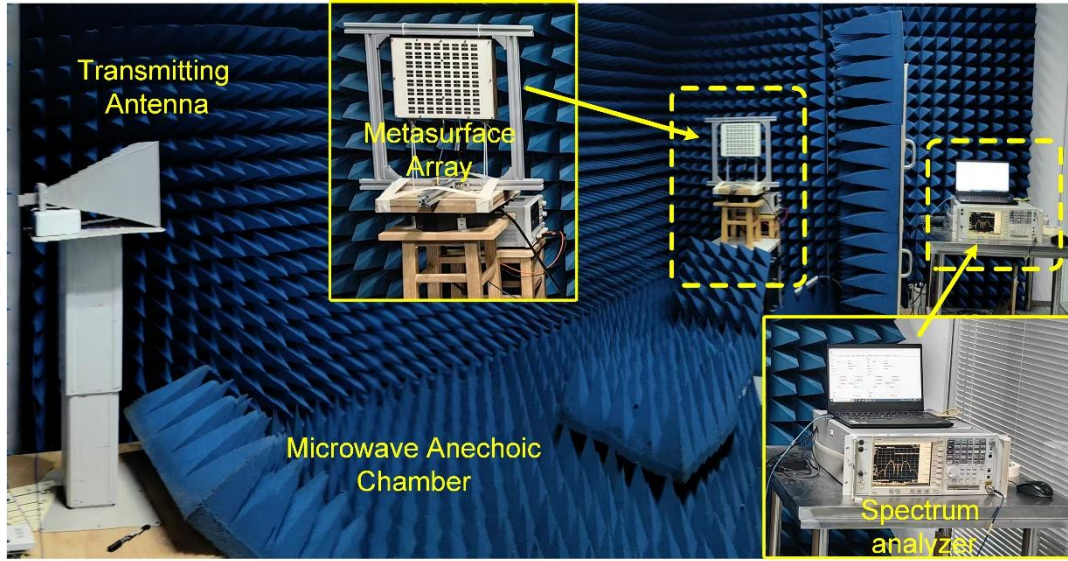


Figure S3 Experimental setup for metasurface characterization in the anechoic chamber.

The fabricated radiation-type metasurface prototype was realized using conventional multilayer printed circuit board (PCB) technology, with a total of 128 PIN diodes integrated across the entire metasurface array. Each metasurface unit cell is individually modulated via 64 independently controlled bias lines driven by a dedicated control logic board. To minimize the interference of the bias circuitry on the radiated field, the metasurface structure is mounted on the top of a custom-designed metal frame, while the control logic board is placed underneath. The connection between the metasurface and the control board is implemented through four flexible flat cables. High-frequency SMA connectors are also installed on the metal frame to enable efficient excitation of the microwave feed network. The control system is powered by an external 12 V DC source, which supplies both positive and negative bias voltages to each meta-atom. An FPGA is employed as the central control unit, which generates independent control signals across the 64 bias channels based on an optimized coding distribution within a specified clock cycle, thereby enabling dynamic and broadband beam modulation. For any given phase state of the meta-atom, each bias line delivers a designed driving current of ± 10 mA along with a DC bias voltage of ± 1.2 V. Based on this configuration, the total power consumption of the entire system is maintained below 1.0 W.

Note S4: Measured performance of the metasurface array.

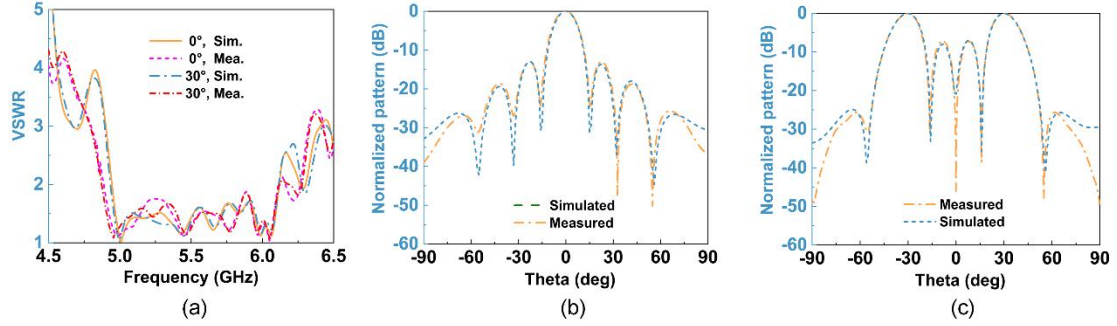


Figure S4. Experimental characterization of the metasurface array. **a**, Simulated and measured VSWR. **b**, comparison between simulated and measured results for the single-beam configuration. **c**, comparison between simulated and measured results for the dual-beam configuration.

Figure S4 presents the performance evaluation of the metasurface array in an anechoic chamber environment. As shown in Fig. S4a, the voltage standing wave ratio (VSWR) of the metasurface array remains below 2 within the operating frequency range of 4.892 to 6.105 GHz, indicating low reflection and good impedance matching. Moreover, the simulated and measured results exhibit good agreement, validating the design accuracy. Figure S4b illustrates the normalized radiation pattern of the metasurface array at 5.5 GHz in a single-beam configuration, revealing a high-efficiency pencil-like directional beam with excellent alignment between simulation and measurement. As shown in Fig. S4c, the normalized radiation pattern at 5.5 GHz in the dual-beam configuration demonstrates two beams steered at $\pm 30^\circ$, showing well-defined directionality. Although slightly elevated sidelobes are observed, they exert minimal impact on the subsequent implementation of the wireless power transfer system involving the receiving antenna. In the single-beam configuration, the sidelobes of the metasurface are significantly lower than the main lobe (below -13 dB), indicating that the receiving rectenna is unable to efficiently capture power from the sidelobe. Therefore, the impact on the wireless power transfer (WPT) system can be considered negligible. In the dual-beam configuration, the sidelobes of the metasurface extend beyond 60° , surpassing the coverage angle of the metasurface itself.