High Scanning Rate Coupled Resonator Array Antenna via Resonant Radiative Coupling Structure

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***Abstract*—This report presents a high-scanning-rate coupled-resonator antenna array based on a resonant radiative coupling (RRC) structure combined with phase-reversal radiators. Leveraging the radiative characteristics of the RRC structure, the proposed architecture achieves enhanced phase control while preserving a fully uniplanar and highly miniaturized geometry. Using a microstrip interdigital structure in conjunction with substrate integrated waveguide (SIW) resonators, a ninth-order five-antenna array is designed and fabricated to validate the concept. Continuous beam scanning across broadside is realized with a measured range of $-42^\circ \sim 44^\circ$ (86°) at a scanning rate of $26^\circ/\%$ within a compact footprint of $2.36\lambda_0 \times 0.60\lambda_0 \times 0.015\lambda_0$. The results confirm the RRC-based architecture as an effective approach for compact high-scanning-rate antenna arrays.**

***Index Terms*—Coupled resonators, high scanning rate, radiative frequency variant coupling, coupling matrix.**

I. Introduction

Frequency-scanning antennas have attracted significant attention in modern microwave systems. High-scanning-rate antennas, which achieve wide-angle beam steering within a narrow frequency band, are particularly desirable for efficient spectrum utilization and alleviating sampling rate requirements of analog-to-digital (A/D) converters [1].

Conventional frequency-scanning antennas based on leaky-wave radiation rely on electrically long transmission lines or periodic structures to generate controllable leakage [2]. Such architectures inevitably introduce large physical dimensions, which hinder on-chip integration and the realization of compact antenna systems.

In this article, we propose a novel architecture based on a resonant radiative coupling (RRC) structure and phase-reversal radiators, as shown in Fig. 1(b), enabling both high-scanning-rate and structural miniaturization. Phase-reversal radiators are employed to facilitate continuously beam scanning across broadside. The major contributions of this work are described as follows. First, a miniaturized and uniplanar high-scanning-rate coupled-resonator antenna is proposed. Second, the RRC structure is investigated in antenna arrays for the first time, demonstrating a modularity that provides guidance for future improvements in functionality and performance.

II. Principle and Design

A. Architecture of Coupled-Resonator Antenna

As shown in Fig. 1(b), the grey circles denote non-radiating resonators that introduce frequency-dependent phase shifts between the radiating elements. These resonators are alternately connected through RRC and phase-reversed RRC structures.

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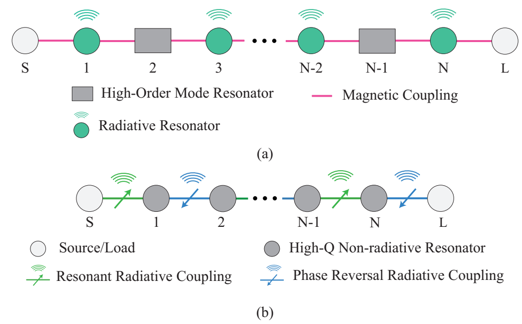

Fig. 1. Topology and mechanism of coupled resonator array antenna: (a) traditional design and (b) proposed design.

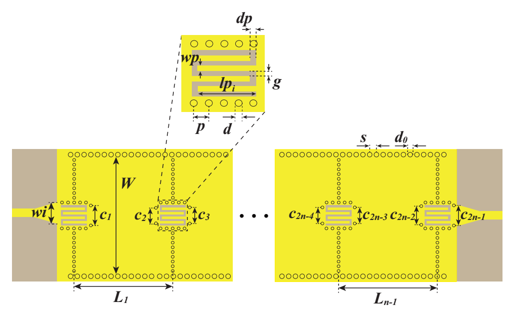

Fig. 2. Architecture of the proposed coupled resonator array antenna.

According to the operational principle of a phased array, continuous beam scanning through the broadside requires phase difference between adjacent antennas to be zero at resonance. As shown in Fig. 1(a), previous coupled-resonator antennas accomplished this condition by operating the non-radiating resonator in the TE_{201} mode, thereby generating a compensating 180° phase shift at the coupling junction [3], [4], which imposes significant constraints on structural miniaturization. In this work, a phase-reversal RRC structure is employed, wherein the inherent 180° phase difference of coupling is preserved, yet the phase reversal enables the equivalent radiating phase to become zero at the resonant frequency. It is worth noting that, being a resonant structure, the RRC also provides a frequency-dependent phase shift that contributes directly to the beam-scanning.

As shown in Fig. 2, the topology in Fig. 1(b) is implemented using SIW and interdigital resonator structures. The non-radiating SIW cavities are interconnected in an alternating sequence of conventional interdigital structures and phase-

TABLE I
OPTIMAL COUPLING MATRIX FOR FIVE-ANTENNA ARRAY WHEN RADIATION RESISTANCES IS 0.25

m_{S1}	m_{12}	m_{23}	m_{34}	m_{45}
0.98	0.65	0.55	0.37	0.42
m_{56}	m_{67}	m_{78}	m_{89}	m_{9L}
0.39	0.41	0.36	0.38	0.40

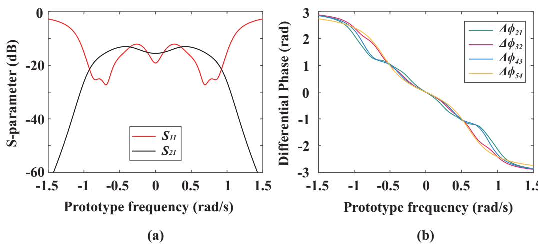

Fig. 3. Response of the optimal coupling matrix. (a) Scattering parameter. (b) phase difference of adjacent RRC structures.

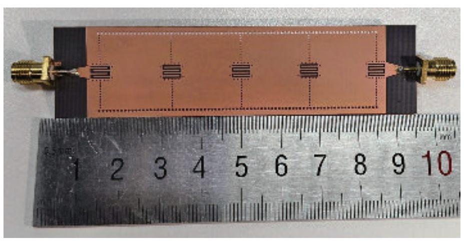

Fig. 4. Fabricated prototype of the ninth-order five-antenna array.

reversed interdigital structures. With in-phase excitation, the radiation of the interdigital structure undergoes a 180° reversal when the branches orientation is flipped, effectively canceling the phase difference introduced by coupling.

B. Coupling Matrix Modeling and Optimization

The proposed coupled-resonator antenna can be modeled as a band-pass RLC coupled-resonator circuit [4]. To ensure that as much energy as possible is radiated rather than reflected or dissipated, the scattering parameters S_{11} and S_{21} are required to remain sufficiently low. At the same time, coherent beam combining and a wider scanning range demand that the phase differences between adjacent radiating elements remain nearly identical across the operating band, while the span $\Delta\phi(\Omega = -1) - \Delta\phi(\Omega = 1)$ is maximized.

For demonstration, a ninth-order array with five radiating elements is synthesized using particle swarm optimization algorithm.The optimized dominant coupling coefficients are listed in Tab. I, and the corresponding scattering and phase responses are shown in Fig. 3. Both S_{11} and S_{21} remain below -10 dB, and the compensated phase differences $\Delta\phi$ exhibit excellent uniformity across the operating band.

III. Illustrative Example

To further validate the proposed physical implementation, a ninth-order five-antenna array is designed using the structure shown in Fig. 2 together with the normalized coupling matrix listed in Tab. I.

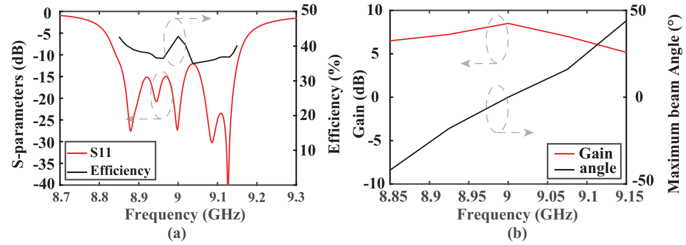

Fig. 5. Simulation and measurement response. (a) Reflection and efficiency. (b) Radiation gain and beam angle.

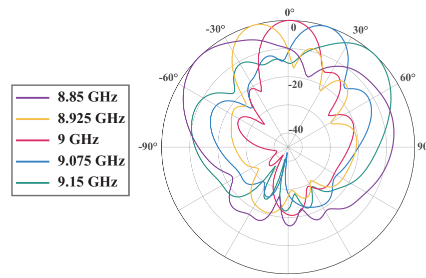

Fig. 6. Normalized radiation pattern of antenna (E-plane).

The fabricated prototype are presented in and Fig. 4. The $|S_{11}|$ remains below -10 dB and total efficiency exceeds 35% over the operating band from 8.85 GHz to 9.15 GHz as shown in Fig. 5. Fig. 6 shows the simulated radiation patterns (The antenna has not been measured yet due to the time limitation.). As shown in Fig. 5, the measured main-beam direction continuously scans from $-42°$ to $44°$ within the narrow 3.3% relative bandwidth. The realized gain within the operating band is approximately 7.5 dBi, with a peak value of 8.5 dBi.

IV. Future Plan and Impact Statement

The MTT-S Scholarship has not only empowered my research but also stood as a profound honor that fuels my passion for scientific exploration. Inspired by this recognition, I aspire to pursue doctoral studies and remain deeply committed to advancing the frontier of coupled resonant antenna technology, striving for impactful innovations in compact, high-efficiency RF/microwave systems.

References

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