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REGULAR ARTICLE

Rotman Lens-Based Combline Series-Feed Beam Steering Antenna Array for 5G IoT Applications

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This article presents a cost-effective and low-profile planar radiating system specifically designed for Internet of Things (IoT) applications operating at 5 GHz. The proposed system provides a beam coverage angle of 35°, utilizing a beamforming (Rotman) lens in combination with a combline array antenna to achieve efficient directional radiation. The configuration incorporates a beamforming lens with four input ports and six output ports, enabling the generation of four controllable beams at angles of 0°, 12°, 23°, and 35°. This ensures flexible beam steering for improved coverage in IoT networks. The combline series-fed antenna array is carefully designed to minimize side lobes while maintaining a compact size, making it particularly suitable for Wi-Fi and other 5 GHz applications. To enhance directivity, the design employs the Villeneuve array method, which optimizes beam shaping and energy distribution. Both the beamforming lens and combline prototypes are fabricated separately using an FR4 substrate, ensuring a cost-effective and practical manufacturing process. The combined beam-steering lens and combline microstrip array achieve a measured gain of 15 dBi at 5 GHz, demonstrating high efficiency and performance. The close agreement between simulated and measured results validates the effectiveness of the proposed system. With its simplified design, ease of fabrication, and strong performance, this system presents a promising solution for next-generation IoT applications requiring directional beamforming capabilities.

Keywords: Internet of Things (IoT), Rotman lens, Combline series feed array.

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1. INTRODUCTION

The Internet of Things (IoT) is a network of connected devices that collect data from the environment, with the number of connected devices expected to exceed 29.3 billion by 2030 [1]. In large-scale IoT networks, pattern reconfigurable antennas, such as beam-switching antennas operating in the 5 GHz band, offer benefits such as optimized energy efficiency and improved interference avoidance, enabling optimal connectivity for low-power wireless devices [2]. Beamforming techniques can be implemented through the control of mechanical, physical, or optical switches [3]. However, mechanical steering presents certain drawbacks. Electronic steering enables rapid scanning capabilities when compared to mechanical steering methods [4].

Various methods for electronic beam steering include the Butler matrix [5], Blass matrix [6], Rotman lens [7], RF PIN diode switches [8], semiconductor-based solutions [9], and RF phase shifters [10]. The Rotman lens offers advantages such as wide-angle beam scanning, low-loss performance, high-power handling, multi-beam steering, and efficient beamforming. It provides improved phase accuracy, reduced complexity, and compact dimensions, making it ideal for radar, wireless communication, and antenna arrays. The Rotman lens uses time-delay structures with sequential phase shifts at antenna ports [11, 12].

In recent years, beam-steering antenna systems have garnered significant attention due to their potential applications in various communication systems. This paper introduces beam steering in 5G IoT antenna systems by integrating a Rotman lens and a combline array. While existing literature has explored similar concepts, such as integrated Rotman lenses with switch networks [13], SIW technology for 2D end fire radiating dipole arrays [14], and microstrip combine arrays for millimeter-wave sidelobe reduction [15], our focus is on addressing the unique challenges posed by developing beam steering systems using Rotman lenses for Wi-Fi frequencies [16].

In [17], a 5×8 beamforming matrix using SIW technology is developed for mm-wave multibeam antennas, operating effectively in the 27 to 30 GHz range. In [18], a compact 0°/90° phase shifter is introduced, using a meander line for phase differentiation and minimal *p-i-n* diodes, demonstrating 2D beam steering at 1.5 GHz. In [19], reconfigurable phase shifting is presented, achieving beam steering at 28 GHz with a maximum angle of 22° and a realized gain of 13.2 dBi. In [20], a novel feedline design for series-fed antenna arrays is proposed to control sidelobes, resulting in a binomial array with no *E*-plane sidelobes and reduced cross-polarization levels.

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This paper presents a novel approach to electronic beam steering for IoT-based smart homes at 5 GHz, integrating a Rotman lens and combline array. Unlike conventional methods, this design is low-cost, compact, and high-gain, offering 35° beam coverage and reduced sidelobes, making it ideal for efficient wireless connectivity in next-generation IoT applications.

2. ANTENNA DESIGN

The overall antenna system consists of two main components: a Rotman lens and a combline antenna array. The Rotman lens is responsible for producing phase activation based on the selected port, while the combline array serves as the radiating system. The construction of the beam-forming lens involves four beam (input) ports and six array (output) ports, as depicted in Fig. 1 (a) and Fig. 1 (b). This configuration incorporates four input ports, labeled P1 to P4, which are located along the arc of the focal circle. The output terminals, A1 to A6, are isotopically positioned at an angle of 75° (denoted as α) with respect to the origin. Each focal location generates a progressive phase difference, enabling the antenna to control the beam in a predetermined direction at a beam steering angle, ψ. The focal length ratio, denoted as β, indicates the ratio between A2 and A1. The length of the transmission line, which connects the inner and outer array outlines, is established based on the foundational work by Rotman. By adjusting the parameters α, ψ, and β, the profiles and overall design of the Rotman lens can be customized to operate effectively at 5 GHz, with a diameter of approximately 130 mm. The specifications of the beamforming lens are as follows: $\alpha_1 = 0°$, $\alpha_2 = 32°$, $\psi = 20°$, $\beta = 1.06$, Se = 30 mm, $L_1 = 34$ mm, $L_2 = 32$ mm, $A_1 = 9$ mm, $A_2 = 3$ mm, $A_3 = 0.3$ mm, $A_4 = 0.3$ mm, $A_5 = 3$ mm, and $A_6 = 9$ mm. The beamforming lens is constructed using an FR4 substrate with a thickness of 1.6 mm.

Fig. 2 shows the simulated and measured results of the *S*-parameters for the beamforming lens, which exhibit resonant behavior at 5 GHz for port 1. Specifically, the S11 parameter indicates the return loss, while S21, S31, and S41 represent the isolation between the ports. The return losses for all beam ports exceed 10 dB at 5 GHz, and the port decoupling is also greater than 10 dB at 5 GHz, indicating good performance in terms of signal reflection and isolation. Fig. 3 presents the transmission phase delays between the ports of the Rotman lens when port P1 is fed. It is important to note that the phase shifters in the Rotman lens can be configured by altering the lengths of the different ports. The figure illustrates the simulated phase differences between port 1 and ports 5, 6, 7, 8, 9, and 10 at 5 GHz, demonstrating the distinct phase delays achieved. These phase differences are crucial for steering the beam to the desired directions.

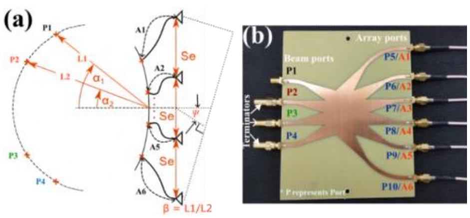

Fig. 1 – (a) Rotman lens design parameters and schematic illustration (b) Rotman lens with input output ports

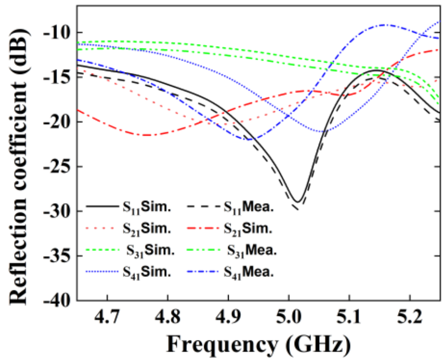

Fig. 2 – The Rotman lens reflection coefficients

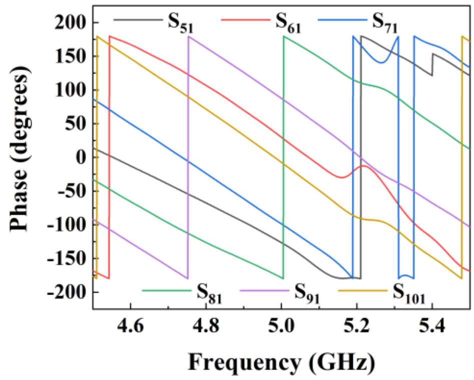

Fig. 3 – The Rotman lens transmission phase delays between the ports when port P1 is fed

3. RESULTS AND DISCUSSION

The described design comprises a beam-forming lens and an antenna array, as illustrated in Fig. 4. The beam-forming lens includes four input terminals and six output terminals, with the latter connected to the combline array. Both measured and simulated S11 for all ports of the antenna system were found to be lower than – 10 dB at 5 GHz, as shown in Fig. 5. When input port 1 of the beam-forming lens is excited, the remaining ports are terminated with impedance-matched loads to prevent undesired reflections. In this configuration, the output terminals of the beam-forming lens provide a phase shift of 30° each, causing the radiating main beam to steer in the direction of 0°, as shown in Fig. 6. Similarly, when beam ports 2, 3, and 4 of the Rotman lens are individually excited, the radiated main lobe directions are 12°, 23°, and 35°, respectively, as shown in Fig. 7.

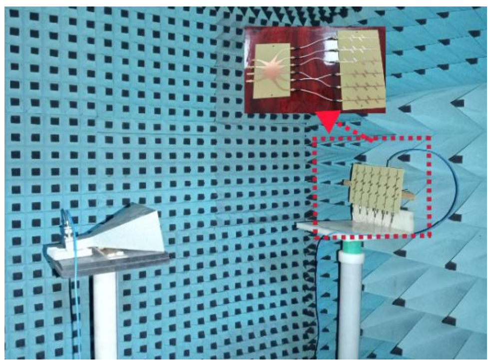

Fig. 4 – Photograph of the fabricated Rotman lens and combline array, with the experimental setup

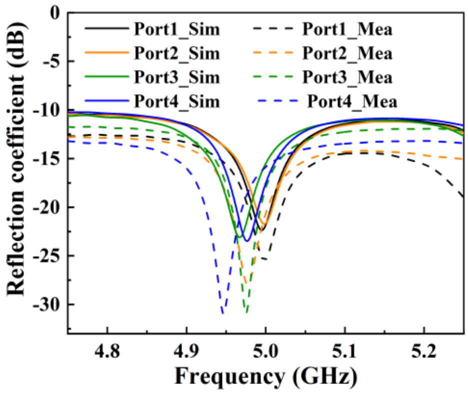

Fig. 5 – Simulated and measured S-parameters of the combined Rotman lens with combline array

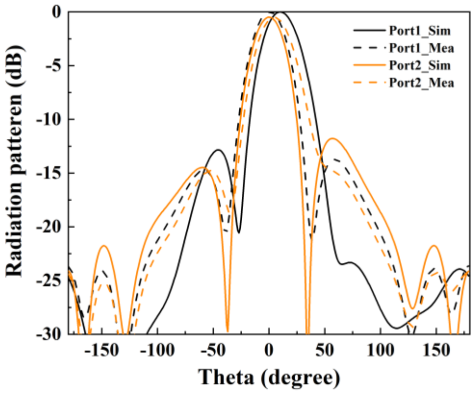

Fig. 6 – Simulated and measured radiation pattern for combined Rotman lens with combline array at 5 GHz

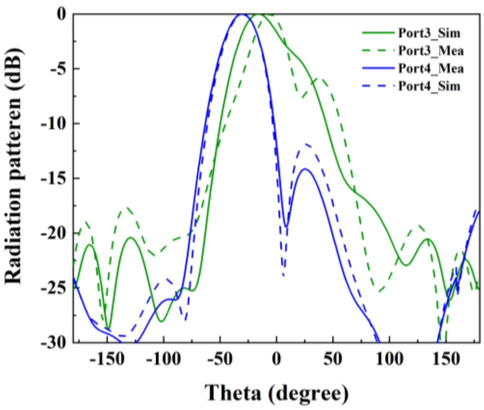

Fig. 7 – Simulated and measured radiation pattern for combined Rotman lens with combline array at 5 GHz

Fig. 8 depicts the gain of the single combline array and the entire proposed design, showing maximum gain levels of 9 dBi and 14.5 dBi at 5 GHz, respectively. The results demonstrate the effective combination of the Rotman lens with a series-fed array for controlling main lobe directions, offering approximately 35° of beam coverage, making it suitable for IoT applications. The small variations between simulated and measured outcomes can be attributed to factors such as fabrication tolerances, connectors, and measurement errors. In this design, the primary focus was on achieving beam steering within an angle range of up to 35°, with the intention of extending this work and using the design as a feed source for a reflectarray. To achieve this, the beam-steering lens and combline array were fabricated as separate components.

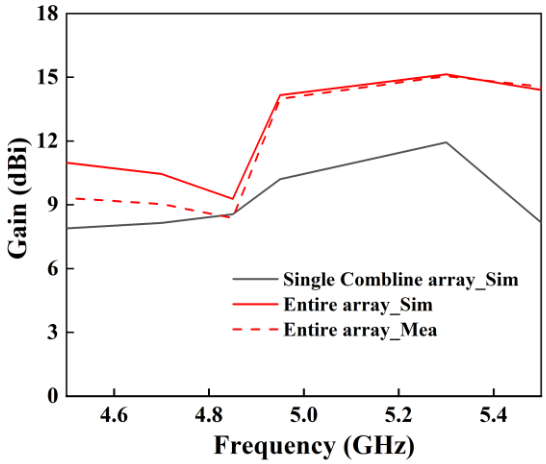

Fig. 8 – Simulated and measured gain

4. CONCLUSION

This work introduced a cost-effective, low-profile, and electronically beam-steerable antenna system for IoT applications at 5 GHz. By leveraging the unique combination of a Rotman lens and a combline array, the proposed system overcame the limitations of conventional beam steering techniques, such as complex phase-shifting networks and mechanical actuators. The fabricated prototype demonstrated a beam coverage of 35° while maintaining a high gain of 13 dBi, making it well-suited for smart home IoT applications that required robust and energy-efficient wireless communication. The integration of this design into IoT networks enhanced connectivity, reduced interference, and enabled flexible coverage adaptation, paving the way for advanced smart home automation and wireless sensor networks.

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Антенна решітка Rotman на основі лінз Rotman з керованим променем та серією Combline для застосувань у 5G IoT

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У цій статті представлено економічно ефективну та низькопрофільну планарну випромінювальну систему, спеціально розроблену для застосувань Інтернету речей (IoT), що працюють на частоті 5 ГГц. Запропонована система забезпечує кут охоплення променя 35°, використовуючи лінзу формування променя (Ротмана) у поєднанні з гребінчастою антенною решіткою для досягнення ефективного спрямованого випромінювання. Конфігурація включає лінзу формування променя з чотирма вхідними портами та шістьма вихідними портами, що дозволяє генерувати чотири керовані промені під кутами 0°, 12°, 23° та 35°. Це забезпечує гнучке керування променем для покращеного покриття в мережах IoT. Гребінчаста антенна решітка з послідовним живленням ретельно розроблена для мінімізації бічних пелюсток, зберігаючи при цьому компактний розмір, що робить її особливо придатною для Wi-Fi та інших застосувань на частоті 5 ГГц. Для покращення спрямованості в конструкції використовується метод решітки Вільньова, який оптимізує формування променя та розподіл енергії. Як прототипи лінзи формування променя, так і гребінчастої антени виготовляються окремо з використанням підкладки FR4, що забезпечує економічно ефективний та практичний виробничий процес. Комбінована лінза для керування променем та мікросмужкова решітка комбінованого типу досягають виміряного посилення 15 дБі на частоті 5 ГГц, демонструючи високу ефективність та продуктивність. Тісна відповідність між результатами моделювання та вимірювань підтверджує ефективність запропонованої системи. Завдяки спрощеній конструкції, простоті виготовлення та високій продуктивності, ця система є перспективним рішенням для застосувань Інтернету речей наступного покоління, що потребують спрямованого формування променя.

Ключові слова: Інтернет речей (IoT), Лінза Ротмана, Решітка подачі сигналу серії Combline.