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One-Dimensional Triple Periodic Dual-Beam Microstrip Leaky-Wave Antenna

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Abstract—In this letter, a novel dual-beam microstrip leaky-wave antenna based on one-dimensional triple periodic (TP) structure is proposed. Through theoretical dispersion relation analysis, it is found that compared to the conventional periodic structure, TP structure has reduced the separation of space harmonics. Hence, more space harmonic modes are brought into the leaky-wave radiation region. Through proper design, \( m = -1 \) and \( m = -2 \) modes are excited simultaneously. Consequently, the forward and backward propagation waves of these two modes generate two radiation beams in the far-field region. At different frequencies, symmetrical and asymmetrical beam pairs are realized. It provides more flexible and richer beam combinations to support dual-beam applications. Through practical implementations, the measured results show very good agreements with the theory. This new design has the single feeding port to avoid the complicated feeding network.

Index Terms—Dual-beam, leaky-wave antenna, microstrip antenna, single simple feeding, triple periodic structure.

I. INTRODUCTION

In recent years, due to the commercial success of the IEEE 802.11x and Bluetooth technologies, indoor wireless systems have attracted a lot of interests. Studies show that the system performance can be dominated by many intrinsic characteristics of the links, such as the multipath effect and the mutual interference [1]–[3]. These effects may degrade the bit error rate and cause signal delays and fades. To achieve high-quality links, directional antennas are adopted as an effective solution from the physical-layer perspective [3]. They can focus greater power in one or more specified directions and reduce the interference toward undesired targets. Hence, the harmful effects in wireless links can be largely decreased. Typical directional antennas can be single-, dual-, or multibeam. For different applications and system requirements, corresponding antenna types can be chosen properly. For systems that require multiple coverage areas, dual- and multibeam antennas also can reduce antenna numbers and further lower the network complexity.

Dual-beam microstrip antennas are favored because of their flexible coverage areas, low profiles, robustness, and low costs [4]. In the past decades, many relevant designs were reported. Reference [5] presents a simple dual-beam leaky-wave antenna by feeding a single-beam microstrip antenna in its center with respect to its longitudinal dimension. In [6], a wideband dual-beam antenna is proposed by utilizing the “U”-slot on the microstrip. The second higher-order leaky mode of even symmetry is employed in [7] to realize the purpose of dual beams. Moreover, several two-terminal designs are also presented [8], [9], and symmetrically steered beams are achieved. Furthermore, an asymmetrically scanning dual-beam antenna using active the HEMT up-converter is also demonstrated [10]. To increase the steering angle, dual-beam steering microstrip leaky-wave antenna arrays are presented in [11] and [12]. However, most of these designs use complex feeding networks, usually more than one terminal with extra power dividers and lumped devices. Most beam-steering antennas have symmetrical scanning, namely, two beams move toward opposite directions.

In this letter, a novel dual-beam microstrip leaky-wave antenna using one-dimensional triple periodic (TP) structure is proposed and developed. Different from previous work, for the antenna structure, three different unit cells are included in a supercell as the basic radiation element. \( m = -1 \) and \( m = -2 \) space harmonic modes are excited simultaneously to form corresponding forward and backward beams. At the same time, for the beam characteristics, most existing dual-beam research is focused on symmetrical beams or lumped components integrated asymmetrical beams. This design can realize symmetrical or asymmetrical beam pairs by engineering dispersion curves. It increases the flexibility of dual-beam applications. In addition, through the frequency variation, the two radiation beams can be simultaneously steered in the same direction with different angular speeds. It could be applied for two objectives’ tracking applications. This antenna does not need complex feeding network. There is only one feeding port that is designed to connect with the 50-Ω device.

II. ANTENNA CONFIGURATION AND THEORY

The configuration of the proposed design is presented in Fig. 1. Identical supercells are periodically cascaded in one dimension. Each supercell is formed by three different unit cells that are connected in series. From the perspective of unit cells, each unit cell is also periodically distributed along the structure. Due to the variety of unit cells, the periodicity of the structure is increased correspondingly. In this design, unit cells are rectangular microstrip patches with different widths. There are two ports with the 50-Ω characteristic impedance on two
sides of the antenna. It is fed from one port, and a matching load is attached to the other one.

According to the two-port network theory, we can relate the voltages and currents on either side of the \( n \)th supercell using its transmission (ABCD) matrix

\[
\begin{bmatrix}
V_n \\
I_n
\end{bmatrix} =
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
V_{n+1} \\
I_{n+1}
\end{bmatrix}.
\]

(1)

Based on the Bloch–Floquet theorem, we have

\[
\begin{align*}
V_{n+1} &= V_n e^{-j\gamma \lambda} \\
I_{n+1} &= I_n e^{-j\gamma \lambda}
\end{align*}
\]

(2)

where \( \gamma = \alpha + j\beta \) is the propagation constant of the supercell. \( \alpha \) and \( \beta \) are the attenuation and phase constant, respectively. \( q \) refers to the number of unit cells in one supercell. \( \lambda \) is the physical length of one unit cell. By substituting (2) into (1), we can get the dispersion relation

\[
\gamma = \frac{\arccos[(A + D)/2]}{q\lambda}.
\]

(3)

From [13], the transmission matrix of the supercell can be represented by the product of individual unit cells’ transmission matrices. For the lossless microstrip line, we have

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \prod_{i=1}^{q}
\begin{bmatrix}
\cos \beta_i \lambda & j Z_{0i} \sin \beta_i \lambda \\
j Y_{0i} \sin \beta_i \lambda & \cos \beta_i \lambda
\end{bmatrix}
\]

(4)

where \( Z_{0i} \) and \( Y_{0i} \) are the characteristic impedance and admittance, respectively. \( \beta_i \) is the phase constant of the \( i \)th unit cell

\[
\beta_i = k_0 \sqrt{\varepsilon_{si}},
\]

(5)

where \( k_0 \) is the wave vector in free space. Also

\[
\varepsilon_{si} = \frac{\varepsilon_e + 1}{2} + \frac{\varepsilon_e - 1}{2} \frac{1}{\sqrt{1 + 12h/W_i}}
\]

(6)

is the effective dielectric constant. It depends on the patch width \( W_i \), the dielectric constant, and height of the substrate.

Based on derivations shown above, a comparison of dispersion relations between conventional (single unit cell) periodic structure and the proposed one is presented in Fig. 2. The design parameters are \( \Lambda = 13.34 \text{ mm}, W_i \in \{3, 5, 7\} \text{ mm}, \) and \( h = 1.6 \text{ mm} \). FR4 substrate with dielectric constant 4.4 and loss tangent 0.02 is used in our design. It is obvious that compared to the conventional periodic structure, the separation of space harmonics is reduced for the TP structure. This leads to the shift of space harmonics along the horizontal axis to the leaky-wave radiation region. Hence, more radiation modes are excited.

In Fig. 2(b), the structure starts to radiate from 2.5 GHz. From 5.2 GHz, more than one mode is simultaneously included in the radiation. At almost 6 GHz, \( m = -1 \) and \( m = -2 \) modes are intersected, and their phase constants \( \beta_{-1} = -\beta_{-2} \). As a result, two axially symmetrical radiation beams are generated in the \( yz \)-plane of Fig. 1. From the dispersion relation, it can be found that \( m = -1 \) and \( m = -2 \) modes have parallel and antiparallel phase and group velocities, respectively. Hence, the proposed TP structure can excite simultaneous right- and left-handed radiations.

In this design, \( m = -1 \) and \( m = -2 \) modes correspond to forward and backward radiations, respectively. Furthermore, it is worth mentioning that TP structure has the bandstop property in the propagation process. The shadow regions in Fig. 2(b) are the stopbands. Due to the increase of periodicity, the discontinuities along the structure are also increased. According to the small reflection theory [13], when the reflected waves from discontinuities have constructive interferences, the stopbands will be created. To examine our theories, the TP structure is simulated in the commercial software Agilent Advanced Design System (ADS). Fig. 3 shows the simulated \( S \)-parameters of
Fig. 3. Amplitudes of $S$-parameters for an eight-supercells case. The simulation results are obtained from ADS software based on a circuit-based method.

Fig. 4. Effects of $\Lambda$ and $h$ on the operating frequency and phase constant. (a) Variation of $\Lambda$. The green, red, and blue curves stand for $\Lambda = 12, 13.34,$ and $15$ mm, respectively. (b) Variation of $h$. The green, red, and blue curves stand for $h = 0.2, 1.6,$ and $3$ mm, respectively. The circled points are the places where symmetrical dual-beam radiation generates. The dashed lines refer to the free-space wave vector.

Fig. 5. Proposed TP microstrip leaky-wave antenna prototype.

Fig. 6. Simulated and measured amplitudes of $S_{11}$ and $S_{21}$ parameters. The simulation is conducted in the full wave software HFSS.

III. SIMULATION AND EXPERIMENT RESULTS

To further verify our theories, the full-wave simulation and practical implementation of the eight-supercell case are conducted. A photograph of the fabricated antenna prototype is shown in Fig. 5. Fig. 6 presents a comparison of simulated and measured $S_{11}$ and $S_{21}$ parameters. Good agreements between simulations and measurements are observed. Compared to the theoretical dispersion diagram in Fig. 2(b) and the circuit-based $S$-parameter simulation in Fig. 3, the practical design matches the simulations very well. From 3 to 8 GHz, two strong stopbands can be found at 4 and 7.8 GHz. The measured amplitudes of $S_{21}$ within stopbands are $-1.6$ and $-4.1$ dB, respectively. Around the operating frequency of 5.8 GHz, from 4.3 to 7.3 GHz, the antenna shows very good impedance matching ($S_{11}$ is below $-10$ dB).

In Fig. 7, normalized radiation patterns at 5.8 GHz in the $y_2$-plane are presented. The arrows indicate main beams’ directions. We can see that two main beams show good agreements...
between simulation and measurement. The difference between main and sidelobes is almost 10 dB. The cross polarization between simulation and measurement is very small. As shown in the dispersion relation, the phase constant of radiation modes change with frequency. It is well known that the radiation angle (from broadside) of the leaky-wave mode is defined by

$$\theta_m = \sin \left( \frac{\beta}{k_c} \right). \quad (7)$$

In Fig. 8, we present the radiation performances at two adjacent frequencies of 5.6 and 6.0 GHz centering at 5.8 GHz. At these two frequencies, two obvious main beams can be found, respectively. Combining with Fig. 7, it can be observed that when the frequency increases, two beams demonstrate the in-directional steering with different angular speeds. Physical explanations are presented through the dispersion analysis. The results of practical implementation and theoretical analysis show good agreements. This design features a very simple feeding network and low cost.

IV. CONCLUSION

A novel dual-beam microstrip leaky-wave antenna using the TP structure is proposed and investigated theoretically and experimentally. The antenna excites two radiation modes $m = -1$ and $m = -2$ simultaneously. The forward and backward waves form two axially symmetrical and asymmetrical radiation beams at different frequencies. When the frequency increases, two beams demonstrate the in-directional steering with different angular speeds. Physical explanations are presented through the dispersion analysis. The results of practical implementation and theoretical analysis show good agreements. This design features a very simple feeding network and low cost.

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