SUMMARY Invention and development of the Yagi-Uda antenna, and the self-complementary antenna are described. Analysis methods of large loop antennas and the improved circuit theory (ICT) for design of linear antennas are presented. Recent developments of axial mode helical antennas and spiral antennas for radiating circularly polarized waves are also described.

key words: Yagi-Uda antenna, self-complementary antenna, loop antenna, spiral antenna, helical antenna

1. Introduction

Research on antennas in Japan has a long history, especially in regard to linear antennas. The invention and development of the Yagi-Uda antenna in 1925 [1], [2] and the self-complementary antenna in 1948 [14], [15] were the highlights of antenna research in Japan. In analysis and design methods of linear antennas, there were outstanding achievements such as the designs of the Yagi-Uda antennas [7], large loop antennas [29] and array of linear antennas [38].

In this paper, the outline of the invention and development of both the Yagi-Uda antenna and the self-complementary antenna are described. Analysis methods of the large loop antennas and improved circuit theory (ICT) for design of linear antennas are presented. Recent developments of axial mode helical antennas and spiral antennas for radiating circularly polarized waves are also described.

2. Yagi-Uda Antenna

The first report describing methods to obtain a sharp beam by using parasitic elements was published by Uda of Tohoku University, Japan in 1925 [1], and details of the geometry of the Yagi-Uda antenna were reported by Yagi and Uda in 1926 [2].

The Yagi-Uda antenna is composed of reflector elements and director elements as well as a driven element. The reflector elements had already been used for directional antennas, but the wave directing effects of parasitic elements had not been reported. Uda performed numerous experiments on antennas having many parasitic elements with varying their length and published eleven papers entitled “On the wireless beam of short electric waves” in Journal of IEE Japan in 1926-29 [3]-[5]. The wave directing parasitic element was named as director. Figure 1 shows examples of the radiation
patterns of multi-element Yagi-Uda antennas measured by Uda [4]. The beam is formed in the direction of the director element array demonstrating the effect of directors.

In 1927, Yagi visited the United States and lectured at several meetings on the experimental results of the Yagi-Uda antennas and the UHF generating split-anode magnetron tubes which were invented by Okabe of Tohoku University. He also published a paper on these results in the Proceedings of IRE in 1928 [6]. The IRE paper stimulated worldwide interests in UHF technology. The Yagi-Uda antennas were recognized as a useful antenna for VHF and UHF because of the simple but high gain property and were used for radar systems during World War II in the United States and Europe. However, little attention was paid to the Yagi-Uda antenna in Japan for radars.

After World War II, theoretical investigation on the Yagi-Uda antenna was performed to establish the design method. Uda and Mushiake [7] extended Hallén’s method [8], which is rigorous but had been limited to the single dipole antenna, for the analysis of the multi-element dipole antenna and presented a large number of numerical and experimental data for various parameters of the geometry of the Yagi-Uda antennas. They showed that not only the length of the driven, reflector and director elements but also their radii are important to obtain optimum geometry of the Yagi-Uda antennas. The characteristics of the folded dipole antenna were also analyzed and an exact step-up impedance-ratio chart was presented [9], since folded dipole antennas are often used for impedance matching of the driven element of the Yagi-Uda antenna.

The Yagi-Uda antenna provides directivities of up to 17dBi or more if the number of director elements is high (e.g., directivities of 3, 6 and 18 element Yagi-Uda antennas are 7dBi, 10.5 dBi and 16.5 dBi, respectively) for a narrow frequency band [10]. The bandwidth can be increased by shortening the directors for high-frequency operation, lengthening the reflectors for low-frequency operation, and selecting the driven element for midband operation, although the gain decreases several dB [10]. The broadband Yagi-Uda antennas have been widely used as TV receiving antennas and the design method developed by Uda and Mushiake was applied to a number of such Yagi-Uda antennas.

In 1995, IEEE sent the Electrical Engineering Milestone entitled “Directive Short-Wave Antenna” to Tohoku University, Japan for the outstanding achievement by Yagi and Uda. This is the first Milestone sent to the Asian region.

After the invention of Yagi-Uda antenna, Uda started research and development of transmitter and receiver in VHF frequency range. He succeeded in communication experiments at 65 MHz and 53MHz for a distance of about 50 km, and at 38 MHz for 30 km in 1931 and 1932, respectively [11]. These transmitters and receivers using the Yagi-Uda antennas were put into public services of radio wave telecommunication systems between main-land Japan and small islands of Japan. He also performed the development of transmitter and receiver in the UHF frequency range and succeeded in a communication experiment at a distance of about 30km operating at 600 MHz [12] in 1929, which was the world’s longest record in UHF radio communication. Figure 2 is a photograph of a replica of the UHF transceiver developed by Uda.

3. Self-complementary Antenna and Log-Periodic Antenna

There is a duality property of the electromagnetic field between electromagnetic fields \((E_1, H_1)\) in structure #1 and \((H_2, E_2)\) in structure #2, if all electric walls, magnetic walls, electric currents, and magnetic currents in structure #1 are interchanged for magnetic walls, electric walls, magnetic currents and electric currents in structure #2. This principle is useful for diffraction problems and is called “Babinet’s principle” in electro-

![Fig. 3 Slot antenna and planar antenna of arbitrary shape.](image)
Mushiake applied Babinet’s principle to the analysis of a slot antenna having arbitrary shape shown in Fig. 3(a). Let the slot antenna having voltage $V_1$ and current $I_1$ at the driving point generate electromagnetic field $E_1$ and $H_1$ as shown in Fig. 3(a), which is equivalent to a slot antenna fed by magnetic current shown in Fig. 3(b). The complementary planar antenna with driving voltage $V_2$ and current $I_2$ generates electromagnetic field $E_2$ and $H_2$ as shown in Fig. 3(c). The driving point voltages $V_1$ and $V_2$ are expressed in terms of the driving currents $I_1$ and $I_2$ as

$$V_1 = -\int_a^b E_1 \cdot ds = \int_a^b H_2 \cdot ds = \frac{I_2}{2}$$

$$V_2 = -\int_d^c E_2 \cdot ds = -Z_0^2 \int_c^d H_1 \cdot ds = \frac{Z_0^2 I_1}{2}$$  \hspace{1cm} (1)

where

$$Z_0 = \sqrt{\mu_0 \varepsilon_0} \simeq 120\pi$$  \hspace{1cm} (2)

is the intrinsic impedance in free space.

By using Eq.(1), the input impedance of the slot antenna $Z_s$ shown in Fig. 3(a) can be obtained by the following equation [14]–[16],

$$Z_s = \left(\frac{Z_0}{2}\right)^2 Z_d$$  \hspace{1cm} (3)

where $Z_d$ is the input impedance of complementary planar antenna shown in Fig. 3(c).

Although Eq.(3) had been derived by Asami et al. [17] in Japan and Booker [18] as the impedance relationship between thin slot antenna and thin wire antenna, the relationship in Mushiake’s theory does not have such limitation for the shape of antenna.

Mushiake [14]–[16] also originated the self-complementary structures and found that the input impedance of the antenna shown in Fig. 4 is constant independently of the frequency and given by

$$Z_{in} = \frac{1}{2} \sqrt{\frac{\mu_0}{\varepsilon_0}} \simeq 60\pi \simeq 188\Omega$$  \hspace{1cm} (4)

since the complementary structure in Fig. 4 is exactly the same to the original structure in Fig. 4. Eq.(4) is known as “Mushiake’s relationship” [19] and this antenna is called “self-complementary antenna” [19], [20]. The principle of the constant impedance of the self-complementary antenna is called the “principle of self-complementarity”.

The self-complementary antennas are very interesting since there is an infinite variety of self-complementary structures. Rumsey [19], [21] and DuHamel [22] found the importance of the principle of self-complementarity. DuHamel [22] developed a wide-
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Fig. 7 Self-complementary type log-periodic antenna [23].

Fig. 8 Self-complementary type log-periodic dipole array antenna (LPDA) [24].

Fig. 9 Large circular loop antenna.

band planar antenna based on the principle of the self-complementarity using log-periodically spaced notches and monopoles as shown in Fig. 5 and showed that the input impedance is almost equal to 188 Ω under the condition that the operating frequency is higher than the frequency at which the length of the longest monopoles is a quarter wavelength. Although infinite structures are required for the constant impedance of the self-complementary antennas, the structures having notches and monopoles shown in Fig. 5 and Fig. 6 can realize the constant impedance with a finite conducting plane, because notches and monopoles radiate electromagnetic power and the truncation effect can be reduced for finite structures.

Since the planar antenna shown in Fig. 5 radiates bi-directionally and a directional antenna is desired, DuHamel [23] tried to deform the structure by bending the planar antenna and obtained a modified self-complementary antenna called a “log-periodic antenna” shown in Fig. 7, which has been widely used for TV receiving antennas. The log-periodic antenna is further deformed to the log-periodic dipole array antenna (LPDA) shown in Fig. 8 [24]. The LPDA has been widely used for extremely wide frequency operation in communications and measurements, especially in the EMC measurements.

As mentioned above, the log-periodic antennas were developed based on the principle of the self-complementarity. The broadband characteristics of the so-called log-periodic antenna is obtained by the principle of self-complementarity rather than the log-periodic structure [25]-[27]. For example, the fractal antenna [28] is a type of log-periodic antenna but it has multiband characteristics rather than broadband properties [27], [28].

Mushiake and his colleagues further developed other types of self-complementary antennas, such as rotationally symmetric 4-terminal planar self-complementary antennas, three-dimensional multiplanar self-complementary antennas and stacked self-complementary antennas. The details of these antennas are presented in [26].

4. One Wavelength Loop Antenna

Prior to the 1950’s, loop antennas were often used in low frequency ranges and quasi-stationary analysis or equivalent treatment as an infinitesimally small magnetic dipole were employed. However, the characteristics of a loop antenna changes drastically in the high frequency range and more rigorous treatment was desired. Adachi and Mushiake [29] performed analyses of loaded and short-circuited loop antenna shown in Fig. 9 as a boundary problem based on the Hallén type integral equation [8]. They also derived a compact solution in the first order approximation which is satisfactory for practical purposes [30].

Although the maximum radiation occurs in the direction perpendicular to the axis of loop for the case of electrically small antenna, a loop antenna having a conducting wire of one wavelength has maximum radiation in the axial direction and its radiation property is almost the same to that of two element half wavelength dipole array antenna with a spacing of 0.27 wavelength. The directivities of one wavelength and 1.4 wavelength loop antennas in axial direction are about 3.5 dBi and
4.5 dBi, respectively [31], and the directivity of the one wavelength loop antenna with reflector elements is 10.5 dBi [32].

Because of the high directivity, the one wavelength loop antenna is used as an element in arrays such as the Yagi-Uda loop array antenna [32], [33] and the log-periodic loop array antenna [34]. The twin loop antenna shown in Fig. 10(a) is a type of antenna using one wavelength loop antennas [35], which has only one driving point but has high gain and wide bandwidth. Four element (4L) twin loop antenna shown in Fig. 10(b) and six element (6L) twin loop antenna were also developed in Japan. The 2L, 4L and 6L twin loop antennas located in front of conducting plane with a spacing of a quarter wavelength shown in Fig. 10(c) have been widely used for UHF TV broadcasting antennas in Japan because of the advantages of the single feed point, high gain and wide bandwidth. Each gain of 2L, 4L and 6L twin loop antenna is approximately 7.5 dBi, 10.5 dBi and 12.3 dBi, and the bandwidth (VSWR<1.1) is about 16%, 13% and 10%, respectively [35].

5. Improved Circuit Theory

The variational method is a highly accurate and useful method for the numerical analysis of linear antennas and had been applied to single cylindrical dipole antennas [36], [37]. However, the variational method had not been applied to multielement antennas since the expression of the input impedance of the multielement antenna is not stationary.

Based on the electric field integral equation, the input impedance of the ith element in the multielement antenna shown in Fig. 11 is given by

\[
Z_i = \frac{-\sum_{j=1}^{N} \int_{-h_i}^{h_i} \int_{-h_j}^{h_j} I_i(z_i) G_{ij}(z_i, z_j) I_j(z_j) dz_j dz_i}{I_i^2(0)}
\]

(5)

where \( I_i \) is the current distribution of the ith element and \( G_{ij} \) is the Green’s function given by

\[
G_{ij}(z_i, z_j) = -\frac{j\omega \mu_0}{4\pi} \left(1 + \frac{1}{k_0^2 \partial^2 \partial z_i^2} \right) \frac{e^{-j k_0 r_{ij}}}{r_{ij}}
\]
\[ r_{ij} = \sqrt{(z_i - z_j)^2 + d^2} \]  

(6)

For the case of single dipole antenna \((N=1)\), it is easy to show that the variation \(\delta Z_i\) of the input impedance is zero for the variation of current distribution \(\delta I_i\) and Eq.(5) is a stationary expression. On the other hand, the variation \(\delta Z_i\) of the input impedance of the multi-element antenna is not individually zero for the variation of current distribution \(\delta I_i\) \((i=1,2...,N)\). Inagaki [38] overcame this difficulty by considering the total power in the multi-element system and found that the summation of the variation is zero if the variation of the input impedance is weighted by the square of the driving current \(I_i^2(0)\), i.e.,

\[ \sum_{i=1}^{N} I_i^2(0) \delta Z_i = 0 \]  

(7)

Equation (7) means that Eq.(5) is an extended variational expression for the multi-element antenna.

Inagaki [38] also employed two trial functions given by

\[
\begin{align*}
    f_1^i(z_i) &= \frac{\sin k_0(h - |z_i|)}{\sin k_0 h_i} \\
    f_2^i(z_i) &= \frac{1 - \cos k_0(h - |z_i|)}{1 - \cos k_0 h_i}
\end{align*}
\]  

(8)

to obtain the current distribution \(I_i(z_i)\) of the dipole array antenna shown in Fig. 11. The trial functions given by Eq.(8) are exactly the same as those introduced by Storer [36] and are known to yield accurate solution. By using the above trial functions and evaluating the self and mutual impedances between trial functions, the problem of the multi-element antenna is expressed by a circuit equation having \(2N\) unknowns. This is an improvement of the circuit equation using the conventional electromotive force (EMF) method and Inagaki called this technique “Improve Circuit Theory (ICT)”. The method of moment (MoM) [39] is a powerful and useful technique and has been widely used for the numerical analyses of antennas and scatterers after about 1975. It can be shown that the MoM using Galerkin’s method is equivalent to the variational method. Moreover, the MoM has wide applicability, e.g., linear antenna and planar antenna having arbitrary shape, etc. However, in the MoM analysis, many trial functions are required to obtain an accurate solution. For example, several trial functions are required to expand the current distribution of each dipole element whose length is up to one wavelength in a dipole antenna. On the other hand, the ICT method yields highly accurate solutions using only two trial functions on each dipole element. It has been widely used for the design of Yagi-Uda antennas as well as the design of arrays of dipole antennas with the desired radiation pattern [40] or optimum directivity [41]. The reason behind its success lies in the simple but dynamic nature of the ICT. It correctly gives the current distribution on each element, which depends on the combination of applied voltages of all the elements.

6. Axial mode helical antennas and spiral antennas

Antennas radiating and receiving circularly polarized waves have become very important since satellite communication and broadcasting systems were introduced. Since the axial mode helical antennas and spiral antenna are nonresonant antennas radiating circularly polarized waves, they have advantages of wide bandwidth of both the input impedance and the axial ratio. However, helical antennas and spiral antennas have many parameters in their respective geometries, and it is not easy to obtain the optimum parameters.

A large amount of research on numerical design of helical antennas in Japan has been reported. Shiokawa...
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References

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