A Report on Japanese Development of Antennas: From the Yagi-Uda Antenna to Self-Complementary Antennas

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Abstract

The self-complementary antenna structure was originated and its constant-impedance property was discovered by the author in 1948. He pursued investigations of this type of antenna for many years, and he attained many extensions of the principle of self-complementarity, from the simplest planar structure to various other cases. In parallel with these studies, extensive developmental investigations of extremely broadband antennas have been carried out in Japan, based on this principle. This article succinctly describes a long history of these studies on self-complementary antennas, including the background of its origination. In connection with the extremely broadband property of this type of antenna, the non-constant-impedance property of incorrectly arranged log-periodic antennas is clearly shown, based on the results of experiments. This experimental fact indicates that the log-periodic shape in an antenna's structure does not guarantee a broadband property for the antenna. Most of experimental details and all of the theoretical treatments are omitted from this article.

Keywords: Self-complementary antennas; broadband communication; log-periodic antennas; antenna theory; history

1. Introduction

The self-complementary antenna is well known for its extremely broadband characteristics. However, almost no information about the historical facts related to the origin of this type of antenna has been reported in any renowned journal. As a matter of fact, the idea of the self-complementary antenna was obtained in the process of the developmental studies for the Yagi-Uda antenna, as a kind of byproduct.

For this reason, this article at first briefly reviews the studies on the design method for the Yagi-Uda antenna that were made by the author, during a period of almost ten years, beginning in the mid-1940s. It then explains the theoretical research on slot antennas that was carried out by other investigators in Japan around the latter 1940s. On the basis of the studies in these two fields, the author originated the self-complementary antenna structure, and discovered its constant-impedance property in 1948.

The extensions of the principle of this antenna to various other types of structures were mostly attained at Tohoku University. Furthermore, the extensive developmental studies of this type of antenna were continued for many years in Japan. The results of these investigations are succinctly explained here. In this connection, an important comment is made on the related developmental work in the United States, by clearly explaining the non-constant-impedance property of log-periodic antennas.

2. Problems Remaining for the Design of the Yagi-Uda Antenna

In this article, the story goes back to the 1940s. As everybody knows, the directors, which are composed of parasitic elements, characterize the Yagi-Uda antenna [1]. However, there were endless arguments about the optimum lengths of the directors around that time, while it was already recognized that the spacing of the director from the radiating element has a certain effect on its optimum length. The author studied this problem by introducing Hallén's theory [2], and it was found that the radii of the directors have decisive effects on the directors' optimum lengths. In spite of this fact, information about the thickness of the directors had not even been included in the experimental data obtained by prior investigators.

For this reason, the author pursued intensive and thorough theoretical investigations of the three-element Yagi-Uda antenna – as shown in Figure 1 – by taking the wire radii into account. Numerical data was obtained. Furthermore, experimental corroborations were also made. The results of these studies were arranged in the form of various design charts [3-5] for practical use (Prof. Kraus kindly recommended the author's paper [5] to the 1955 URSI symposium when the author was a Research Associate at The Ohio State University).

One example of a design chart that is related to the wire radius of the directors is shown in Figure 2. The curves in this
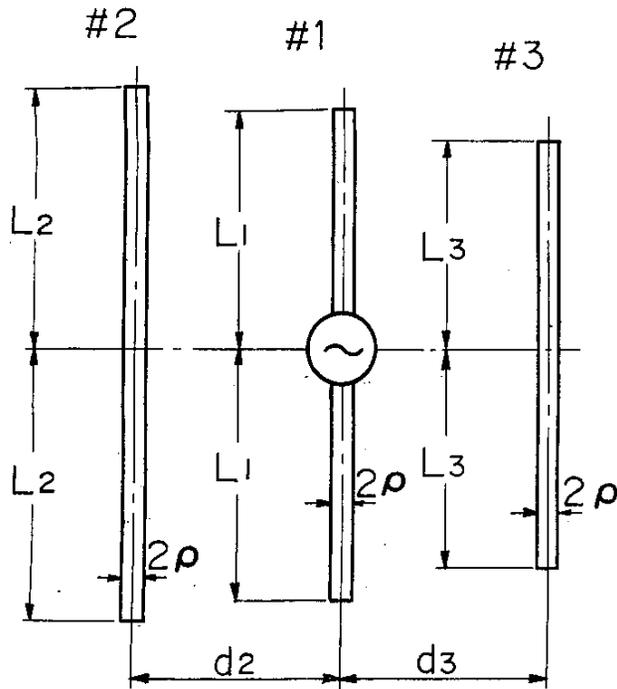
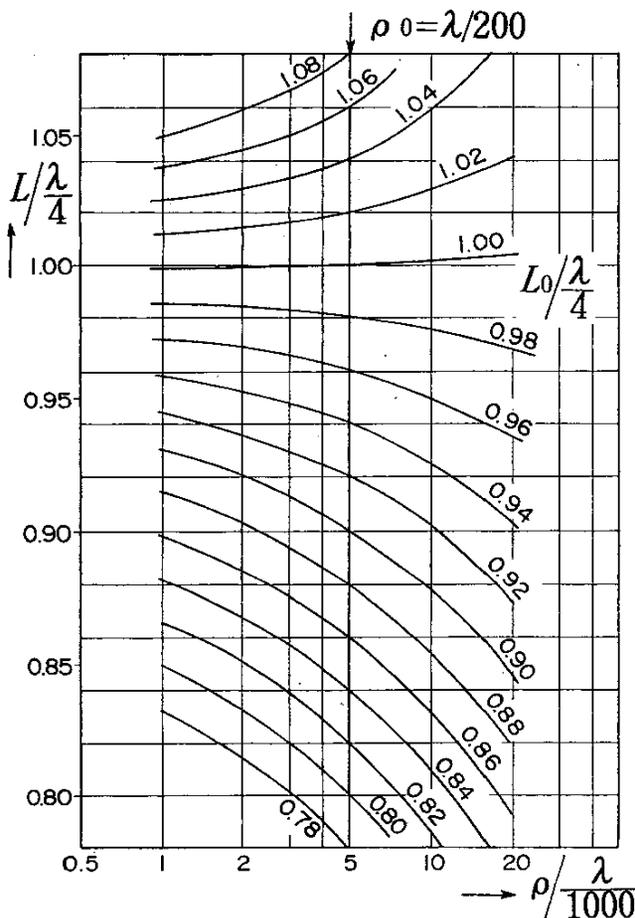**Figure 1. The simplest structure for a Yagi-Uda antenna [3].**

Figure 2. The equivalent length of the parasitic element [3].

chart show the geometrical lengths, $2L$, of the parasitic elements that give practically equivalent effects as parasitic elements with varying radius ρ. The value of the parameter shows such an equivalent half-length of the element, L_0, when a parasitic element with the reference radius $\rho_0 = \lambda/200$ is substituted for it. For example, by using this design chart the optimum length of a director with any wire thickness can be obtained from an already-known optimum length of the director with a particular thickness. Details are shown in the comprehensive book on Yagi-Uda antennas [3] (Prof. E. C. Jordan reviewed this book in *Proc. IRE*, **43**, 2, February 1955, p. 235).

Around that time, the slot antenna attracted wide attention as a low-profile antenna element. The author thought that the introduction of such an element into a Yagi-Uda antenna might be worthwhile for its improvement. However, for that purpose the effects of the varying width of the slot element had to be numerically clarified, similarly to the effects of the thickness in Figure 2 for the case of parasitic elements of conducting wire. Thus, slot antennas were included among the subjects of the author's investigations.

3. Theoretical Studies on Slot Antennas in Japan Around the mid-1940s

In Japan, studies of slot antennas made much progress in the mid-1940s. A narrow, half-wavelength slot antenna, which is formed on a perfectly conducting plane as shown in Figure 3, was theoretically treated as an antenna with a magnetic current[1]. Its input admittance was calculated by the "magneto-motive force method," which corresponds to the "electromotive-force method" for s half-wavelength antenna with thin wire. From these studies, a relation between two input impedances, and for mutually complementary wire antennas and slot antennas, was obtained [6, 7]:

$$Z_1 Z_2 = (Z_0/2)^2, \tag{1}$$

where

$$Z_0 = \sqrt{\mu_0/\varepsilon_0} \approx 120\pi \tag{2}$$

is the intrinsic impedance of the medium. However, for Equation (1) both the thickness of the wire and the width of the slot are assumed to be of negligible size, and, hence, this relation is not relevant to a discussion of slot antennas with general dimensions. Incidentally, Equation (1) had been obtained in Japan earlier than the paper of H. G. Booker [9], and the paper [10] was a more detailed report of the unpublished earlier paper [6].

In the meantime, a rigorous treatment of the extension of Babinet's Principle to electromagnetic fields was reported [8]. The expressions for this extended principle for electromagnetic fields are much more complicated than those for the original principle in

[1]This concept came from J. A. Stratton's book *Electromagnetic Theory* (New York, McGraw-Hill, 1941), because this book had been well-studied in Japan. The author also studied this book very hard, and he pointed out many misprints in the text in a letter directly to Prof. Stratton. Prof. Stratton acknowledged this by his kind letter of November 2, 1947, to the author, who was still a graduate student at Tohoku University.

optics. The author thought that the theory of this extended principle might be utilized in generalizing Equation (1) for a revised relation between an arbitrarily shaped slot antenna and its complementary planar antenna.

4. A Generalization of the Relation to the Case of Arbitrarily Shaped Slot Antennas

Let the electromagnetic fields for an arbitrarily shaped planar antenna and a complementary slot antenna (as shown in Figures 4a and 4b) be E_1, H_1, and E_2, H_2, respectively. Here, Figure 4c is
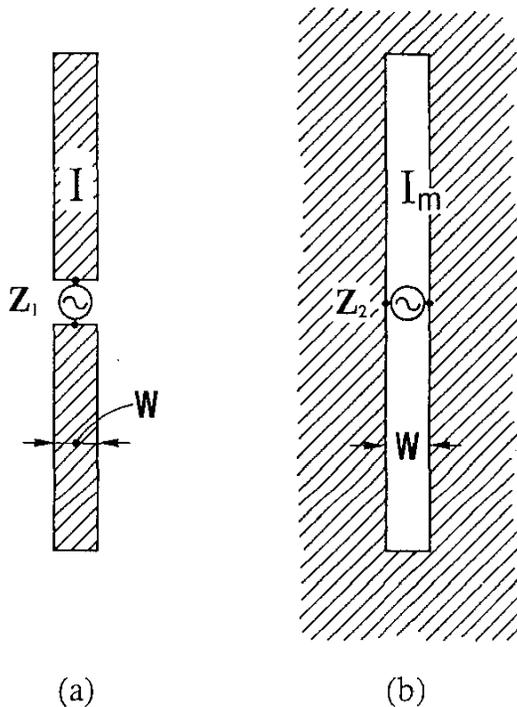

(a)   (b)

Figure 3. A narrow planar antenna (a) and a complementary slot antenna (b).
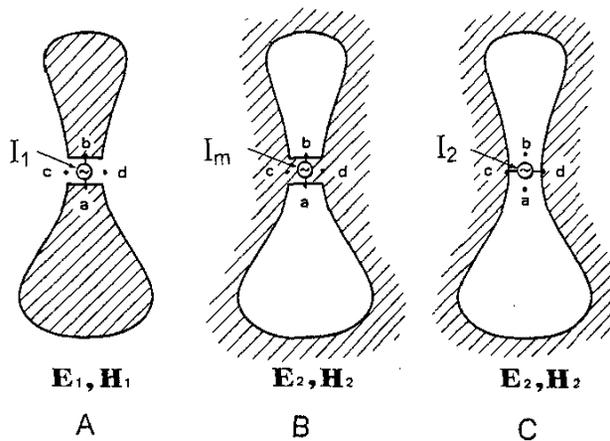

Figure 4. An arbitrarily shaped planar antenna and the complementary slot antenna [42, 45].

equivalent to Figure 4b. Then, by applying the duality relation in the electromagnetic fields – which was used in the process of extending Babinet's Principle, mentioned above [8] – one eventually finds

$$E_2 = \mp H_1,$$

$$H_2 = \pm (1/Z_0)^2 E_1,$$

(3)

where the upper signs are for the front side of the conducting plane, and the lower signs are for its reverse side. The terminal voltages of these antennas are given by the line integrals of the electric fields in the vicinity of the feed points, and their input currents are given by the contour integrals around the feed lines. Therefore, the input impedances of these two antennas, Z_1 and Z_2, can be expressed by the ratios of those integrals. By taking a product of the expressions for these two impedances and introducing the relations given by Equation (3), the author finally obtained an advanced relation for arbitrarily shaped and mutually complementary planar antennas and slot antennas, as shown in Figure 4:

$$Z_1 Z_2 = (Z_0/2)^2.$$

(4)

This new relation, Equation (4), for the general case is unexpectedly identical to the previous relation, Equation (1), which is for the simplest, limiting case. This was – fortunately or unfortunately – a surprising result for the author. Actually, the new Equation (4) includes tremendously more physical information than the previous Equation (1). In spite of this fact, the forms of these two expressions were exactly identical, and it looked like no advancement had been attained. Unfortunately, for this reason the author could not publish any paper on this undoubtedly new achievement. This work involved really time-consuming and troublesome theoretical calculations of the electromagnetic fields, and the present author was quite discouraged by this inconceivable outcome.

5. Origin of Self-Complementary Antennas with Constant-Impedance Property

Several months later, the author reconsidered about this matter, and realized that some entirely novel application of the new Equation (4) should be presented, in order to demonstrate the excellence of this new tool. With concentrated and intensive consideration to this end, he finally hit on a new idea. This was the origin of a structure where the shape of the planar conducting sheet for a slot antenna is exactly identical to the shape of its complementary planar antenna. Such a new structure is the self-complementary antenna structure, shown in Figure 5a as an image of the simplest shape. Immediately after that, the author tried to calculate the input impedance of such an antenna by utilizing the new tool, Equation (4), and easily found that the value, Z, is given by

$$Z = Z_1 = Z_2 = Z_0/2 \approx 60\pi \approx 188.4\Omega.$$

(5)

This means that the input impedance of the self-complementary antenna is always constant, independent of the source frequency, while there are infinite varieties to its shapes. Prof. V. H. Rumsey [23] later called this equation "Mushiake's relation (relationship)." (Prof. Rumsey called this equation "Mushiake's relation" in his book [23], but it was revised later to "Mushiake's relationship" when the book [47] was published in London.)

Another simple type of self-complementary structure, Figure 4b, was also found when a manuscript for an oral paper was being prepared [11]. Then, fortunately, the author was able to publish two more papers on this subject [12, 13]. Later, it was found that various types of self-complementary structures have constant-impedance properties in general, and such a general principle was
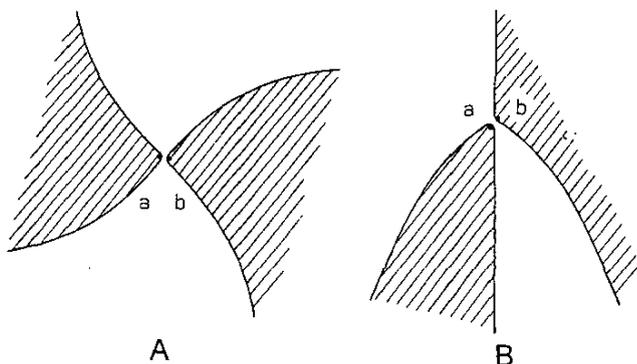

Figure 5. The simplest shapes of self-complementary antennas at their origin [12]: (a) The rotationally symmetric type; (b) The axially symmetric type.
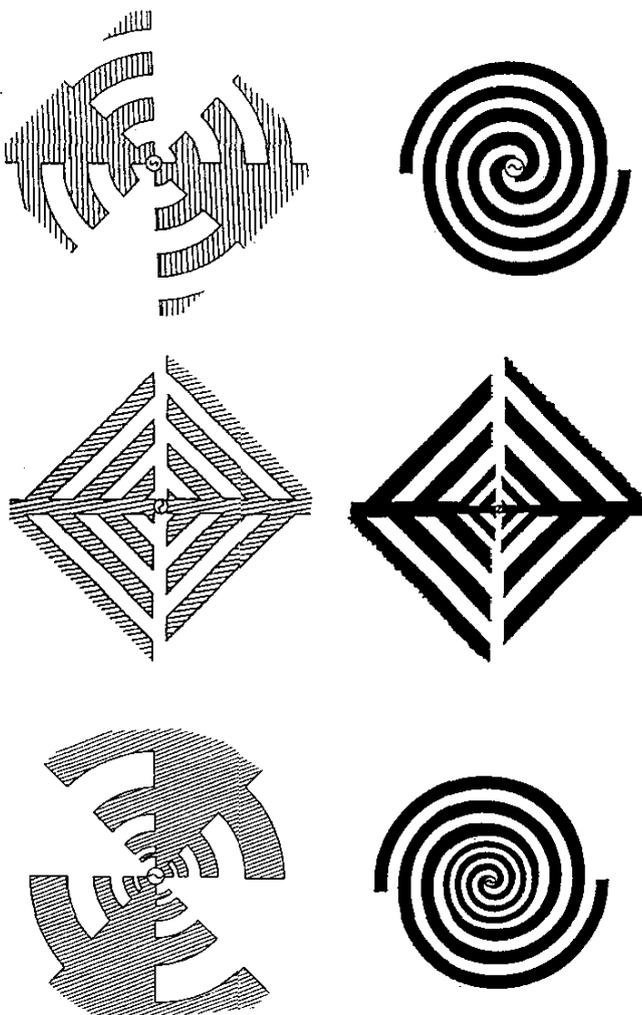

Figure 6a. Rotationally symmetric examples of some of the infinite varieties of the shapes of self-complementary structures.
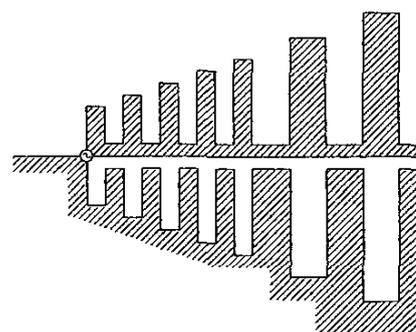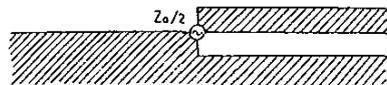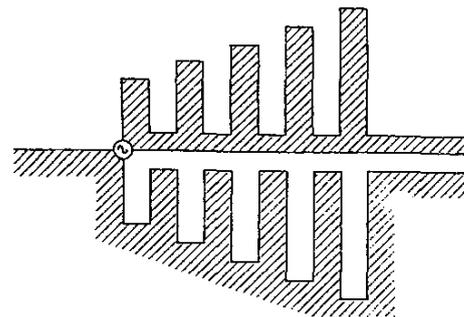

Figure 6b. Axially symmetric examples of some of the infinite varieties of the shapes of self-complementary structures.

named the "Principle of Self-Complementarity" (in Japanese, it had been identified by a word equivalent to "Principle of Self-Complement," but this was revised when the book [47] was published in London.)

Just after the publication of those papers, Prof. K. Fukushima, at Tohoku University, pertinently incited the author to apply this principle for realizing some practical broadband antennas. However, at that time television broadcasting in Japan had been scheduled to be inaugurated in 1953, and the establishment of the design method for television receiving antennas as a practical application of the Yagi-Uda antenna was the most urgent project for the author.

6. Extensions of the Principle for Other Cases

The initial self-complementary antennas were two types of two-terminal structures, although there are infinite varieties in their shapes, as shown in Figure 6. In this connection, the author imagined that there might be some different types of constant-impedance structures in a self-complementary shape other than these.

With such prospects, the author first tried to extend this principle to the case of a turnstile-type four-terminal structure, as shown in Figure 7. In this case, the feeding system for the com-

plementary structure is in a ring connection, while that for the original structure is in a star connection, as explained in Figure 8. Accordingly, the value of the input impedance for the latter structure is not identical to that of the former structure. However, the impedance for the ring connection can be transformed to that of the star connection. Hence, one finds that

$$2Z_1 = Z_2. \tag{6}$$

In the mean time, it is easily shown that Equation (4) also holds for the structure in Figure 5. Therefore, one finally finds that the input impedance, Z, for the structure in Figure 7 is given by

$$Z = Z_1 = Z_0/2\sqrt{2} \approx 30\sqrt{2}\pi \approx 133.2\,\Omega \text{ each.} \tag{7}$$

This is an extension of Mushiake's relationship [14].

On the other hand, Prof. Victor H. Rumsey proposed the frequency-independent antennas in the United States, and his co-workers utilized the constant-impedance property of the self-complementary antennas by introducing it into their developmental investigations [15-19, 23]. In this connection, the author published a comment on their work [20].

Incidentally, it should be noted here that a much more detailed report on the extension of the principle to multi-terminal structures was published by G. A. Deschamps [18], just after the author's paper [14].

Another notable extension of the principle was attained by the author for the case of a three-dimensional structure (as shown in Figure 9), where two infinitely-extended planar conducting-sheets comprise a crossing of the vertical and horizontal planes. The idea of this extension flashed through author's mind with a consideration based on "duality," which is a concept of higher order than "complementarity" for the two-dimensional structure. Therefore, such a new structure might be called "self-dual," rather than "self-complementary." In the process of considering this extension, the introduction of fictitious magnetic perfect conductors was very helpful. But they were eventually eliminated without any discrepancies in the actual electromagnetic fields. Thus, the input impedance for this structure was obtained, and it was found [21] that the value of the input impedance is given by
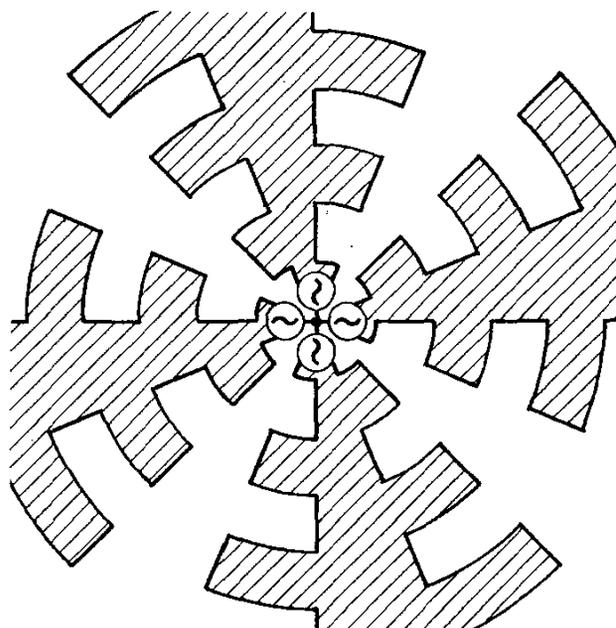

Figure 7. A rotationally symmetric turnstile-type four-terminal self-complementary antenna [42, 45].
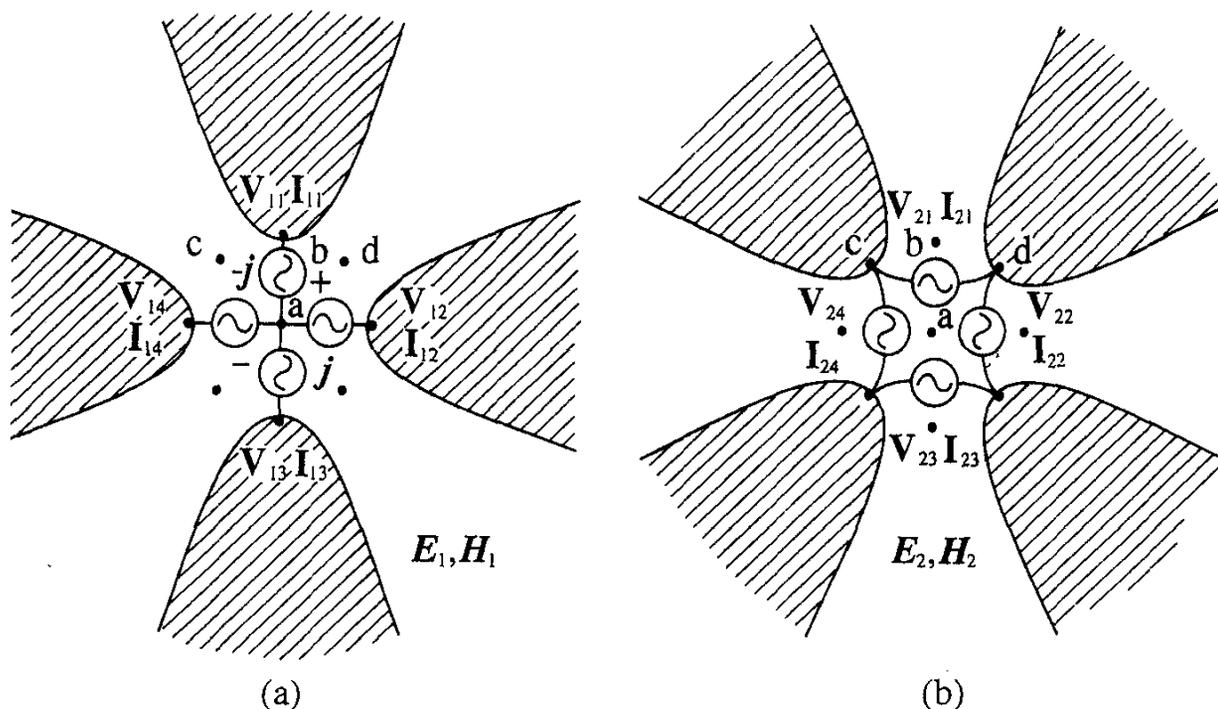

(a)

(b)

Figure 8. The feed systems for mutually complementary structures of the turnstile-type four-terminal self-complementary antenna [47].

$$Z = Z_0/4 \approx 30\pi \approx 94.2\,\Omega, \qquad\qquad (8)$$

independently of the source frequency and the shapes of the structure. A further generalization of this structure was also made for a cross of multiple conducting sheets, where the number of the sheets is N: for Figure 9, $N = 2$. The input impedance for this generalized case [22] is also always constant, and it is given by

$$Z_N = Z_0/2N \approx 30\pi/N \approx 188.4/N\ \Omega. \qquad\qquad (9)$$

Furthermore, in the process of developmental studies by the author and his associates [24-43, 46], various other new types of constant-impedance antennas were originated as extensions of the principle. Among those antenna structures, the stacked antenna [33, 43] is the most promising structure for an extremely broadband and, at the same time, high-gain antenna. An example of a side-by-side stacked self-complementary antenna is shown in Figure 10, where the electric sources applied to each feed point are identical. It was found that for this antenna, the input impedance is $Z_0/2$ at each feed point, including the effect of mutual coupling among the antenna elements [33].

For the purpose of summarizing a long history of the origin and the extensions of the "Principle of Self-Complementarity," the major items are listed in chronological order in Table 1, including the background for the origin of this principle.
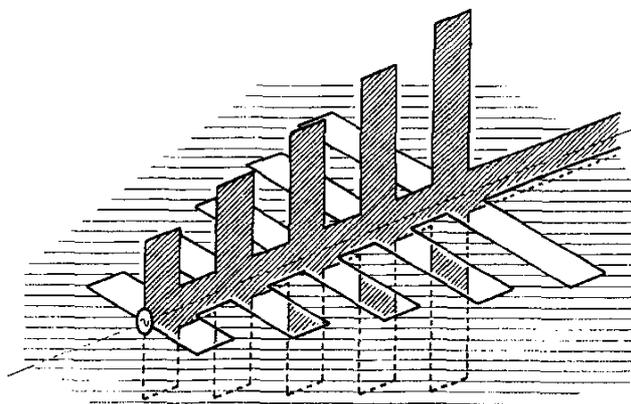

Figure 11a. A log-periodic antenna arranged in a self-complementary manner (a modified self-complementary antenna) [22].

Figure 9. A three-dimensional self-complementary antenna [42, 45].

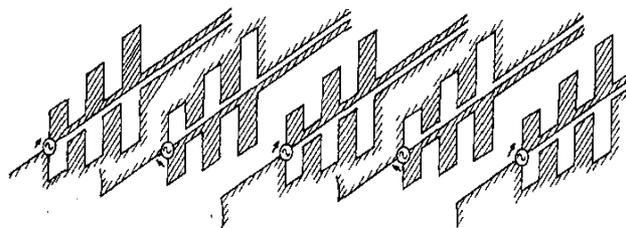

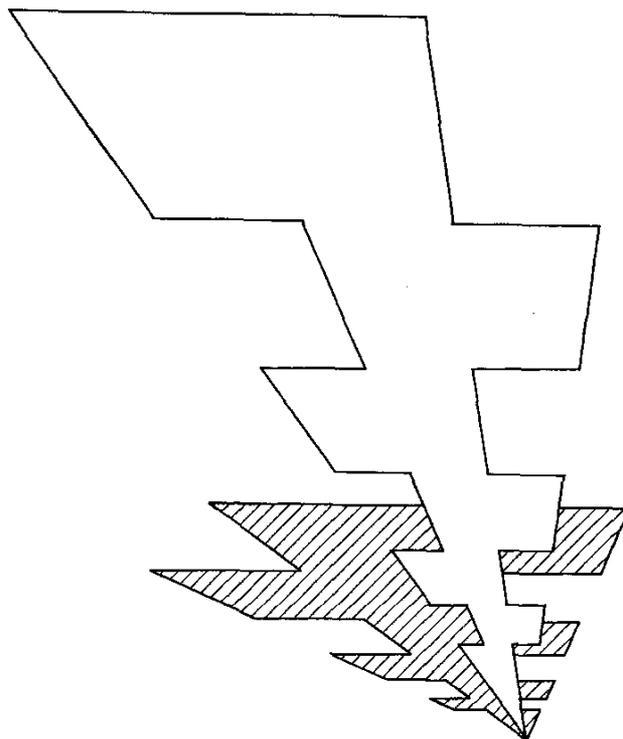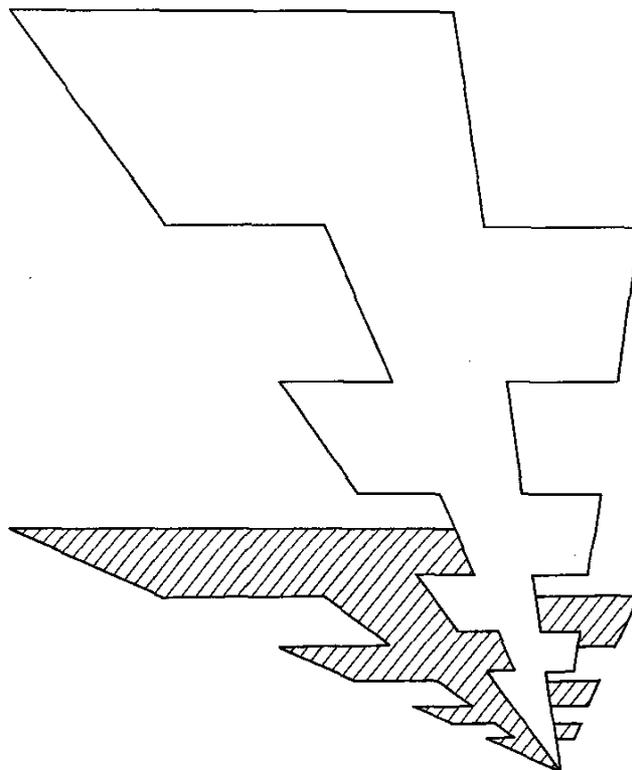Figure 10. A side-by-side stacked self-complementary antenna [33, 45].

Figure 11b. A log-periodic antenna arranged in an anti-complementary manner [22].

Table 1. The history of the "Principle of Self-Complementarity" from the background of the origin and the discovery to the extensions.

-4	1941	New expressions of the electromagnetic fields where both the electric and the magnetic quantities are treated on an equal basis: J. A. Stratton (USA)
-3	1945	A relationship between two radiation impedances for a narrow slot antenna and a complementary wire antenna derived from classical antenna theory: T. Matsumoto (Hokkaido U.), M. Ito (Hiroshima Tech. Col.); (1946) H. G. Booker (UK)
-2	1945	Babinet's Principle for electromagnetic fields: M. Kotani (U. of Tokyo), G. Sunouchi (Tohoku U.)
-1	1947	A general relationship between two input impedances for an arbitrarily shaped slot antenna and a complementary planar sheet antenna: Y. Mushiake (Tohoku U.)
0	1948	Discovery of the Principle of Self-Complementarity (origin of the self-complementary antenna structure and the discovery of its constant-impedance property): Y. Mushiake (Tohoku U.)
1	1948	Rotationally symmetric two-terminal self-complementary planar antenna (balanced type, $60\pi \approx 188.4\,\Omega$): Y. Mushiake (Tohoku U.)
2	1948	Axially symmetric two-terminal self-complementary planar antenna (unbalanced type, $60\pi \approx 188.4\,\Omega$): Y. Mushiake (Tohoku U.)
3	1959	Rotationally symmetric four-terminal self-complementary planar antenna (turnstile type) (star-connection type, $30\sim 30\sqrt{2}\pi \approx 133.2\,\Omega$ each): Y. Mushiake (Tohoku U.)
4	1959	Rotationally symmetric multi-terminal self-complementary planar antennas (star, ring, and other connections for various values of input impedances): G. A. Deschamps (USA)
5	1963	Three-dimensional multi(N)-planar axially symmetric two-terminal self-complementary antenna (unbalanced type, $60\pi/N \approx 94.2\,\Omega$ for $N = 2$): Y. Mushiake (Tohoku U.)
6	1972	Checkerboard type multi-terminal self-complementary planar antenna* (balanced type, $60\pi \approx 188.4\,\Omega$ each): N. Inagaki (Nagoya Tech. U.)
7	1978	Modified three-dimensional self-complementary antenna** (unbalanced type, $30\sqrt{2}\pi \approx 133.2\,\Omega$: T. Kasahara, T. Ishizone, Y. Mushiake (Tohoku U.)
8	1981	Modified three-dimensional self-complementary transmission line (unbalanced type, $30\sqrt{2}\pi \approx 133.2\,\Omega$): T. Ishizone (Tohoku U.)
9	1982	Co-planar stacked self-complementary antenna. (unbalanced type, $60\pi \approx 188.4\,\Omega$ each): Y. Mushiake (Tohoku U.)
10	1982	Side-by-side stacked self-complementary antenna (unbalanced type, $60\pi \approx 188.4\,\Omega$ each): Y. Mushiake (Tohoku U.)
11	1982	Compound-stacked self-complementary antenna (unbalanced type, $60\pi \approx 188.4\,\Omega$ each): Y. Mushiake (Tohoku U.)
12	1994	Axially symmetric self-complementary antenna with loaded multi-element (unbalanced type, $60\pi \approx 188.4\,\Omega$ each): Y. Mushiake (Tohoku U.)

* Freedom in the shape is restricted to similitude-transformation. **Theoretical proof for general cases has not been successful, except for the monopole-slot type array antenna.

7. Non-Constant-Impedance Property of an Incorrectly Arranged Log-Periodic Antenna

Some copies of the first English paper [13] on self-complementary antennas were sent to several institutions in the United States in the early 1950s, in accordance with the suggestion of Prof. S. Uda. Fortunately, Prof. Rumsey, of the Antenna Laboratory of The Ohio State University, accurately recognized the importance of this work. Afterwards, he and his colleagues at the University of Illinois introduced this principle into their studies of frequency-independent antennas, as mentioned in Section 6. Along the lines of those studies, extremely broadband practical antennas were developed, including the so-called log-periodic antenna and the log-periodic dipole array [15-19, 23]. However, it must be particularly noticed here that the origin of the broadband characteristics of those antennas is in their shapes derived from the self-complementary antennas [20, 22], rather than their log-periodic shapes.

The author experimentally verified [22] this important truth to avoid the necessity of such an argument. For that purpose, two exactly identical half-structures of a log-periodic antenna were prepared. At first, they were arranged in a self-complementary manner, as shown in Figure 11a (which is a modified self-complementary antenna), and the input impedance was measured. Then, only the lower half-structure was rearranged, upside down, as shown in Figure 11b. This is evidently a log-periodic antenna too, but the arrangement is in an anti-complementary manner. The input impedance was also then measured.

The measured input resistances for these two antennas are compared in Figure 12. The results show that the value of the input resistance for the antenna of Figure 11b, which is arranged in an anti-complementary manner, varied distinctively with the source frequency, while it remained almost constant for the antenna of Figure 11a, which is arranged in a self-complementary manner. This test showed that incorrectly arranged log-periodic antennas are indisputably not frequency independent [44]. Furthermore, the

Figure 12. A comparison between the measured input resistances of two types of log-periodic antennas [22].

Figure 13. A typical structure of a rotationally symmetric self-complementary antenna [25].

original structure of Figure 11a — before the modification — has a typical self-complementary shape, as explained in, e.g., [23, pp. 58-63]. Therefore, it can be well understood from the results of these measurements that the "Principle of Self-Complementarity" is an undoubtedly useful principle.

8. Developmental Studies of Self-Complementary Antennas in Japan

In the 1950s, the fields of the author's research were gradually also extended to millimeter-wave and optical-wave transmission. But the studies on self-complementary antennas were always continued as a minor research project, until the mid 1970s. In that period, some of the developmental studies [24, 25] were performed in parallel with the extensions of the principle. But in the late 1970s, the situation of the studies on this subject abruptly improved, due to financial aid from the Ministry of Education and others in Japan. Thus, intensive and systematic investigations of this type of antenna were made possible for the author and his co-workers for several years, and a number of papers [26-43, 46] were published in the early 1980s. Some of the extensions of the principle mentioned in Section 6 were also achieved in this period. The results of these developmental studies are succinctly described below.

As explained in Section 5, self-complementary antennas have infinite varieties to their shapes. Some examples of the shapes for typical planar types are shown in Figure 13 and Figure 14, where each structure has an infinitely-extended geometry. For this reason, the truncation of the structure is always needed, in practice. However, it is in general well understood that a reduction of the reflected electric currents at the truncated end of the antenna structure is effective in reducing the truncation effects. In the above examples, teeth-type shapes were introduced for this purpose. Thus, the constant-impedance property can be practically realized with a finite structure, although there is a certain low-frequency limit, in practice. Such general properties for the truncations were examined in detail [24, 25, 28, 29, 31] with the structures shown in Figure 13 and Figure 14. Also, the broadband property of their measured radiation patterns was examined [25, 31]. An example of the results obtained from the measurements is shown in Figure 15.

It is interesting that the infinitely long strip in the unipole-notch type of structure, or the tail in Figure 14, is equivalent to the infinitely long self-complementary transmission line with a characteristic impedance $Z_0/2$ when the width of the strip is assumed to be sufficiently small compared with the wavelength. Therefore,
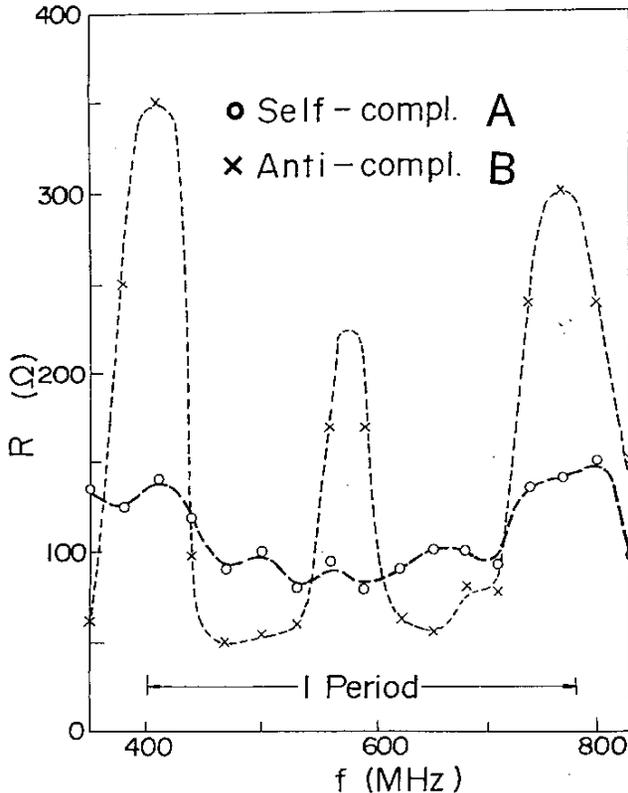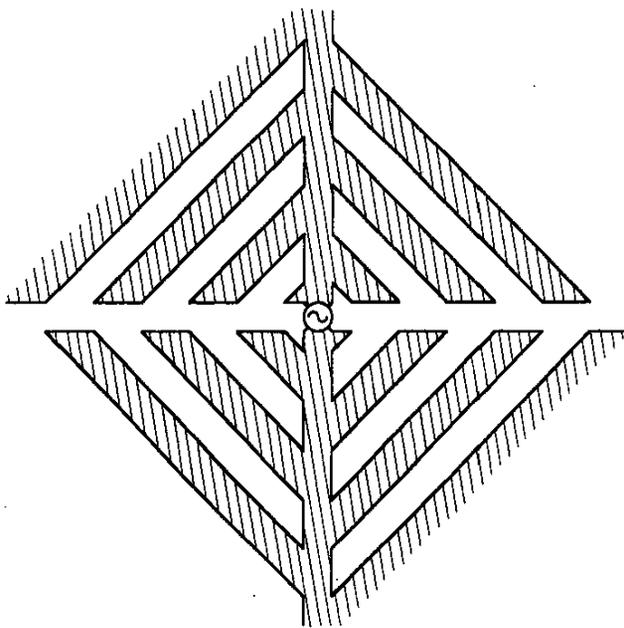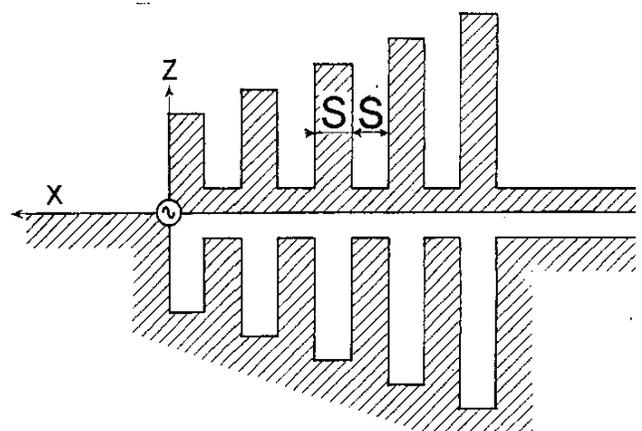

Figure 14. A typical structure of an axially symmetric self-complementary antenna [42, 45].
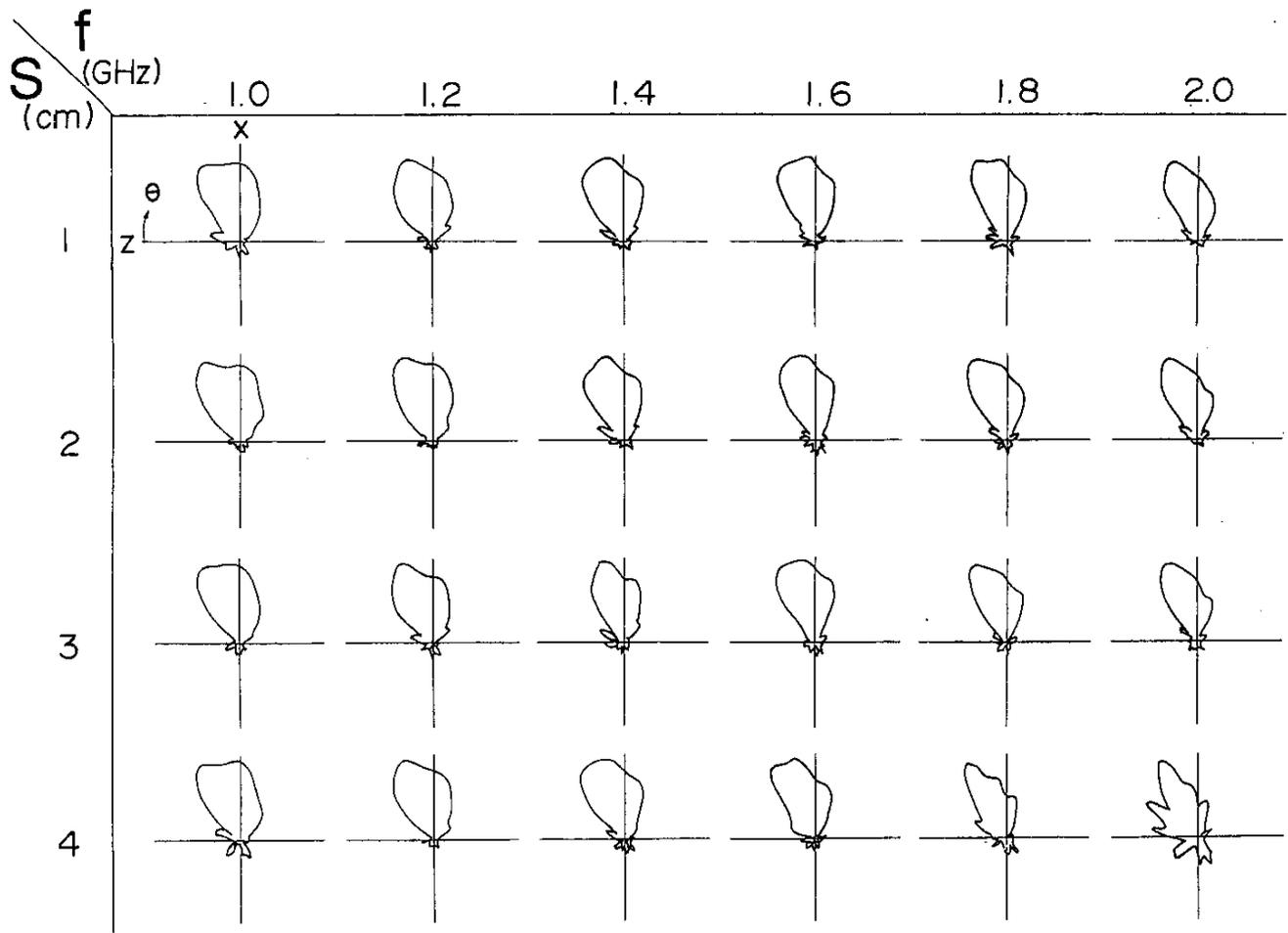
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Figure 15. The measured radiation patterns of an equally-spaced unipole-notch type of self-complementary antenna [31].
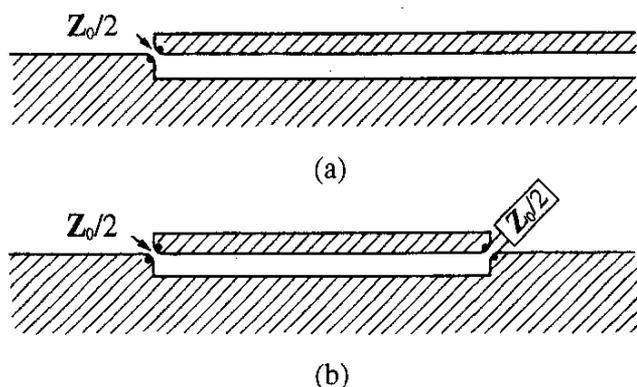

(a)

(b)

Figure 16. A self-complementary transmission line and its substitute [47].

the long tail can be practically substituted for by a lumped constant impedance $Z_0/2$, as shown in Figure 16. However, it was found from the experiments that the difference in the value of the loaded impedance at the end terminal has almost no effect on the input impedance of the antenna, if most of the supplied power is radiated from the antenna structure. However, there is a low-frequency limit for such a property, which depends on the largest dimension of the antenna's structure.

On the other hand, one company in Japan developed extremely broadband practical antennas. Two examples are shown in Figure 17. Both of them are modified self-complementary antennas that are derived from the original two-dimensional structures.

As an application of the three-dimensional self-complementary antenna that was explained in Section 6, detailed experimental investigations were carried out at Tohoku University with the geometries shown in Figure 18. In this structure, the lower half of the vertical conductor was excised off of the original structure, so as to utilize the radiation into only the upper half-space. This modified structure is actually a monopole-slot type of array antenna. According to the results of the experiments, the radiation characteristics were almost unchanged in the frequency range of 0.95~4.0 GHz, as shown in Figure 19. But it was found that the value of the input impedance became higher than that of the original structure, and the measured values on the Smith chart concentrated around $Z_0/2\sqrt{2} \approx 133.2\,\Omega$, as shown in Figure 20, instead of the original value of $92.4\,\Omega$. Heretofore, this value, $133.2\,\Omega$, has not yet been proven in general by the theory, except for some limiting cases [26, 30, 36, 37].

The size of antenna structures for higher frequencies become smaller, in general, and the introduction of the printed-circuit technique for fabricating antenna structures was useful. Two types of experimental structures were prepared for the measurements. One
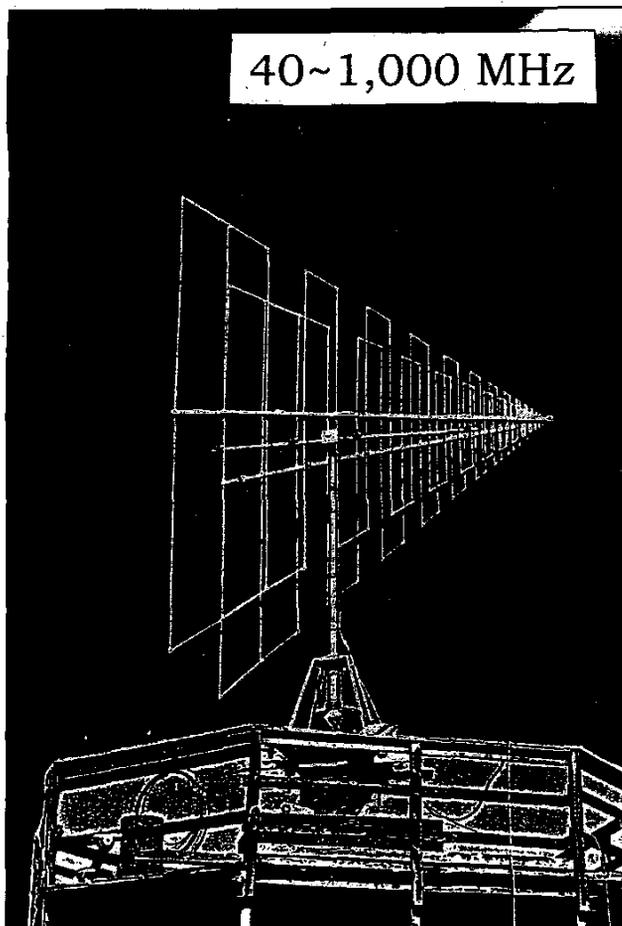
Figure 17a. An example of an extremely broadband practical antenna developed in Japan for noise measurements (30~1000 MHz) (courtesy of Denki Kogyo Co. Ltd., Tokyo).
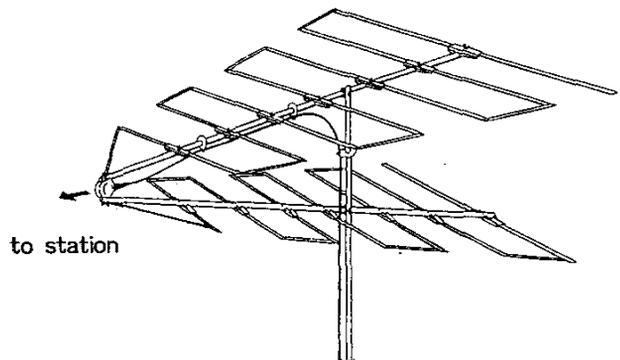
Figure 17b. An example of an extremely broadband practical antenna developed in Japan as an FM-TV receiving antenna (80~222 MHz) (courtesy of Denki Kogyo Co. Ltd., Tokyo).

Figure 18. The geometry of a modified three-dimensional self-complementary antenna [36, 45].

Figure 19a. The measured radiation pattern in the x-y plane of the modified three-dimensional self-complementary antenna [36, 45].

Figure 19b. The measured radiation pattern in the ϕ_{max} - z plane of the modified three-dimensional self-complementary antenna [36, 45].

Figure 20. The measured input impedance of the modified three-dimensional self-complementary antenna [36, 45].
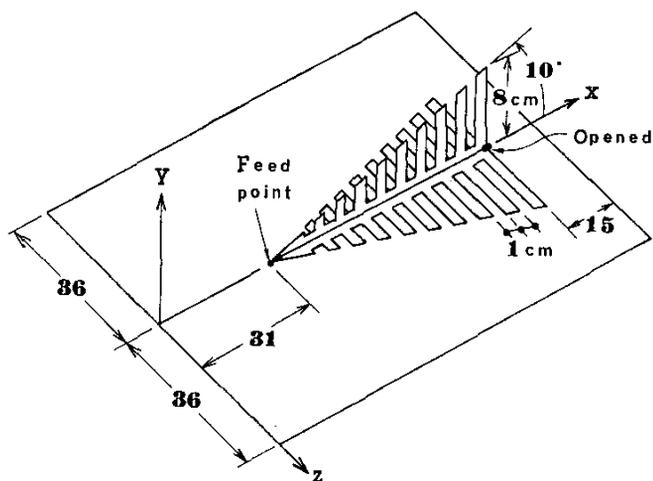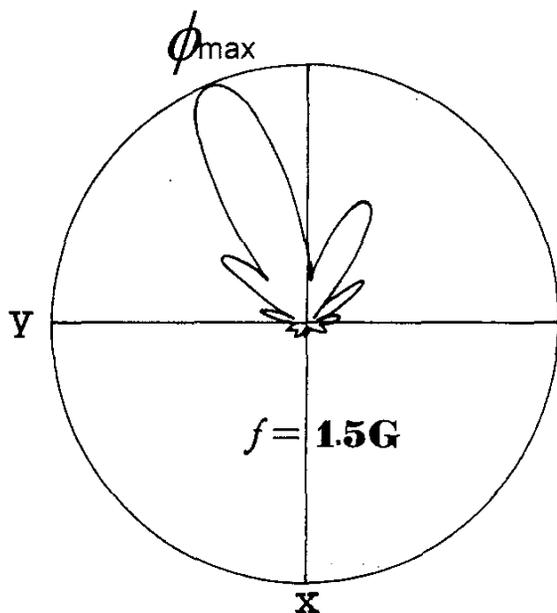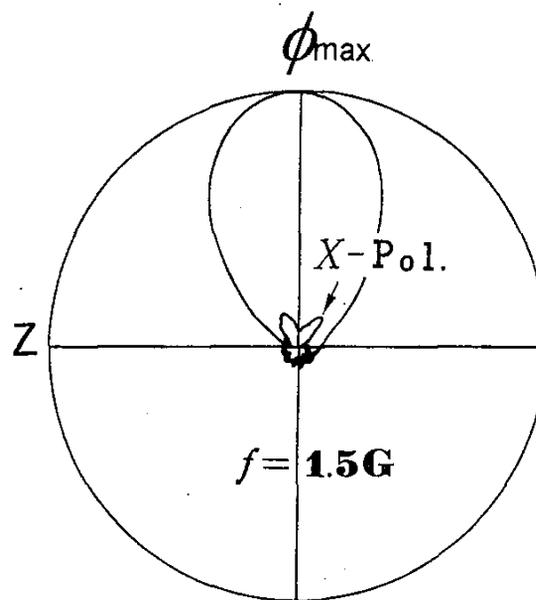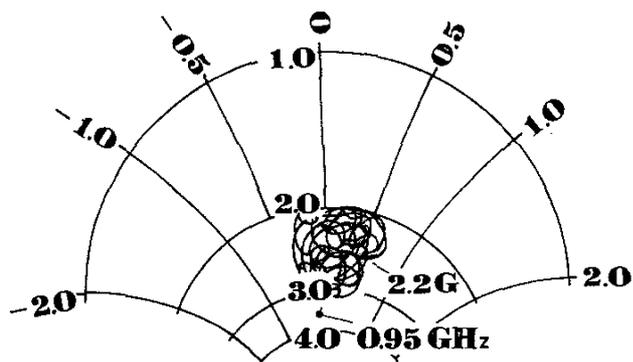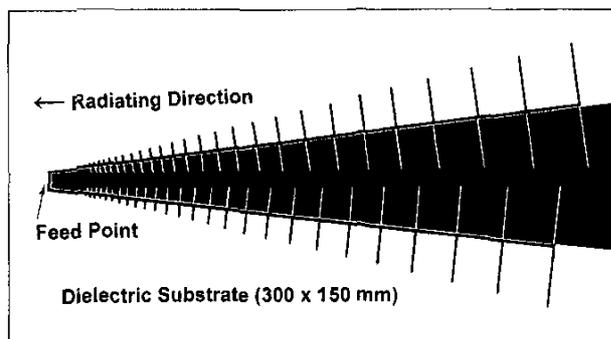

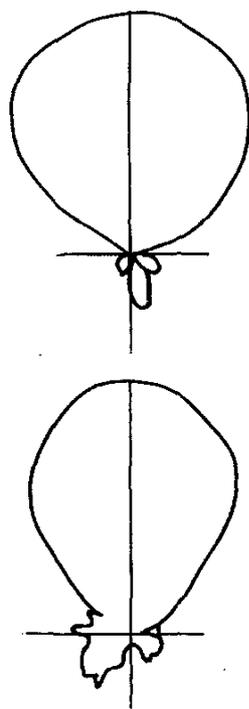Figure 21. A printed self-complementary antenna on a dielectric substrate [38].

Figure 22a. The measured E-plane radiation pattern of the printed self-complementary antenna at 1.8 GHz (top) and 4.0 GHz (bottom) [38].
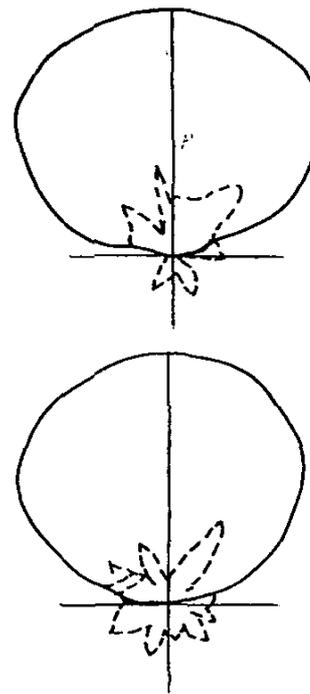

Figure 22b. The measured H-plane radiation pattern of the printed self-complementary antenna at 1.8 GHz (top) and 4.0 GHz (bottom) [38].

was constructed on poly-foam without a substrate, and the other was on a dielectric substrate. Figure 21 shows an example for the latter case, and it has proportionally spaced monopole-notch elements with equal widths. The effects of the substrate for this structure were studied in detail, and it was found that the actual wavelengths on various portions of this antenna structure were not identical, though all of them were shorter than those in free space. Here, the portions of the structure refers to the monopole, the notch, and the transmission line. The values of the input impedance and the characteristic impedance decreased with certain proportions, respectively. However, various characteristics of this antenna remained almost unchanged for the frequency range of 1~7 GHz, and their values are as follows:

Constant impedance: about 145 Ω (instead of 188 Ω)

Gain: 10.5 ± 0.3 dBi.

Some of the radiation patterns are shown in Figure 22. Besides this, various other useful design data for this type of antenna were also obtained from the experimental studies [34].

The major results of these extensive developmental studies were published in Japan in the form of reports [32, 38], which include a number of various practical data. In addition, a short overview of the studies of self-complementary antennas in Japan was published in the IEEE Antennas and Propagation Magazine [45]. Furthermore, the present author published a comprehensive book on self-complementary antennas [47] through Springer-Verlag, London, in 1996. Prof. Chen-To Tai, Dr. W. Ross Stone, Prof. P. J. B. Clarricoats, and Prof. S. Adachi encouraged the publication of this comprehensive book. Prof. W. L. Stutzman reviewed this book (IEEE Antennas and Propagation Magazine, 38, 4, August 1996, p. 63) just after its publication. In addition, a long series of hard struggles during the author's academic life,

related to self-complementary antennas, was explained with simple stories in a book published in Japanese [48].

9. Conclusion

The studies on the remaining problems for the design of the Yagi-Uda antenna and the theoretical studies of slot antennas in Japan around the later 1940s were briefly reviewed, where a methodological connection of the studies between these two antennas was mentioned. Then, the origin of the self-complementary antenna and the related findings were explained in some detail. A long history of this principle, from the origin to the extensions to various cases, was described. Major results of the developmental studies in Japan for extremely broadband antennas were also succinctly explained. Finally, it should be stressed here that the non-constant-impedance property of incorrectly arranged log-periodic antennas is an indisputable truth.

The oral presentation of this paper [49] with the same title was made at the special session Honoring Prof. J. Kraus by the invitation of Prof. Chen-To Tai and with the helpful advice of Prof. Ronald J. Marhefka and Prof. K. Sawaya. After that, Dr. W. Ross Stone recommended the submission of this article. The author wishes to express his sincere thanks to all the persons mentioned, not only in this paragraph but in this whole article, for their warm support of this work in their respective situations.

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Introducing the Feature Article Author

Yasuto Mushiake was born in Japan on March 28, 1921. He received the BEng in Electrical Communications, Graduate Course Certificate, and the DrEng degrees, all from Tohoku (Imperial) University, Japan, in 1944, 1949, and 1954, respectively. From 1949 to 1960, he was an Assistant Professor there, and from 1954 to 1956, he was a Research Associate at The Ohio State University, USA. In 1960, he became a Professor at Tohoku University, and worked there until 1984, when he moved to Tohoku Institute of Technology, Japan, as President. Since his retirement from this in 1989, he has been Advisor to the same Institute to date, and also to Matsushita Communication Sendai R&D Labs, until 2001.

His research was at first concerned with the Yagi-Uda antenna and linear antennas. His studies were then extended to those of self-complementary antennas and antennas in plasmas. His research has also covered electromagnetic wave theory, radio

propagation, and millimeter- and optical-wave transmission. He is the author or coauthor of numerous papers and eleven technical books. He is also the editor and coauthor of *Antenna Engineering Handbook* (in Japanese). Dr. Mushiake was the organizer and Chair of the IEEE AP-S Tokyo Chapter, and Chair of the Organizing Committee and Executive Committee for the 1978 International Symposium on Antennas and Propagation, Japan. He served as Vice President of the IEICE, Visiting Research Officer at CRL (formerly, RRL), and a member of several technical committees of the Japanese government. He received the Second Order of Merit with the Sacred Treasure (1991) and Medal of Honor with Purple Ribbon (1985), both from the Emperor of Japan, Medal of Honor of IEICE (1982), and seven other awards. He is Professor Emeritus at Tohoku University and also at Tohoku Institute of Technology. He is an Honorary Member of IEICE and of the Institute of IITE, a Life Member of IEE of Japan, and a Member of the Electromagnetics Academy and Engineering Academy of Japan. He is a Life Fellow of the IEEE. His URL is http://www.sm.rim.or.jp/~ymushiak/. ⓔ

Editor's Comments *Continued from page 46*

number of improvements that have been made over the years in the edge-diffraction model of such horns to take into account the three-dimensional nature of the horn. He then compares the results obtained with this extended theoretical model to measurements made at standards laboratories. The results are that the newly predicted values are within a few times the uncertainties of the measurements, with the exact amount depending on the gain of the horn.

If an antenna and/or its matching network are characterized as a series of tuned circuits, a classic problem is determining the interrelationships among the maximum possible bandwidth, the Q of the antenna and the tuned circuits, the maximum permissible reflection magnitude, and the number of tuned circuits. Alfred Lopez reviews this problem in the Antenna Designer's Notebook, edited by Tom Milligan, and provides a formula with improved accuracy for the Q-bandwidth product. He also provides previously unavailable design curves for the single- and doubly-tuned cases.

Michael Johnson's PACE report brings us another interesting case study. This time, Michael McCorquodale and Richard Brown describe a University of Michigan program that teaches engineering students how to invent, develop, and commercialize technology. This has resulted in a number of new companies being started by the students. Michael McCorquodale should know: he's the CEO of a company that was started as a result of his graduate research.

Tuli Herscovici and Christos Christodoulou bring us an interesting contribution in this issue's Wireless Corner. Ali Dakdouki and Moti Tabulo discuss the eigenvalue distribution of smart antenna arrays, and how it can be used with a variety of physical, signal-processing, and coding methods to provide parallel channels to increase the capacity of wireless systems. This is an excellent overview of an important topic.

Holes that are very much smaller than a wavelength normally do not transmit much light. However, under certain conditions a periodic array of such holes can transmit much more light than standard aperture theory predicts. Rajeev Bansal discusses this in his AP-S Turnstile column.

We're Having Even More of an Impact!

Journal Citation Reports is published by the Institute for Scientific Information, publishers of the *Science Citation Index* series. Two important measures of our publications' value as sources of information to our field are the Impact Factor and the Cited Half-Life. Without going into details, the Impact Factor is approximately the average number of citations of articles over a two-year period, divided by the number of articles published in the publication in the same period. The Cited Half-Life is the number of publication years going back from the current year that account for 50% of the total citations received by the publication during the current year. Roughly speaking, the Impact Factor is a measure of how often the publication is cited; the Cited Half-Life is a measure of how long information in the publication continues to be used.

Table 1 summarizes our *Magazine*'s Impact Factor and Cited Half-Life over the past eight reporting periods. Also shown are how our *Magazine* ranked with respect to other IEEE magazines in the "Electrical and Electronic Engineering" category in which we are listed. Our Impact Factor has improved nicely over the last period. However, our ranking among IEEE magazines in the category remains the same. That's good: it means that other IEEE magazines have improved, as well. Within this category for 2002-2003, our *Magazine* outranked 19 IEEE *Transactions, Letters*, and *Journals* in Impact Factor. For comparison, for 2001-2002, our *Magazine* outranked 11; for 2000-2001, we outranked 29; for 1999-2000, we outranked 23; and for 1998-1999, we outranked 31 IEEE *Transactions, Letters*, and *Journals*.

As shown in Table 1, our Cited Half-Life (5.4 years) tied with *IEEE Circuits and Devices Magazine* for third among the longest Cited Half-Lives of all IEEE magazines. *IEEE Electrical Insulation Magazine* (6.7 years) and *IEEE Spectrum* (5.5 years) had longer Cited Half-Lives. However, our Impact Factor was higher than the Impact Factors for both of those magazines.

We actually could insure that our *Magazine* had a significantly higher Impact Factor by having some of our columns that are less likely to be cited by other authors not be included as "articles" (i.e., not be indexed and abstracted). However, that would be unfair, and it would make our material less useful to our readers – even though it would probably increase our Impact Factor by more than a factor of two!

Table 1. Impact Factor and Cited Half-Life for the *IEEE Antennas and Propagation Magazine*.

Period	Impact Factor	Impact Rank Among IEEE Magazines	Cited Half-Life (Years)	Half-Life Rank Among IEEE Magazines
2002-2003	0.831	8	5.4	3
2001-2002	0.625	8	5.0	4
2000-2001	0.930	6	4.5	3
1999-2000	0.717	7	4.7	1
1998-1999	0.972	6	4.1	3
1997-1998	0.588	8	3.8	6
1996-1997	0.852	5	3.3	N/A
1995-1996	0.855	3	2.7	N/A