Four-Arm Sinuous Antenna With Low Input Impedance for Wide Gain Bandwidth

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ABSTRACT An improved method of reducing the input impedance of a four-arm sinuous antenna is demonstrated for a wide gain bandwidth. The proposed antenna has a dual-linear polarized response for electronic support measures (ESM) systems and is designed with a planar substrate. The structure for reducing the input impedance is developed based on the transmission and coupled line theory and is shown to be in excellent agreement with theoretical predictions. The proposed antenna achieves an impedance bandwidth in the range of 0.45-6 GHz with a reference impedance of 100 $\Omega$. Simulations for comparison according to the difference in input impedance of designed antennas with feeding structures are also presented. Finally, the performance of the fabricated antenna with wideband balun is verified by measuring co- and cross-polarization radiation patterns. As a result, the proposed antenna achieves a wide gain bandwidth (>2.5 dBi) and a cross-polarization isolation (>−13 dB) of more than 12:1 in the frequency range over 0.6 GHz, which can be used in ESM systems.

INDEX TERMS Four-arm sinuous antenna, low input impedance, electronic support measures, wide gain bandwidth.

I. INTRODUCTION

One of the frequency-independent (F.I.) antennas, the sinuous antenna, was published in a patent by DuHamel, describing a combination of spiral and log-periodic antenna concepts [1], [2]. The combination brings out the attribute of polarization diversity, which makes the sinuous antenna useful in ground penetrating radar [3], direction finding [4], [5], radio astronomy [6], [7], electromagnetic pulse [8], and other ultrawideband (UWB) applications. In particular, the four-arm sinuous antenna with dual-linear polarization capability and wide beam-width is compelling candidate in the electronic support measures (ESM) systems [9], [10]. In [10], it is demonstrated that the receiver antenna of the ESM system can obtain better performance with dual-linear polarization than circular polarization capability. Therefore, in order to reduce the number of antennas for ESM system, the frequency response of high radiation efficiency, high gain, and excellent cross-polarization isolation is required over a very wide frequency range covering the electronic warfare (EW) band.

However, the four-arm sinuous antenna is disadvantageous for wideband operation because of the loss due to the need for a long wideband balun for high input impedance (267 $\Omega$) [11], [12]. To address these flaws, various miniaturization techniques for the balun have been investigated [13], [14]. However, these techniques are not appropriate for use in sinuous antennas because it deteriorates the baluns’ balancing properties, which adversely impact the antenna performance. As a result, in the high-frequency band, conventional planar four-arm sinuous antennas have a relatively low peak gain and a narrow gain bandwidth [15]–[18]. With a similar structure, the planar slot sinuous antenna has high gain from unidirectional radiation pattern, but it is difficult to achieve uniform peak gain in ultra-wide frequency response [19]. Since these antennas cannot include a wide frequency range, antennas are further required for each band. For high and uniform gain in ultra-wide bandwidth, conical sinuous antennas have been studied [7], [20]. However, these antennas are very complex, bulky and difficult
In this paper, to reduce the input impedance efficiently and to obtain the wide bandwidth, the modified parallel radiator structure is applied to the four-arm sinuous antenna with the coupled line analysis. Through this, the partial metal width adjustment structure is newly applied to reduce the coupling effect and enhance the bandwidth. For comparison, the antenna performance is compared by the simulation with wideband baluns according to the input impedance. The analysis results are verified by the measured results of the fabricated antenna.

II. THEORY OF SINUOUS ANTENNA

A. OPERATION PRINCIPLE

The sinuous antenna has a log-periodic structure with switch-backed arms on the edges. The sinuous curvature proposed by DuHamel [1] can be written as

\[ \phi = (-1)^p \cdot a_p \cdot \sin \left( \pi \cdot \frac{\ln (r/R_p)}{\ln \tau} \right) \pm \delta \]  

where \( \phi \) and \( r \) are polar coordinates, \( R_p \) is the inner radius of the \( p \)th cell, \( p = 1, 2, \ldots, P \), \( \tau \) is the expansion rate that indicates the scaling ratio for continuous cells, \( R_{p+1} = \tau R_p \). The sinuous arms are formed by rotating the curve by angles \( \alpha \) and \( \delta \) to as illustrated in Fig. 1. The sinuous antenna is composed of \( N \) arms that are duplicated \( N \) times as it rotates by \( 2\pi/N \). Depending on the required antenna polarizations, the number of arms \( N \) is usually two or four. \( \delta \) is set to \( \pi/2N \) to design the self-complementary structure. The sinuous antenna with \( N = 4 \) is required to support dual-linear polarization, and accordingly, \( \delta \) is fixed at 22.5 degrees. The self-complementary condition helps to maintain that the input impedance of the sinuous antenna is frequency independent [21]. The sinuous antenna support a traveling wave that radiates efficiently when the curved length, \( L_p \), of a single cell is an odd multiple of one-half guided wavelength [1], [2]. The smallest radius at which this applies may be approximated as

\[ R_{act} = \frac{\lambda_g}{4(\alpha + \delta)} \]  

where \( \lambda_g \) is the guided wavelength of the traveling wave [1], [2]. Thus, large values for \( \alpha \) may be selected for improved low frequency response without destroying self-complementariness. However, this selection results in unintended resonance modes, making sharp variations in the frequency response of the antenna gain. Analysis of the correlation between the related design parameters and the resonance properties is provided in [15]. Therefore, when selecting \( \alpha \) value, a compromise between properties of the resonance and the low frequency response should be considered.

B. ANTENNA IMPEDANCE

The mode impedance expressed by Deschamps’s theory [11] for the \( N \)-arm self-complementary antenna, can be
represented as:

\[ Z_m = \frac{30\pi}{\sin(m\frac{\pi}{N})} \]  

(3)

where \( m = [1, 2, \ldots, N] \) is one for \( N \) eigenmodes. The number of sinuous arms \( N \) must be four or more for the polarization diversity. The four-arm (\( N = 4 \)) sinuous antenna is considered in this study. Each arm of the four-arm self-complementary antenna operating in mode-1 has an impedance of 133 relative to the ground. According to theory, the input impedance of the four-arm sinuous antenna for linear polarization is \( Z_{in} = 267 \Omega \) [21].

**III. DESIGN OF THE PROPOSED ANTENNA**

Using the parallel radiator structure and the partial metal width adjustment, this section discusses how to reduce the input impedance of the four-arm sinuous antenna to a ratio bandwidth of 13:1 or greater. The substrate with a low dielectric constant is employed to prevent the substrate mode and obtain a stable reflection coefficient, as indicated in Section I. Therefore, the antennas were designed using the Taconic TLY-5 substrate with a dielectric constant of 2.2 and a loss tangent of 0.0009. The substrate had a thickness of 0.5 mm. CST Microwave Studio was used for simulations in this study.

**A. PARALLEL RADIATOR STRUCTURE**

This analysis is restricted to avoid unintended resonance modes while having a relatively small antenna diameter (\( \alpha = 45^\circ \)), and a comparative study of various expansion rates (\( \tau = 1.238, 1.322, 1.496 \)) is included [15], [31]. Initially, to reduce the input impedance, the parallel radiator structure is applied to the four-arm sinuous antenna [30]. To maintain the self-complementary condition, two radiators in a parallel relationship must be kept as close together as possible. Thus, the designed antenna is composed of self-complementary radiators on both sides of the substrate, as illustrated in Fig. 2(a) and (b). The simulated input impedance of the parallel radiator structure is shown in Fig. 3 in comparison to the conventional four-arm sinuous antenna for three different expansion rates. In both antennas (conventional and parallel), as the value of the expansion rate decreases, the average input impedance and its log-periodic fluctuations decrease. This occurs because of the smaller trace width between adjacent arms and the sharper bends in the geometry for lower expansions rates, respectively [21]. Thus, the lowest value of the observed expansion rate was selected in the parallel radiator structure. The average input resistance of the parallel radiator is reduced to ca 130 \( \Omega \) whereas a conventional four-arm sinuous antenna would be ca 200 \( \Omega \).

Unlike the Archimedean spiral antenna, the sinuous antenna has relatively high variation of the input impedance, even with the conventional type. This is not only due to the influence of the dielectric substrate but also due to the non-uniform arm width of the sinuous antenna. As shown in Fig. 2, the sinuous antenna’s input impedance can be equivalent to a coplanar strip transmission line, similar to the spiral antenna [32], and the transmission line capacitance...
C\textsubscript{t} occurs between adjacent arms on the same plane. Thus, the non-uniform width of the sinuous antenna fluctuates the transmission line capacitance \( C\textsubscript{t} \) more rapidly as the expansion rate increases, resulting in increase of impedance fluctuations. In addition, the parallel structure causes the coupling capacitance \( C\textsubscript{c} \) between radiators in different planes. This coupling effect is frequency-sensitive and increases the impedance ripple in higher frequency bands, as illustrated in Fig. 3. Therefore, the problem that appears in the parallel radiator structure prevents access to the broadband match while also degrading the antenna performance.

To suppress impedance fluctuation caused by the coupling effect, the parallel radiator structure can be thought of as a coupled line with two strip transmission lines close together. Increasing the transmission line capacitance to be relatively larger than the coupling capacitance results in a similar even-odd mode impedance and allows the coupling coefficient to be reduced in the coupled line theory [12].

**B. THE PARALLEL RADIATOR STRUCTURE WITH THE PARTIAL METAL WIDTH ADJUSTMENT STRUCTURE**

To increase the transmission line capacitance \( C\textsubscript{t} \), the partial metal width adjustment method that increases the arm width is used. The design parameter controls the arm width \( \delta\textsubscript{in} \) within the radius of the adjusted region \( R\textsubscript{a} \) in consideration of the active region of the high-frequency band, as shown in Fig. 4. The adjusted region’s radius \( R\textsubscript{a} \) varies with the number of cells in the sinuous curve, and the design parameter \( \delta\textsubscript{in} \) varies with the inner rotation angle.

Fig. 5 shows a comparison of input impedance based on the design parameters \( \delta\textsubscript{in} \) and \( R\textsubscript{a} \). The metal width adjustment method is used only slightly from the first cell to minimize metallic loss [26]–[28]. When the inner rotation angle of the first cell is set to 27.5°, the average input resistance in the operation band decreases. When the adjustment is applied to the second cell, the input resistance becomes very low as it goes toward the high-frequency band. This adjustment results in a very large difference in input impedance in the entire frequency band. In addition, increasing \( \delta\textsubscript{in} \) too much results in a very high transmission line capacitance, resulting in very high input reactance for the high frequency band. Therefore, \( \delta\textsubscript{in} = 27.5° \) and \( R\textsubscript{a} = 4.7 \) mm were chosen. The frequency response to the reflection coefficient of the modified parallel antenna according to reference impedance

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**FIGURE 5.** Simulated input impedance of the four-arm sinuous antennas with the parallel radiator and the partial metal width adjustment structure for design parameters \( \delta\textsubscript{in} \) and \( R\textsubscript{a} \). Sinuous parameters: \( \tau = 1.238 \).

**FIGURE 6.** Frequency response of the reflection coefficient for the four-arm sinuous antennas with the reference impedance \( Z\textsubscript{ref} = 100 \Omega \) and 200Ω. Sinuous parameters: \( \tau = 1.238 \).

**FIGURE 7.** The four-arm sinuous antenna with the parallel radiator and the partial metal width adjustment structure: (a) designed antenna, (b) designed antenna with sharp end clipped, and (c) designed antenna with sharp end clipped and an annular ring.
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Figure 8. Frequency response of the reflection coefficient for modified four-arm sinuous antennas with the reference impedance $Z_{ref} = 100\Omega$.

Table 1. Design parameters of sinuous antenna.

| Parameter | Description | Value |
|-----------|-------------|-------|
| $P$       | The number of cells | 16    |
| $r$       | Expansion rate | 1.238 |
| $\alpha$  | Angular width | 45°   |
| $\delta$  | Rotation angle | 22.5° |
| $\delta_{in}$ | Inner rotation angle | 27.5° |
| $N$       | The number of arms | 4     |
| $D$       | Diameter of antenna | 290.46 mm |
| $R_0$     | Minimum radius | 3.8 mm |
| $R_n$     | Metal width adjustment radius | 4.7 mm |

Figure 9. Geometry of sinuous antennas for performance comparison.

(a) Exponentially tapered balun with two-input ports. (b) Conventional antenna with balun 1. (c) Proposed antenna with balun 2.

Table 2. Design parameters of Baluns.

| Parameter | Balun 1 | Balun 2 |
|-----------|---------|---------|
| $L_1$     | 200 mm  | 100 mm  |
| $L_2$     | 10 mm   | 10 mm   |
| $L_3$     | 40 mm   | 40 mm   |
| $S_1$     | 2 mm    | 2 mm    |
| $S_2$     | 6.2 mm  | 6.2 mm  |
| $w_1$     | 0.3 mm  | 1.3 mm  |
| $w_2$     | 42 mm   | 42 mm   |
| $w_3$     | 3.1 mm  | 3.1 mm  |
| $w_4$     | 23.8 mm | 23.8 mm |
| $w_5$     | 60 mm   | 60 mm   |
| $\varepsilon_r$ | 4.3 (FR4-0600) | 4.3 (FR4-0600) |
| Impedance transition | 50 to 200 Ω | 50 to 100 Ω |

The simulation with wideband baluns is performed to verify the improved performance of the proposed sinuous antenna. The proposed sinuous antenna aims to generate dual-linear polarization (mode-1). To this end, two opposite arms are attached as a set to one port in the balun, and the entire feeding structure consists of two sets intersecting. Thus, the exponentially tapered balun with two-input ports was designed as shown in Fig. 9(a). In addition, two types of baluns for different impedance transformations are designed to compare antenna performance (balun 1, 2). Each balun has a different overall length and is designed according to the impedance transition in that order (50 to 200 Ω and 50 to 100 Ω). The design parameters are presented in Table 2. Fig. 9 (b) and (c) show four-arm sinuous

is shown in Fig. 6, together with the conventional and the parallel radiator structure antenna. In consideration of the applicability of the commercial 100 Ω coaxial cable, the reference impedance of the feed port is set to 100 Ω. The conventional antenna shows reflection coefficients of $-10$ dB or less at 0.43 GHz with the reference impedance $Z_{ref}$ of 200 Ω, but for $Z_{ref}$ of 100 Ω, matching characteristic deteriorates. The parallel radiator structure antenna exhibits poor matching characteristics in high frequency band, while the modified parallel antenna shows reflection coefficients of $-10$ dB or less within 0.45-6 GHz.
antennas to which the balun is connected. The balun 1 is connected to the conventional sinuous antenna, while the balun 2 is connected to the proposed antenna in section III. B. The broadside realized gain and radiation efficiency of the proposed antenna are better than the conventional antenna in the entire band, as shown in Fig. 10. Both performances show improved frequency response with a difference of up to 5 dBi and 20%, respectively, toward the high frequency band. In addition, the unintended resonance in the conventional antenna was observed at 0.7 GHz, but the proposed antenna does not. In the frequency response to antenna performance, the fluctuation is the effect of coupling that occurs when the balun is connected to the center of the antenna.

**IV. MEASUREMENT RESULTS OF THE FABRICATED ANTENNA**

Fig. 11 shows photographs of the fabricated antenna. In addition, for antenna measurement, a 0.15 $\lambda_L$ long exponentially tapered balun with an impedance transition from 50 to 100 $\Omega$ is used. The resulting reflection coefficient is shown in Fig. 12. The ratio bandwidth for a reflection coefficient $<-10$ dB criterion is approximately 13.3 (across a design frequency range of 0.45 GHz to 6 GHz). Fig. 13 shows simulated and measured co- and cross-polarized radiation patterns at 0.5, 1.5, 3, and 6 GHz. In addition, the peak gain in the broadside direction is measured at 0.3-6 GHz (30 points). The measured results achieve a gain ratio bandwidth (>2.5dBi) of 12:1 and a cross-polarization isolation of less than $-13$dB in the frequency range above 0.6 GHz, as shown in Fig. 14. The radiation efficiency was measured to be about 50% or more in the frequency band above 0.6 GHz, and it was very
similar to the simulation results. The sharp variation due to unintended resonance mode in the operating band were not observed.

Table 3 summarizes the antenna performances of similar works. Compared to the planar four-arm sinuous antennas [15]–[19], the proposed antenna has the widest impedance and gain bandwidth with a similar or smaller diameter. These antennas have a high input impedance and thus have a very narrow gain bandwidth compared to the proposed antenna. In the case of conical sinuous antenna [20], it has high gain and wide bandwidth, but it is bulky and difficult to apply the cavity-backed structure for ESM systems. Similarly, the four-arm sinuous antennas on a hemispherical diametric lens [21], [22] have relatively high gain, but has a narrow bandwidth compared to the proposed antenna. The planar four-arm sinuous antenna with reduced input impedance by applying the M.S. ratio adjustment structure [26] has the same input impedance as the proposed antenna, but has a very narrow bandwidth. According to the comparison results, the proposed antenna covers a very wide frequency band, so it is very advantageous in improving the performance of the ESM system compared to other antennas. Compared to the spiral antennas to which other input impedance reduction structures are applied, the proposed four-arm sinuous antenna has the same input impedance with a broader impedance and gain bandwidth.

V. CONCLUSION

In this paper, a four-arm sinuous antenna with low input impedance is proposed for wide gain bandwidth. In order to reduce the input impedance, the modified parallel radiator structure is applied and analyzed as a coupled line. Through the analysis, the partial metal width adjustment structure is newly attempted to reduce the coupling effect and improve the impedance bandwidth. In addition, the proposed method minimizes metallic losses by adjusting the conductor width of the antenna very finely. As a result, in the 0.45-6 GHz bandwidth range, the proposed antenna has a wide gain bandwidth (>2.5 dBi) of 12:1 or greater with the reference input impedance of 100 Ω.

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