Balanced gain for a square metaloop antenna

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Abstract. A square loop antenna implemented using a metamaterial line, referred to as a metaloop, is discussed. The metaloop radiates a counter circularly polarized (CP) broadside beam when the loop circumference equals one guided wavelength. The frequency response of the gain shows two different maximum values: gain $G_{L \text{max}}$ for a left-handed CP wave at frequency $f_{GL \text{max}}$ and gain $G_{R \text{max}}$ for a right-handed CP wave at frequency $f_{GR \text{max}}$, where $G_{L \text{max}}$ is smaller than $G_{R \text{max}}$. In order to increase $G_{L \text{max}}$ while not affecting the original $G_{R \text{max}}$ as much as possible (i.e. balance the gain), a parasitic natural conducting loop (paraloop), whose circumference is one free-space wavelength at $f_{GL \text{max}}$, is placed at height $H_{\text{para}}$ above the metaloop. It is found that the difference in the gains can be reduced by choosing an appropriate $H_{\text{para}}$. The radiation pattern at $f_{GL \text{max}}$ is narrowed by the paraloop, while the VSWR is not remarkably affected.

Keywords: Square metaloop antenna / circularly polarized radiation / gain balance

1 Introduction

A loop antenna radiates a linearly polarized (LP) wave [1]. When the circumference of the loop is one wavelength, the maximum LP radiation appears in the broadside direction. This broadside LP radiation can be changed to circularly polarized (CP) radiation by adding perturbation elements [2] to the loop, as shown in Figure 1. The rotational sense of the CP radiation, either a right-handed (RH) sense or a left-handed (LH) sense, is uniquely determined by the location of the perturbation elements relative to feed point $F$: the loop in Figure 1 radiates an RHCP wave. In other words, the loop antenna radiates a CP wave with a single rotational sense.

The single rotational sense also holds true for a grid loop array in [3]. Although perturbation elements are not added to the loops, a traveling current is generated along the arrayed loops and radiates a CP wave. The rotational sense is determined by the winding sense of the loops.

It is often required that an antenna has dual-band counter CP radiation to keep sufficient separation of signals, i.e., the LHCP and RHCP radiation in two different frequency bands, in order to avoid interfering with each other. When a pair of dual-band counter CP antennas is adopted as a transmitting antenna and a receiving antenna, it is desirable for these antennas to have the same gain. If the LHCP and RHCP gains are different, the receiving antenna captures LHCP and RHCP waves with different receiving power levels. Therefore, a post-process circuit connected to the receiving antenna needs additional amplification circuits to enhance the weak power. This complicates the post-process circuit designs. To avoid such an issue, the same gain (balanced gain) is desired.

Recent study has shown that a metamaterial (MTM) loop antenna, referred to as a metaloop, is an antenna that meets the requirement of dual-band counter CP radiation [4], where the loop is realized using the concept of a composite RH and LH transmission line [5–7], referred to as a metaline. The maximum gain for the metaloop within the low frequency band (LoFB) in [4] is smaller than that within the high frequency band (HiFB). This is attributed to the antenna size relative to the free-space wavelength (electrical antenna size); the free-space wavelength within the LoFB is larger than that within the HiFB, and hence the electrical antenna size within the LoFB is smaller than that within the HiFB.

Thus, a question arises as to how the difference in the gains can be reduced. This paper presents a technique for reducing the band gain difference for a dual-band counter CP metaloop antenna, where a parasitic loop (paraloop) is placed above the metaloop. Note that the metaloop antenna in this paper is analyzed using a full wave analysis tool, HFSS [8], and experimental work is performed in an anechoic chamber.

So far, other authors have designed MTM-loaded and MTM-inspired loop antennas. For example, the MTM-loaded loop in reference [9] and MTM-inspired loop [10] are designed as an LP antenna. An antenna using complementary capacitively loaded loop in reference [11]
and loop antennas in [12–20] are also designed as an LP antenna. The design requirements for these antennas differ from ours, i.e., dual-band counter CP radiation with balanced gain, while meeting two additional requirements: (1) broadside radiation and (2) simple feed system without balun circuits. To our best knowledge, there have not been such MTM-related loop antennas.

2 Metaloop structure

The metaloop antenna to be considered here is shown in Figure 2. The antenna arm is printed on a square dielectric substrate of side length $S_{\text{sub}}$, relative permittivity $\varepsilon_r$ and thickness $B$. The substrate is backed by a square ground plane (GP) of side length $S_{\text{GP}}$ (= $S_{\text{sub}}$). The antenna arm, symmetric with respect to the $x$-$z$ plane, is composed of five straight metalines, whose lengths are $L_1 = L_5$ and $L_2 = L_3 = L_4$. Each metaline is made of numerous conducting subwavelength segments of width $w$ and length $p_0$, where the gap between neighboring segments is denoted as $\Delta g$. Repeating arm sections, each having length $2(\Delta g + p_0) \equiv p$, are designated as the arm unit cells. The central segment of the cell is short-circuited to the GP through a chip inductor, $L_Y$. Neighboring segments are connected through a chip capacitor, $2C_Z$. Point $F$ is the feed point and point $T$ is the terminal point connected to the GP through a resistive load, $R_B$, to suppress reflected currents from point $T$ to point $F$.

Table 1. Parameters.

| Symbol | Value    | Symbol | Value    |
|--------|----------|--------|----------|
| $w$    | 6.6 mm   | $p$    | 10 mm    |
| $\varepsilon_r$ | 2.6    | $p_0$  | 4.5 mm   |
| $B$    | 3.2 mm   | $\Delta g$ | 0.5 mm  |
| $L_1 = L_5$ | 20 mm  | $L_Y$  | 1.8 nH   |
| $L_2 = L_3 = L_4$ | 50 mm | $2C_Z$ | 1.2 pF   |
| $S_{\text{sub}} = S_{\text{GP}}$ | 110 mm | $R_B$ | 60 $\Omega$ |

Note that $L_Y$ and $2C_Z$ are determined as follows. First, using HFSS [8], we obtain the frequency response of the scattering parameters (S-parameters) for the unit cell including $L_Y$ and $2C_Z$. Second, based on the obtained S-parameters, we draw the dispersion curve (phase constant $\beta = \pm 2\pi/\lambda_g$ vs. frequency $f$ [4], where $\lambda_g$ is the guided wavelength). These two steps are repeated until the dispersion curve is balanced (smoothly connected at a preselected transition frequency $f_T$), changing $L_Y$ and $2C_Z$. The values for $L_Y$ and $2C_Z$ when the dispersion curve is balanced are what we need.

The parameters used for the following discussion are summarized in Table 1; these parameters create a balanced are what we need.

3 Frequency response of the gain

By resistive load $R_B$, a traveling wave current flows along the loop from point $F$ to point $T$, with frequency-dependent...
guided wavelength $\lambda_g$. In other words, the metaline acts as a leaky wave antenna. Generally, the radiation efficiency of the leaky wave antenna is not high due to absorption of the power input to the antenna by $R_B$. If $R_B$ is removed, the input impedance (and hence Voltage Standing Wave Ratio (VSWR)) becomes unstable and CP radiation is not obtained by a reflected current from point $T$.

The current at frequency $f < f_T$ has a progressive phase distribution from point $P$ to point $T$ due to a negative phase constant ($\beta = -2\pi/\lambda_g < 0$). Hence, the current behaves as if it travels from point $T$ to point $F$ (clockwise). This results in LHCP radiation in the broadside direction at a frequency where the loop length is one guided wavelength ($1\lambda_g$). Conversely, the current at $f > f_T$ has a regressive phase distribution from point $P$ to point $T$ due to a positive phase constant ($\beta = 2\pi/\lambda_g > 0$). Hence, the current flows from point $P$ to point $T$ (counter clockwise), resulting in RHCP radiation in the broadside direction at a frequency satisfying a $1\lambda_g$-loop length. Thus, dual-band counter CP radiation in the broadside direction is obtained.

From Figure 3, it is expected that CP broadside radiation will be obtained around frequencies $2.60$ GHz $\equiv f_N$ and $3.50$ GHz $\equiv f_H$, because the loop length normalized to guided wavelength $\lambda_g$ is one at $f_N$ and $f_H$: $(L_1 + L_2 + \ldots + L_5)/\lambda_g = 1$. For the remainder of the paper, $f_N$ and $f_H$ are referred to as the Nion frequency and Hion frequency, respectively. Figure 4 shows the gain as a function of frequency, where $G_L$ denotes the gain for an LHCP wave, called the LHCP gain, and $G_R$ denotes the gain for an RHCP wave, called the RHCP gain. It is found that $G_L$ is dominant at frequencies below $f_T = 3$ GHz, because the current flows with a negative phase constant ($\beta < 0$). Conversely, $G_R$ is dominant at frequencies above transition frequency $f_T$ due to $\beta > 0$. Maximum gain $G_L$ appears at a frequency near Nion frequency $f_N$ and maximum gain $G_R$ appears at a frequency near Hion frequency $f_H$. These frequencies are denoted as $f_{GL_{max}}$ and $f_{GR_{max}}$, respectively. The difference in the maximum gains, $G_{L_{max}}$ at $2.58$ GHz $\equiv f_{GL_{max}}$ (close to $f_N$) and $G_{R_{max}}$ at $3.51$ GHz $\equiv f_{GR_{max}}$ (close to $f_H$), is approximately $5.5$ dB.

### 4 Reduction in the gain difference

In this section, the difference in maximum gains $G_{L_{max}}$ and $G_{R_{max}}$ is reduced as much as possible. For this, the antenna system shown in Figure 5 is considered, where a parasitic natural conducting strip loop of width $w_{para}$ and peripheral length $L_{para}$ is located at height $H_{para}$ above the metaloop. The parasitic loop is designed such that only the smaller gain, $G_{L_{max}}$ at $f_{GL_{max}}$, is increased, without reducing the larger gain, $G_{R_{max}}$ at $f_{GR_{max}}$.

The CP radiation from the metaloop excites the parasitic loop and generates a rotating/traveling current along the loop.

The parasitic loop acts as a director for the driven metaloop, like Yagi–Uda antenna. If the radiation from the parasitic loop at $f_{GL_{max}}$ is constructively superimposed onto the radiation from the metaloop in the broadside direction, gain $G_{L_{max}}$ increases. For this to occur, parasitic loop length $L_{para}$ is chosen to be one free-space wavelength ($1\lambda_0$) at $f_{GL_{max}}$: $L_{para} = 116.7$ mm. The remaining task is to optimize loop height $H_{para}$.
Figure 6 shows $G_L$ at $f = 2.58$ GHz and $G_R$ at 3.51 GHz as a function of parasitic loop (paraloop) height $H_{para}$, where $w_{para} = 2$ mm and $L_{para} = 116.7$ mm ($\approx \lambda_0$ at 2.58 GHz) are used.

Based on the result shown in Figure 6, the loop height is determined to be $H_{para} = 11$ mm, corresponding to 0.09 wavelength at $f_{GLmax} = 2.58$ GHz. Figure 7 shows the frequency response of the gain. The bandwidth (BW) for a 3-dB gain drop criterion for $G_L$, denoted as $G_L$-BW, is 13.5% and the BW for a 3-dB gain drop criterion for $G_R$, denoted as $G_R$-BW, is 14.6%. For confirmation of the analysis/simulation results, measured/experimental results are also presented (see fabricated antenna in Fig. 5b).

5 Radiation pattern and VSWR

Figure 8a shows the analysis/simulation results of the radiation patterns at the maximum-gain low frequency $f_{GLmax} = 2.58$ GHz (radiation efficiency of $\eta \approx 69\%$) and high frequency $f_{GRmax} = 3.51$ GHz ($\eta \approx 60\%$), together with experimental results, where $E_L$ and $E_R$ denote the LHCP wave component and the RHCP wave component, respectively. For comparison, the analysis/simulation results in the absence of a parasitic loop are also shown in Figure 8b. It is clearly seen that the radiation pattern at low frequency $f_{GLmax}$ is narrowed by virtue of the presence of the parasitic loop, while the radiation pattern at high frequency $f_{GRmax}$ is less affected by the parasitic loop, as desired. Figure 9 shows the frequency response of the VSWR, which remains almost unchanged in the presence of the parasitic loop. Discrepancy between the analysis and experiment results is attributed to the fact that soldering the capacitive chips to the subwavelength segments is not uniform due to handwork.

Finally, the following comments are added. The metaloop antenna in this paper could be operated as a dual-band CP element with the same rotational sense (dual-band mono-CP radiation), although this is not our objective. Such dual-band mono-CP radiation is performed by introducing switching circuits to points $F$ and $T$ so that each point can be chosen to be either a feed point or a terminal point. (1) For dual-band mono-LHCP radiation, set points $F$ and $T$ to be the feed ($fd$) and terminal ($trmnl$) points, respectively, at low frequency $f_{low} < f_T$, which is
expressed as $[F : T]_{\text{LHCP}}^{\text{LHCP}} = [\text{fd} : \text{trmnl}]$. And at a high frequency $f_{\text{high}} > f_T$, change the role of points $F$ and $T$ by using switching circuits: $[F : T]_{\text{LHCP}}^{\text{LHCP}} = [\text{trmnl} : \text{fd}]$. (2) For dual-band mono-RHCP radiation, set $[F : T]_{\text{RHCP}}^{\text{RHCP}} = [\text{trmnl} : \text{fd}]$ at $f_{\text{low}}$ and $[F : T]_{\text{RHCP}}^{\text{RHCP}} = [\text{fd} : \text{trmnl}]$ at $f_{\text{high}}$ by using switch-circuits.

6 Conclusions

The dual-band counter CP wave radiated by a square metaloop antenna has a maximum gain of $G_{L_{\text{max}}}$ at frequency $f_{G_{L_{\text{max}}}}$ that is different from maximum gain $G_{R_{\text{max}}}$ at frequency $f_{G_{R_{\text{max}}}}$, where $G_{L_{\text{max}}} < G_{R_{\text{max}}}$. To reduce the difference in these gains, a square parasitic natural conducting loop of one free-space wavelength at $f_{G_{L_{\text{max}}}}$ is placed at height $H_{\text{paral}}$ above the metaloop. It is found that there is an antenna height where the parasitic loop increases gain $G_{L}$ while not remarkably affecting gain $G_{R}$. Thus, the gain difference can be reduced, i.e., $G_{L_{\text{max}}} \approx G_{R_{\text{max}}}$, with the VSWR remaining almost unchanged in the presence of the parasitic loop.

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