Design for Triple Band Patch Array Antenna with High Detection Ability

In-Hwan Kim · Kyeong-Sik Min*

Abstract

This paper proposes a theoretical analysis of hidden device detection and a design of multiband circular polarization patch array antenna for non-linear junction detector system application. A good axial ratio of circular polarization patch antenna is realized by a new approach that employs inclined slots, two rectangular grooves and a truncated ground for the conventional antenna. A good axial ratio of the 1.5 dB lower is measured by having an asymmetric gap distance between the ground planes of the coplanar waveguide feeding structure. The common ground plane of the linear array has an optimum trapezoidal slot array to reduce the mutual coupling without increasing the distance between the radiators. The higher gain of about 1 dBi is realized by using the novel common ground structure. The measured return loss, gain, and axial ratio of the proposed single radiator, as well as the proposed array antennas, showed a good agreement with the simulated results.

Key Words: Circular Polarization, Multiband Antenna, Non-linear Junction Detector, Patch Array Antenna, Trapezoidal Slot Array.

I. INTRODUCTION

Technological developments in the super minimal electronic device industry have led to miniaturization of expensive devices, such as semiconductors and memory chips. These devices are illegally used as hidden devices containing industrial information including top secret data. The methods used to hide these illegal devices are often skillful and ingenious, so that detection is becoming increasingly difficult. A wireless non-linear junction detector (NLJD) with high performance has been studied as one method for detection of a hidden device [1]. This has introduced a need for a high gain antenna that can detect hidden devices, had been raised. High performance NLJD systems as well as broadband antennas with high gain are now being studied in many countries, including Korea [2]. For example, a hidden device composed of a semiconductor is easily detected by the amplitude signal level received by a NLJD, because the 2nd

harmonic amplitude of a hidden device that is a pure semiconductor is higher than the amplitude level of the 3rd harmonic frequency. On the other hand, a false junction material composed of a semiconductor and a metal has a 3rd harmonic amplitude level that is higher than the 2nd harmonic amplitude. These harmonic amplitude differences allow easy detection of a hidden device. This phenomenon is theoretically derived by the analysis of the semiconductor current-voltage ($I-V$) equation using the Fourier transform. The NLJD antenna has to satisfy the transmitting frequency (Tx) band and the receiving frequency (Rx) band simultaneously, so a wideband antenna is required for the NLJD [3].

The circular polarization (CP) antenna has been mainly used for the NLJD system applications because of its high capability for recognizing and detecting hidden devices [3]. The CP pattern of a proposed circular disc patch antenna has been applied and designed by a truncated corner structure of a ground plane [4, 5] with 45° inclined slots [5], two rec-

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tangular grooves on the circular disc patch [6] and an asymmetric gap at the feeding structure. Sections II and III present a theoretical analysis of the frequency response characteristics for the NLJD system and a novel design for wideband circular patch antenna, respectively. The linear array design of 2×1 is considered to increase the gain as described in Section IV. In Section V, a proposed antenna for single element and two element arrays was fabricated and measured. The measured and simulated results are discussed and compared.

II. THEORETICAL ANALYSIS OF HIDDEN DEVICE DETECTION

The harmonic response difference between the semiconductor and the false junction results from a non-linear I–V equation. The I–V equation of semiconductor is as follows [7].

$$I = I_s \left[e^{\frac{qV}{kT}} - 1 \right] \quad (1)$$

q : electron charge
 k : Boltzman's constant
 T : temperature
 I_s : saturation current
 I : current
 V : voltage

The I–V of the semiconductor and the false junction is calculated by Eq. (1). Fig. 1(a) and (b) show the I–V characteristics

(a)

(b)

Fig. 1. The current-voltage (I–V) characteristics of semiconductor (a) and false junction (b).

characteristics of the semiconductor and the false junction, respectively. The I–V characteristics of semiconductor shown in Fig. 1(a) are similar to an exponential graph. Those of the false junction, shown in Fig. 1(b), are similar to a tangential graph. For example, the I–V equation of the false junction is derived and analyzed by current with respect to voltage response of the forward-reverse bias of the two zener diodes. The false junction has the symmetric voltage characteristics as shown in Fig. 1(b). A non-linear device has special characteristics having harmonic components for an input of the frequency. These harmonic characteristics give the semiconductor and the false junction different harmonic amplitude levels. A Fourier transform is employed for transformation of the frequency domain with respect to the time domain. The frequency domain for Fig. 1 is expressed using the Fourier transform as follow [8]:

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t} dt, \quad \omega = 2\pi f \quad (2)$$

In Eq. (1), when $V = v_0 \cos(\omega t)$, it is possible to generate time domain function. Eq. (1) is the expressed $I(t)$ function substitution of the I function. The function $x(t)$ in Eq. (2) is replaced with the function $I(t)$. The amplitude of the frequency domain is calculated by Eq. (2) of the Fourier transformation. Fig. 2 shows the amplitude of the semicon-

(a)

(b)

Fig. 2. The amplitude of the semiconductor (a) and false junction (b) in the frequency domain (sampling number = 1,000).

ductor and the false junction calculated and analyzed in the frequency domain. The calculated relative amplitude of the semiconductor in the frequency domain is 1 at 2.44 GHz, 0.5 at 4.88 GHz, and 0.2 at 7.32 GHz, as shown in Fig. 2(a). A comparison between the 2nd and the 3rd harmonic amplitude levels confirmed that the calculated 2nd harmonic amplitude level of the semiconductor is higher than the 3rd harmonic amplitude.

The relative amplitude of the false junction in the frequency domain is 1 at 2.44 GHz, 0.2 at 4.88 GHz and 0.39 at 7.32 GHz, as shown in Fig. 2(b). The false junction calculation shows that the 3rd harmonic amplitude level is higher than the 2nd harmonic amplitude, as shown in Fig. 2(b). Therefore, the hidden device is simply detected by the difference in harmonic response.

III. ANTENNA DESIGN

Fig. 3 shows the structure of the wideband patch antenna to radiate the CP. A coplanar waveguide (CPW) fed circular disc monopole with linear polarization for ultra-wideband (UWB) application has been proposed [9]. The antenna in [9] was composed of a radiating patch and a CPW feeder on a single layer-metallic structure. We have selected the antenna structure from [9] to realize the wide bandwidth and the CP radiation because that antenna had the wide bandwidth characteristics for UWB application and a circular disc patch with an easily modified structure for the CP radiation. In the present study, the thickness of the substrate and relative permittivity for the antenna design were 1.6 mm and 4.4 + $j0.02$, respectively. The CPW feeding structure, with an asymmetric gap to realize a wide bandwidth and a good axial ratio, was also modified in this design. The 45° inclined slots on disc patch were included for realization of the CP patterns. Fig. 3 shows the structure of the 45° inclined slot on disc patch, which is able to control the current direction, and the structure of the two rectangular grooves that radiate the CP. Different groove sizes of 9 mm × 4.5 mm and 7 mm × 6 mm were used for the CP and created a smooth flow of

Fig. 3. Structure of a modified antenna with circular polarization.

Table 1. The geometric parameters of the antenna (Fig. 3)

Parameter	Dimension (mm)	Description
W	84	Width of the antenna
L	81	Length of the antenna
W_{G1}	9	Width of the groove
W_{G2}	7	Width of the groove
L_{G1}	4.5	Length of the groove
L_{G2}	6	Length of the groove
W_S	2	Width of the slot
L_S	40	Length of the slot
W_{Gap1}	0.25	Width of the gap
W_{Gap2}	0.33	Width of the CPW gap
W_{Gap3}	0.33	Width of the CPW gap
W_W	4	Width of the signal line
L_T	2.282	Length of the truncation

CPW = coplanar waveguide.

electric current on the disc patch antenna. Truncating the corner of the ground plane by 2.282 mm created a strong electric current flow that generated the CP. One theoretical approach to improve the axial ratio of the CP antenna was to cut a corner of square patch [4, 5]. The CP was radiated by the degree and length of the inclined slot, and by the position and size of the groove. This design has the electric current flow in a counterclockwise direction.

Fig. 4 shows the simulation results for the reference antenna [9] and the modified antenna shown in Fig. 3. The reference antenna with the linear polarization had been studied for the UWB application with the wide bandwidth. The CP design was the structure that included a truncated corner of the ground plane, a 45° inclined slot, two rectangular grooves on the circular disc patch and the CPW feeding structure with an asymmetric gap ($W_{Gap2} \neq W_{Gap3}$). While the reference antenna structure with wide bandwidth [9] was modified for the CP as shown in Fig. 3, it still remained -10 dB (voltage standing wave ratio [VSWR] 2:1) lower, as shown in Fig. 4(a), even though the various structures of the CP radiation were also changed. On the other hand, the axial ratio strongly depends on the antenna structure as shown in Fig. 4(b). The axial ratio was obviously improved by the CP antenna structure shown in Fig. 3 and the simulated results were still, on average 4.5 dB, as shown in Fig. 4(b), even though the CP was not yet perfectly satisfied.

A good axial ratio was realized by varying the gap of W_{Gap3} between the grounds. Because the surface electric current direction on a circular disc patch can be controlled by an asymmetric gap ($W_{Gap2} \neq W_{Gap3}$), a complete axial ratio can be realized by the various gap distances. Fig. 5 shows the simulated return loss and axial ratio results as functions of W_{Gap3}

Fig. 4. Comparison of the simulation results between the reference antenna [9] and the modified antenna shown in Fig. 3. (a) The return loss and (b) axial ratio.

Fig. 5. Simulated results as functions of W_{Gap3} variations. Simulated (a) return loss and (b) axial ratio.

variations. Consideration on an asymmetric gap design improves the return losses at the bands of interest, and depends on the coupling of current strength with the wide bandwidth realized by the CPW feeding [10].

Fig. 6 shows the operating principle of the axial ratio change realized by the various gap distances. It supports the validity of the simulation results analyzed in Fig. 5.

Fig. 6(a) and (b) show the electric currents distributions for a symmetric gap and an asymmetric gap, respectively, based on the antenna structure of Fig. 3 at transmitting band (2.44 GHz). In the case of the symmetric gap shown in Fig.

Fig. 6. The electric current distributions with respect to the antenna structure in Fig. 3 at transmitting band (2.44 GHz). (a) Symmetric gap ($W_{Gap2} = W_{Gap3} = 0.33$ mm), (b) asymmetric gap ($W_{Gap2} = 0.33$ mm, $W_{Gap3} = 2.5$ mm).

Fig. 7. Proposed antenna structure with modified slots.

6(a), when the phase equals to 60° and 260° in Fig. 6(a), the surface currents on radiating patch and ground 2 plane flow in opposite directions to each other. This disturbs the radiation of the CP. On the other hand, when the phase is equal to 0° and 210° , as marked by a circle in Fig. 6(b), the flow of the surface currents on ground 2 plane with the asymmetric gap changes to compare with the current direction in Fig. 6(a). This current phase difference appears to depend on the asymmetric gap distance and influences the improvement in axial ratio. The asymmetric gap from Fig. 5 is considered in the remainder of this paper.

Even though the axial ratio was improved by asymmetric gap control, as shown in Fig. 6(b), it is still not 3 dB lower at the transmitting band. In order to solve the problem of the axial ratio improvement at the transmitting band, the modified 45° inclined slots were considered in the simulation design, as shown in Fig. 7. Table 2 indicates the simulated parameters of the modified slots in Fig. 7. The W_{Gap2} and W_{Gap3} are fixed at 0.33 mm and 2.5 mm, respectively. Fig. 8 shows one example of parameter studies for the simulated results of a change in length (L_{S1}). In order to improve the axial ratio, L_{S1} is chosen among parameters, because L_{S1} has the most influence of parameters for center frequency of each band. The simulated return loss shown in Fig. 8(a) was essentially unchanged with respect to slot length variation. On the other hand, the axial ratio as shown in Fig. 8(b) depended on the slot length variation. The selected optimum length of L_{S1} is 29 mm hereafter, as shown in Table 2.

However, the good axial ratios are still shifted from the center frequency of each band. In order to solve this pro-

Table 2. The simulated modification slot parameters in Fig. 7

Parameter	Dimension (mm)	Description
L_{S1}	29	Length of the slot
L_{S2}	40	Length of the slot
L_{S3}	13	Length of the slot
W_{S1}	8	Inter slot gap
W_{S2}	6	Inter slot gap

Fig. 8. Simulated results as functions of variation of L_{S1} . Simulated (a) return loss and (b) axial ratio.

Fig. 9. The simulation results comparison of Fig. 3 with asymmetric gap and an inclined slot, antenna structure in Fig. 7, and a proposed antenna with the tapering sharp slot edge shape. (a) Return loss and (b) axial ratio.

blem, the edge configuration of the rectangular slots shown in Fig. 7 changes the tapering sharp slot edge shape.

The effect of varying the slot edge shape on the return loss and the axial ratio was studied by conducting a simulation of tapering sharp slot edge shape, as shown in Fig. 9. The simulated return loss shown in Fig. 9(a) was essentially unchanged by variation in the modified slots and the sharp slot edge shape. On the other hand, the axial ratio shown in Fig. 9(b) showed a slight dependence on the shape of the slot edge. A reasonable axial ratio for the proposed antenna, expressed blue line with triangle symbols, was obtained at each center frequency of the triple bands. It was conformed that the slot edge shape can be control the frequency shift.

IV. ARRAY DESIGN

The performance of the proposed antenna was investigated in linear array environments. A linear array composed of two elements was considered, in order to assess the behavior of the individual elements in the array environment. A common ground for the linear array was also proposed to reduce the array dimension size and to increase the antenna gain. Many slots lie between the common ground as shown in Fig. 10. They blocked the field directly coupled from one element to its neighbors [11]. This novel technique allows reduction in the mutual coupling without increasing the distance between the elements.

The dimensions of the array antennas are shown in Table 3. The mutual coupling can be controlled by the slot num-

Table 3. The geometric parameters of the linear array antennas shown in Fig. 10

Parameter	Dimension (mm)	Description
W	168	Width of the antenna
L	81	Length of the antenna
D_s	84	Distance of single radiator
L_{Slot}	2	Length of the slot
G_{S1}	2	Inter slot gap
G_{S2}	1	Inter slot gap
W_{Slot}	1	Width of the slot
W_{Gap4}	2.33	Width of the CPW gap
W_{Gap5}	2.33	Width of the CPW gap

CPW = coplanar waveguide.

ber, slot shape, slot size and slot array structure. Even though the common ground plane with trapezoidal slot array looks like a connection, it actually operates as a separate single element by slots located on the common ground plane [11]. Therefore, the slot array design on the common ground plane is important.

Fig. 10. Structure of the linear array with common ground.

Fig. 11. Common ground plane structure for the various slot shapes.

Fig. 12. Comparison between the simulated results of single radiator in Fig. 7 and array antennas with the common ground plane of four types. Simulated (a) return loss and (b) axial ratio.

Fig. 11 shows three configurations with and without slots on the common ground plane, which is placed between two antenna elements.

The effect of the shape, the size and the number of slots on the characteristics of the proposed antenna was investigated by simulating the linear array structure with four types of common ground plane, as shown in Fig. 12.

The simulated return loss shown in Fig. 12(a) was essentially unchanged, which meant that the mutual coupling between two radiators was very weak and independent. However, the axial ratios of 2nd band and 3rd band strongly depended on the shape of the slot, as shown in Fig. 12(b), even though the axial ratio of the transmitting band was slightly changed.

Type 4 in Fig. 11 shows an excellent axial ratio. The good axial ratio for the 2nd band was shifted about 70 MHz. This was due to the gap distance of W_{Gap4} and W_{Gap5} as explained in Figs. 5 and 6. This phenomenon was amplified by adjusting W_{Gap4} and W_{Gap5} , because the gap parameters of W_{Gap4} and W_{Gap5} have the most influence of the axial ratio at 2nd band.

Fig. 13 shows the simulated results as functions of gap distance variation of W_{Gap4} and W_{Gap5} . The simulated return loss shown in Fig. 13(a) was essentially unchanged. In addition,

Fig. 13. Simulated results as functions of variation of W_{Gap4} and W_{Gap5} . Simulated (a) return loss and (b) axial ratio.

Fig. 14. Simulated results with respect to variation of D_s for Type 4 with/without slot of Fig. 11. The simulated (a) return loss, (b) isolation, and (c) axial ratio.

tion, when W_{Gap4} and W_{Gap5} are fixed at 2.33 mm, the return loss and the axial ratio of the linear array antennas show good agreement with those of the single radiator in Fig. 9.

Fig. 14 shows the simulated results as functions of variation of D_s distance between the two radiators shown in Fig. 10. These results indicate simulation values for Type 4 structure with/without slot of Fig. 11. When D_s equals 84 mm, the simulated return loss and the simulated isolation

was better than $D_s = 50$ mm. The simulated isolation level was remarkably maintained -20 dB lower at the all bands of interest, which meant that very weak mutual coupling appears when $D_s = 84$ mm.

Furthermore, the axial ratio strongly depended on the distance of D_s . When $D_s = 84$ mm, the simulated axial ratio was obtained about 2 dB below at the all bands of interest.

V. MEASUREMENT

In order to verify the propriety of two proposed antennas, the novel antennas with CP were fabricated as shown in Fig. 15.

Fig. 16(a) indicates a comparison of the simulated and measured S -parameter. The bands of interest show reasonable agreements with enough bandwidth.

Simulated and measured isolation was also -20 dB lower at the all bands of interest. The axial ratio as shown in Fig. 16(b) was measured and compared. It shows very fine agreement with predicted values.

Figs. 17 and 18 show the simulated and measured gain directivity patterns at the each center frequency of the bands of interest. The measured patterns showed reasonable agreement with the simulated patterns. The simulated gains of array antenna are 3.3, -4.8 , and 1.7 dBi at 2.44, 4.88, and

Fig. 15. Photograph of the fabricated proposed antennas. (a) Single radiator and (b) the linear array antennas.

Fig. 16. Comparison between the simulated and measured results for a single radiator and linear array antennas. (a) The simulated and measured S -parameter, (b) the simulated and measured axial ratio.

7.32 GHz, respectively. The measured and the simulated gain directivity patterns agreed with those of the single radiator.

Fig. 19 shows the gain comparison between the single radiator and array antennas from 2 to 8 GHz, where at $\theta = 0^\circ$ and $\phi = 0^\circ$. The gain of the array antennas was about 1 dBi higher than the gain of a single radiator.

VI. CONCLUSION

This paper presents a theoretical analysis of small hidden device detection and a design for a triple band CP patch array antenna that uses the NLJD system. The axial ratio of a disc radiator was improved by including an asymmetric gap and an inclined slot modification. The axial ratio of the single radiator was also improved by truncating the corner at the ground edge. A good axial ratio that was 1.5 dB lower at the bands of interest was realized by the modified slot length and the asymmetric gap distance obtained from current distribution control on the radiating and ground planes. Improvement in the gain of a single radiator was achieved with linear array antennas with common ground plane. The

Fig. 17. Simulated and measured gain directivity patterns of single radiator (solid line, x-z plane; dotted line, y-z plane).

Fig. 18. Simulated and measured gain directivity patterns of array antennas (solid line, x-z plane; dotted line, y-z plane).

Fig. 19. Simulated and measured gain from 2 to 8 GHz.

common ground plane includes the optimum trapezoidal slot array to reduce mutual coupling without increasing the distance between the radiators. A higher gain is realized by using the novel common ground structure. The measured return loss was -12 dB lower at the bands of interest. The simulated return loss and the axial ratio of the proposed antenna agreed well with the measured results. The measured E-field gain patterns of the x-z plane as well as the y-z plane are also showed very good agreement with the simulated results.

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REFERENCES

- [1] S. J. Holmes and A. B. Stephen, *Non-linear Junction Detector*, US Patent 6897777, to Audiotel International Limited, Washington, DC: Patent & Trademark Office, 2003.
- [2] V. N. Tkach and G. N. Shcherbakov, "Use of non-linear junction detectors to ensure the safety of IED search," in *Detection and Disposal of Improvised Explosives*, H. Schubert and A. Kuznetsov, Eds., Heidelberg, Germany: Springer, 2006, pp. 237–239.
- [3] T. G. Kim, K. S. Min, and K. K. Lee, "Design of broadband spiral antenna of non-linear junction detector," *Journal of Korea Electromagnetic Engineering Society*, vol. 22, no. 1, pp. 81–88, Jan. 2011.
- [4] J. R. James and P. S. Hall, *Handbook of Microstrip Antennas*. London, UK: Peter Peregrinus, 1989.
- [5] M. Haneishi and H. Takazawa, "Broadband circularly polarised planar array composed of a pair of dielectric resonator antennas," *IEEE Electronics Letters*, vol. 21, no. 10, pp. 437–438, May 1985.
- [6] E. T. Rahardjo, S. Kitao, and M. Haneishi, "Circularly polarized planar antenna excited by cross-slot coupled coplanar waveguide feedline," in *Proceedings of the IEEE*

- Antenna and Propagation Society International Symposium*, Seattle, WA, 1994, pp. 2220–2223.
- [7] D. A. Neamen, *An Introduction to Semiconductor Devices*. Boston, MA: McGraw-Hill, 2006.
- [8] Si. S. Haykin and B. Van Veen, *Signals and Systems*, 2nd ed. New York, NY: John Wiley & Sons, 2002.
- [9] J. Liang, L. Guo, C. C. Chiau, and X. Chen, "CPW-fed circular disc monopole antenna for UWB applications," in *Proceedings of the IEEE International Workshop on Antenna Technology*, Singapore, 2005, pp. 505–508.
- [10] D. W. Han, G. T. Jeong, C. H. Lee, H. C. Lee, and K. S. Kwak "Design of an internal antenna for hepta-band using CPWG-fed," *Journal of Korean Institute of Communication Sciences*, vol. 33, no. 9, pp. 934–940, Aug. 2008.
- [11] F. M. Tanyer-Tigrek, I. E. Lager, and L. P. Ligthart, "A CPW-fed printed loop antenna for ultra-wideband application, and its linear-array performance," *IEEE Antennas and Propagation Magazine*, vol. 52, no. 4, pp. 31–40, Aug. 2010.

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