Optimization of Reception Antenna Composed with Unbalanced Fed Inverted L Element for Digital Terrestrial Television

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Abstract **─** The structure of the array antenna for the reception antenna of the digital terrestrial television broadcasting in Japan is optimized by PSO algorithm. The unbalanced fed ultra low profile inverted L antenna is used as the driven element and two wires are located at the forward and backward directions of the driven element. In the case of antenna size of 170 mm by 325 mm by 29 mm, the return loss bandwidth less than -10 dB is satisfied at the whole broadcasting frequency band (240 MHz) and the directivity of 5.44 dBi to 7.19 dBi is obtained. In the numerical analysis, the electromagnetic simulator WIPL-D based on the method of moment is used.

Index Terms **─** Inverted L antenna, PSO, reception antenna, WIPL-D.

I. INTRODUCTION

The digital terrestrial television broadcasting in Japan started on December 2003, and the analog broadcasting ended on July 2011 except the devastated area by the Great East Japan Earthquake [1]. For the reception of the conventional analog terrestrial broadcasting, directional antennas with high gain, and high front-to-back ratio, such as the Yagi-Uda antenna, are used in order to suppress the ghost image due to the echo. On the other hand, a small antenna with low front-to-back ratio is sufficient for the reception of the digital terrestrial broadcasting. By now, many antennas such as a square loop antenna, a planar antenna, and a W-loop antenna mounted on a car window are proposed for the reception antenna of the terrestrial television broadcasting [2 - 4]. The authors have proposed the planar sleeve antenna composed of a coplanar waveguide for the reception antenna of the digital terrestrial television [5]. Although the good return loss characteristics are obtained at the whole broadcasting frequency band, the directivity becomes low (2.32 dBi to 3 dBi). The high gain antenna is desired for the reception at the far area from the broadcasting station.

The authors have proposed two element phased array dipole antenna [6]. Two half-wave dipoles with 90 degree phase difference feed are located with a distance of less than a quarter wavelength. By controlling the mutual coupling between two dipoles, a front-to-back ratio of 15.3 dB is obtained. Then the authors have proposed an ultra low profile inverted L antenna located on parallel wire conductors [7]. This antenna consists of a coaxial line. The inner conductor of the coaxial line is extended from the end of the outer conductor, that is, this antenna is excited at the end of the outer conductor. The antenna height is around $\lambda/30$ (λ: wavelength). The length of the horizontal element of this antenna is almost a quarter wavelength. In the case of the length of parallel wires is 0.49 λ and three wires are located with the width of 0.124 λ, the maximum gain becomes 3.99 dBi and the return loss bandwidth less than -10 dB is 6.13 %. The authors used an

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ultra low profile inverted L antenna located on parallel conducting wires for the driven element of three element array antenna for the reception antenna of the terrestrial television [8]. In order to widen the return loss bandwidth, the antenna height *h* becomes larger and the distance between horizontal wires *pxp* = *pxm* are shorter compared with those in [7]. Although the directivity of 6.0 dBi to 7.77 dBi is obtained, the return loss bandwidth is satisfied only for 170 MHz of the television frequencies from 470 MHz to 710 MHz.

In this paper, the particle swarm optimization (PSO) algorithm [9, 10] is used for the optimization of the geometry parameters of the antenna proposed in the reference [8] to satisfy the return loss less than -10 dB from 470 MHz to 710 MHz. The genetic algorithm is also used for the optimization of the antenna structure [11-13]. Since there are ten parameters should be optimized and the handling of the real number is easy in the PSO, the PSO algorithm is used for the optimization in this paper. In the numerical analysis, the electromagnetic simulator WIPL-D based on the method of moment is used [14].

II. ANALYTICAL MODEL

Figure 1 shows the structure of the analytical model. The driven element No. 1 is an ultra low profiled inverted L antenna located on three parallel wires. The inverted L antenna is composed of a coaxial radiator. This antenna consists of a horizontal arm in the *y*-direction and a small leg in the *z*-direction. The inner conductor of the coaxial line is extended from the end of an outer conductor, that is, this antenna is excited at the end of an outer conductor. The parallel wires are connected to each other by a single perpendicular wire at the base of the inverted L antenna. The length of horizontal element *L* determines the resonant frequency. The length *L*1 is adjusted for the impedance matching. The radii of outer and inner conductors of the coaxial line are 1.095 mm and 0.255 mm, respectively. The radius of parallel wire *a* is 1.5 mm. The height of the horizontal element is *h*. The wire elements No. 2 and No. 3 are located in the forward and backward directions of antenna. In this paper, the Smith chart and the return loss are normalized by the characteristic impedance 75 Ω of feeder of television receiver.

III. ALGORITHM OF OPTIMIZATION

The PSO algorithm is a population-based stochastic approach for solving continuous and discrete optimization problems [9, 10]. The PSO algorithm and its conditions used, in this paper, are described as follows.

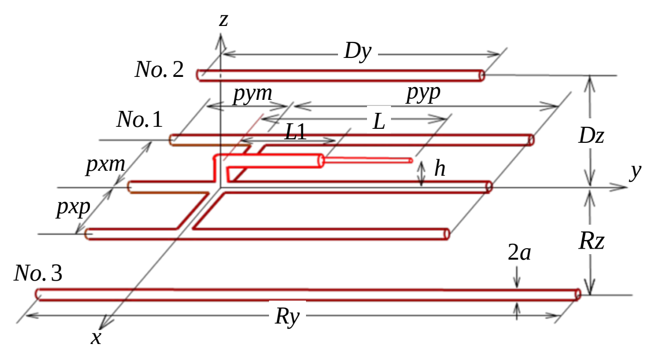
A. Solution space

Solution Space: 10-dimension

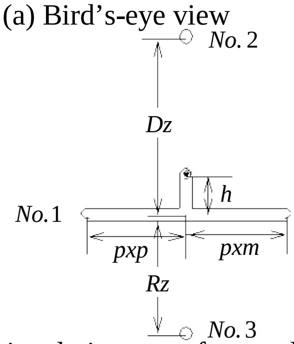
Dz: 40 to 120[80],
Dy: 130 to 290[208],
Rz: -120 to -40[-65],
Ry: 300 to 460[320]
h: 15 to 35[24.5],
L: 90 to 170[130],
*L*1: 25 to 65[41]
pxp=pxm: 10 to 70[40],
pym: 14 to 74[44],
pyp: 150 to 270[210]

A unit of all parameters is mm. The value in [ ] shows a value shown in the reference [8].

A minimum and maximum value for each dimension in the 10-dimensional optimization is referred to as $Xmin_n$ and $Xmax_n$, respectively, where *n* ranges from 1 to 10.



(a) Bird's-eye view



(b) Cross sectional view seen from *y*-direction
Fig. 1. Analytical model of antenna.

B. Fitness function

In this paper, the fitness value is calculated by a bandwidth. The bandwidth is defined as the frequency range where the return loss is less than -10 dB at 75 Ω system. The fitness value is defined by the following equation:

$$fitness\ value = \min\left(F_L, F_H\right) + 0.1\left|F_H - F_L\right|, \quad (1)$$

$$F_L = f_c - f_{lowest}, \quad F_H = f_{highest} - f_c$$

where f_{lowest} and $f_{highest}$ is the lowest and highest frequency of calculated frequency band, respectively. f_c is defined as the center frequency 590 MHz of the frequency band of the digital terrestrial television broadcasting in Japan. If F_L or F_H becomes less than zero, then it is set to be zero. If the calculated frequency band differs from the broadcasting frequency band, F_L differs from F_H. Then, the first term of equation (1) takes smaller value of F_L and F_H. The fitness value is increased in the updating step. Therefore, lower value of F_L and F_H becomes large. This means that the center frequency of the calculation frequency band approaches to f_c in the optimization process. The second term of equation (1) accelerates the extending the return loss bandwidth. In this paper, the coefficient of the second term is fixed as 0.1 based on our experience.

C. Initialization

Each particle begins at its own random location with a velocity that is random both in its direction and magnitude. Initial position in each dimension is given in the following equation:

$$x_n = \text{rand}(\ ) * \left(Xmax_n - Xmin_n\right) + Xmin_n, \quad (2)$$

where x_n is the particle's coordinate in the n-th dimension. The random number function rand( ) returns a number between 0.0 and 1.0.

In this paper, the absolute value of velocities of each particle is limited to 10% of the analytical range in each dimension. $Vmax_n$ shows maximum limit of the absolute value of velocities. $Vmax_n$ is defined as

$$Vmax_n = 0.1 * \left(Xmax_n - Xmin_n\right). \quad (3)$$

The initial velocity defined as

$$v_n = \left\{2 * \text{rand}(\ ) - 1\right\} * Vmax_n, \quad (4)$$

where v_n is the velocity of the particle in the n-th dimension. v_n takes an arbitrary value from $-Vmax_n$ to $Vmax_n$.

D. Iterations

The following procedures are iterated.

1) Evaluate the Particle's Fitness:

The fitness value is computed by the coordinate of each particle. In the numerical analysis of antenna characteristics, the electromagnetic simulator WIPL-D based on the method of moment is used. The coordinate and the velocity of each particle are calculated by the program written in FORTRAN. This program generates an input file of WIPL-D and executes the solver of WIPL-D. In addition, this program demands the return loss from the input impedance value that WIPL-D output. The antenna characteristics and the return loss are calculated at every 5 MHz from 450 MHz to 1 GHz. The larger frequency increment is preferable from the standpoint of the computation time. However, the input impedance characteristics rapidly vary as shown in Figure 4. Therefore, the frequency increment of 5 MHz is chosen.

2) Compare to *pbest*, *gbest*:

pbest is the location in parameter space of the best fitness returned for a specific particle. *gbest* is the location in parameter space of the best fitness returned for the entire swarm. If the fitness value resulting from a change in coordinate of a particle is larger than the fitness value at *pbest* of each particle, *pbest* is changed by that coordinate. In the first iteration, each *pbest* is defined as the initial state of each particle.

If the fitness value resulting from a change in coordinate of each particle is larger than the fitness value at *gbest*, *gbest* is changed by that coordinate. In the first iteration, *gbest* is defined as the coordinate of the particle with best fitness.

3) Update the particle's velocity:

For the next iteration, the velocity of the particle is changed according to the relative locations of *pbest* and *gbest*. It is accelerated in the directions of these locations of greatest fitness according to the following equation:

$$\begin{aligned} v_n = {} & w * v_n + c_1 * \text{rand}(\ ) \times \left(pbest_n - x_n\right) \\ & + c_2 * \text{rand}(\ ) \times \left(gbest_n - x_n\right). \end{aligned} \quad (5)$$

The new velocity is simply the old velocity scaled by w and increased in the direction of *gbest* and *pbest* for that particular dimension. c_1 and c_2 are scaling factors. In this paper, w=0.729, c_1=c_2=1.494 [10]. If the absolute value of v_n is greater than $Vmax_n$, v_n is assumed to be $Vmax_n$ or -$Vmax_n$.

4) Move the particle:

For the next iteration, new coordinate x_n is calculated for each dimension according the following equation:

$$x_n = x_n + v_n * \Delta t. \tag{6}$$

In this paper, Δt is assumed to be 1.

5) Boundary conditions:

In this paper, as for the boundary condition to limit the coordinate of each particle in solution space, the absorbing wall is adopted. That is, if new calculated coordinate x_n is less than $Xmin_n$, x_n is replaced as $Xmin_n$. If x_n is greater than $Xmax_n$, x_n is replaced as $Xmax_n$. In either case, v_n is set to zero.

IV. RESULTS AND DISCUSSION

Table 1 shows the comparison of the fitness value for the different number of population. The number of trial is 10. gFIT indicates the best fitness at the number of iteration IX. If the return loss bandwidth is satisfied at the whole broadcasting frequency band (240 MHz), IX indicates the number of iteration when the return loss bandwidth of 240 MHz is obtained at the first time. As the number of population is increased, the good results satisfying the return loss bandwidth are slightly increased. Therefore, from the standpoint of computation time, the number of population is fixed to 50 in the optimization in the subsequent sections.

Based on the above-mentioned algorithm, the antenna parameters with the bandwidth of 240 MHz and more are obtained. The number of unknowns on WIPL-D is 25. The average computation time for the population of 50 and the iteration of 50 is about 6 hours 40 minutes by using PC with AMD Turion^{TM} 64 processor driven at 2 GHz.

Figure 2 shows the example of the convergence of fitness value in the case of population of 50 and the number of maximum iteration is 50. In this trial, the fitness value which satisfies the return loss bandwidth of 240 MHz is obtained at the number of iteration of 25.

Table 1. Fitness value for different number of population

	50		60		70		80	
	IX	gFIT	IX	gFIT	IX	gFIT	IX	gFIT
1	37	115.0	29	116.5	29	111.0	20	120.0
2	38	120.0	37	120.5	47	120.0	30	120.0
3	33	120.0	45	120.0	26	116.0	21	121.0
4	49	105.0	46	116.5	32	120.0	40	115.0
5	23	120.0	44	120.5	49	121.5	22	115.0
6	36	110.0	47	86.0	49	120.5	44	115.0
7	42	110.5	34	105.0	36	116.0	18	120.0
8	45	120.0	29	120.5	42	95.5	11	120.0
9	33	105.5	38	115.0	18	120.0	47	115.5
10	37	66.0	47	115.5	35	116.5	46	116.0

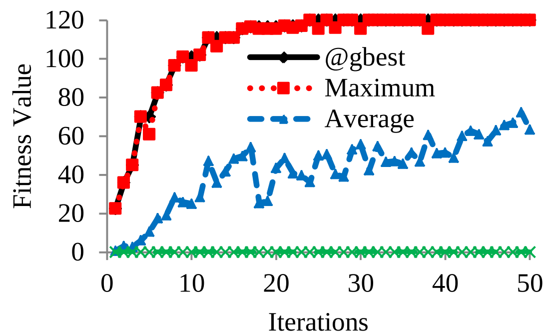
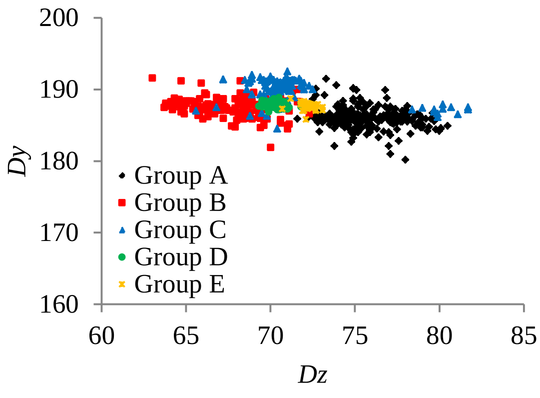


Fig. 2. Convergence of fitness value.

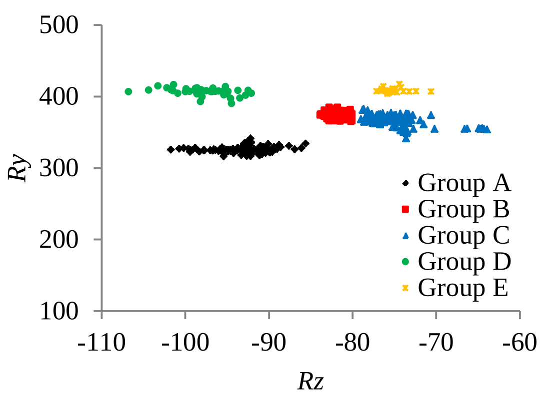
Figure 3 shows the distribution of *Dy* as the function of *Dz*, and *Ry* as the function of *Rz* from the obtained antenna parameters. The distribution of *Ry* can be divided to the following five groups:

Group A: *Rz*<-85, *Ry*<347.5,
Group B: -84<*Rz*<-80, 365<*Ry*<385,
Group C: *Rz*>-79.2, *Ry*<382.5,
Group D: *Rz*<-91.5, *Ry*>385,
Group E: *Rz*>-77.6, *Ry*>400.

In each group, the typical antenna parameters are choosing from the solution in the dense portion in the figure of *Rz* – *Ry*. Figures 4 and 5 show the input impedance and the reflection coefficient characteristics of the antenna of each group, respectively. Figure 6 shows the directivities of antennas of all groups. The directivity of the antenna in Group A becomes higher at the lower frequencies. The parameters of antenna in Group A are as follows; *Dz* = 74.0 mm, *Dy* = 185.9 mm, *Rz* = -92.7 mm, *Ry* = 325.0 mm, *h* = 30.6 mm, *L* = 121.4 mm, *L1* = 25.9 mm, *pxp* = *pxm* = 12.9 mm, *pym* = 31.6 mm, *pyp* = 214.8 mm. The element No. 3 is located for extending the return loss bandwidth at lower frequencies. The average value of the length of the element No. 3 is 325.5 mm in the Group A, as shown in Figure 3. This length is almost a half wave length at the lowest frequency. Therefore, the directivity of the Group A is improved at lower frequencies.



(a) *Dz-Dy*



(b) *Rz-Ry*

Fig. 3. Distribution of optimized results.

Figure 7 shows the distribution of *Dy* as the function of *Dz*, and *Ry* as the function of *Rz* in Group A. Four sample data are shown in these figures. Figures 8 and 9 show the input impedance and reflection coefficient characteristics of four sample antennas, respectively. Figure 9 shows the directivity of these antennas. The directivity of these antennas are almost the same.

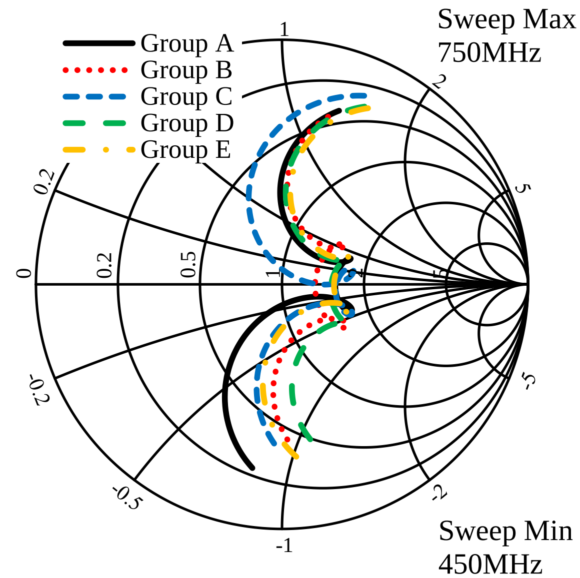


Fig. 4. Input impedance characteristics.

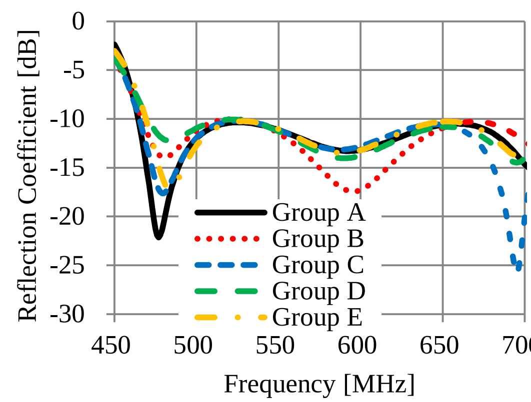


Fig. 5. Reflection Coefficient characteristics.

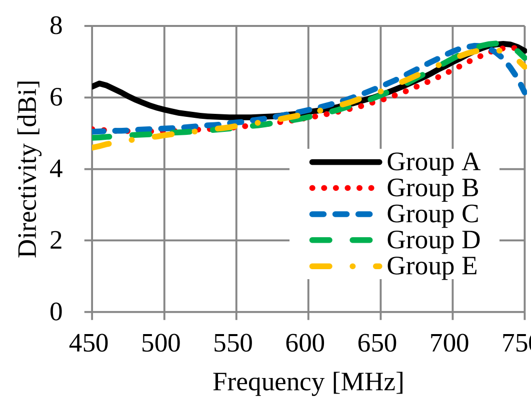
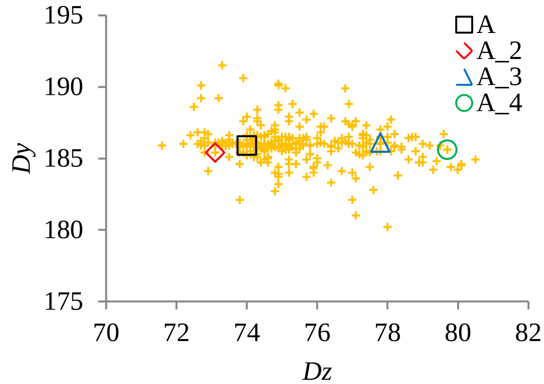
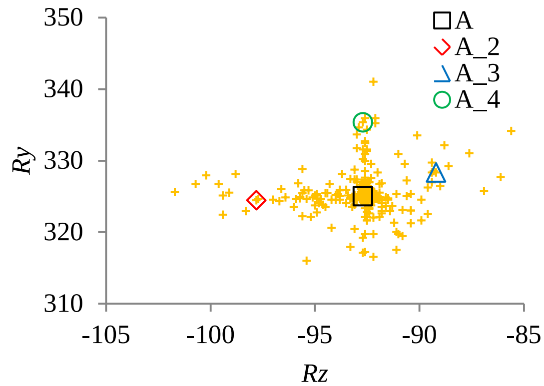


Fig. 6. Directivity characteristics.



(a) *Dz-Dy*



(b) *Rz-Ry*

Fig. 7. Distribution of optimized results.

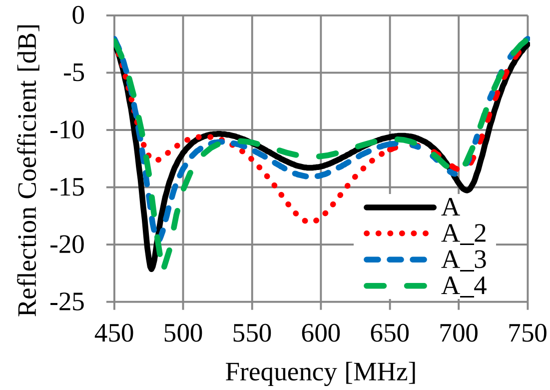


Fig. 8. Reflection Coefficient characteristics.

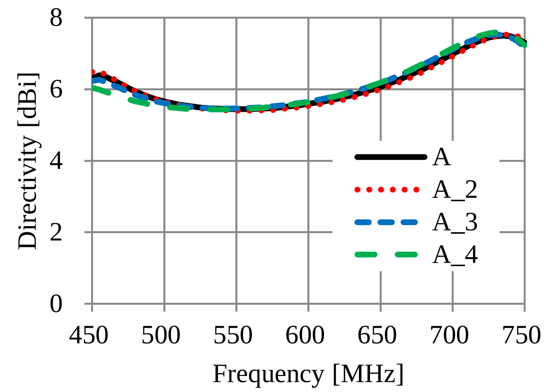


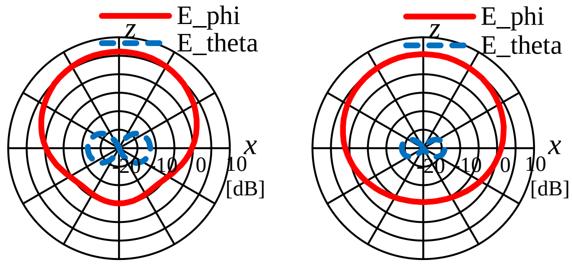
Fig. 9. Directivity characteristics.

Figures 10 and 11 show the electric field radiation patterns of the antenna of Group A in *xz*-plane and *yz*-plane, respectively. Figure 12 shows the comparison of the return loss and the directivity characteristics for the initial design [8] and the optimized solution (Group A).

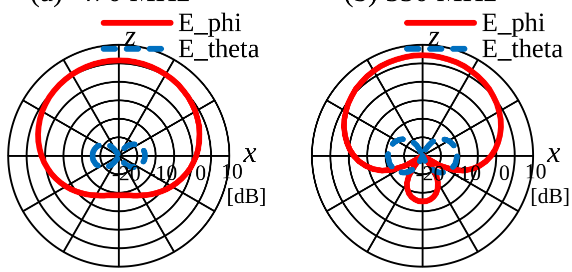
Figure 13 shows the photograph of fabricated antenna. The inverted L element is fabricated by the semi rigid coaxial cable with the characteristic impedance of 50 Ω. The coaxial cable is extended from the base point of antenna to the backward of parallel wires. The antenna is fixed by the expanded polystyrene. In order to measure the input impedance at the feed point not the return loss, the length of coaxial cable has to be compensated. Since this compensation is not so easy, the return loss is measured by the vector network analyzer with the characteristic impedance of 50 Ω. Figure 14 shows the comparison of measured and calculated reflection coefficient characteristics normalized by 50 Ω. Since the width of parallel wires (*pxm* + *pxp*) is narrower than the wavelength, the leakage current may flow on the surface of semi rigid cable. This may cause the discrepancy between calculated and measured data at the lower frequencies.

V. CONCLUSION

As the reception antenna of the terrestrial digital television, three element array antenna has been proposed and its structure has been optimized by applying PSO algorithm. The unbalanced fed ultra low profile inverted L antenna on three parallel wires is used as the driven element of proposed antenna. In the case of antenna size of 170 mm by 325 mm by 29 mm, the return loss bandwidth of 240 MHz and the directivity of 5.44 dBi to 7.19 dBi are obtained.

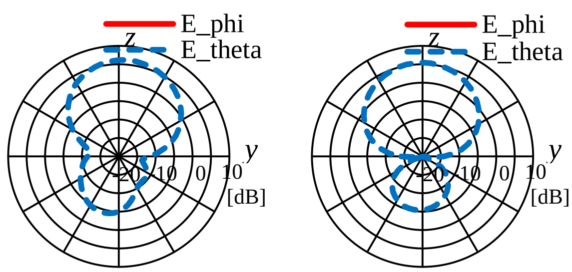


(a) 470 MHz (b) 550 MHz

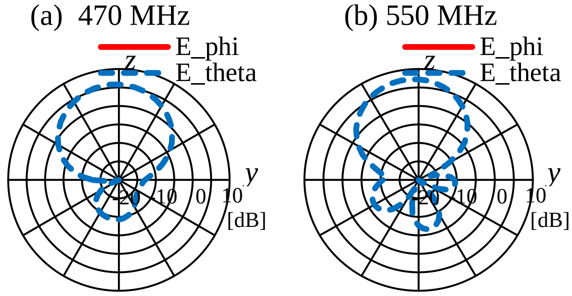


(c) 630 MHz (d) 710 MHz

Fig. 10. Electric field radiation patterns in *xz*-plane. *Dz* = 74.0 mm, *Dy* = 185.9 mm, *Rz* = -92.7 mm, *Ry* = 325.0 mm, *h* = 30.6 mm, *L* = 121.4 mm, *L1* = 25.9 mm, *pxp* = *pxm* = 12.9 mm, *pym* = 31.6 mm, *pyp* = 214.8 mm.



(a) 470 MHz (b) 550 MHz



(c) 630 MHz (d) 710 MHz

Fig. 11. Electric field radiation patterns in *yz*-plane. *Dz* = 74.0 mm, *Dy* = 185.9 mm, *Rz* = -92.7 mm, *Ry* = 325.0 mm, *h* = 30.6 mm, *L* = 121.4 mm, *L1* = 25.9 mm, *pxp* = *pxm* = 12.9 mm, *pym* = 31.6 mm, *pyp* = 214.8 mm.

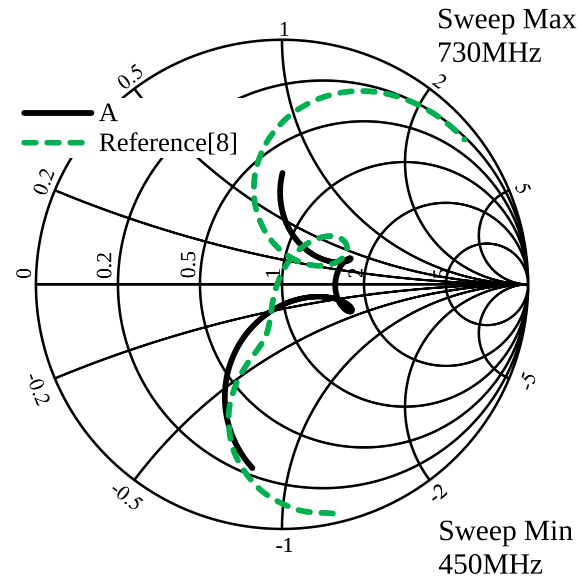


Fig. 12. Comparison of input impedance characteristics for initial design and optimized solution. *Dz* = 74.0 mm, *Dy* = 185.9 mm, *Rz* = -92.7 mm, *Ry* = 325.0 mm, *h* = 30.6 mm, *L* = 121.4 mm, *L1* = 25.9 mm, *pxp* = *pxm* = 12.9 mm, *pym* = 31.6 mm, *pyp* = 214.8 mm.

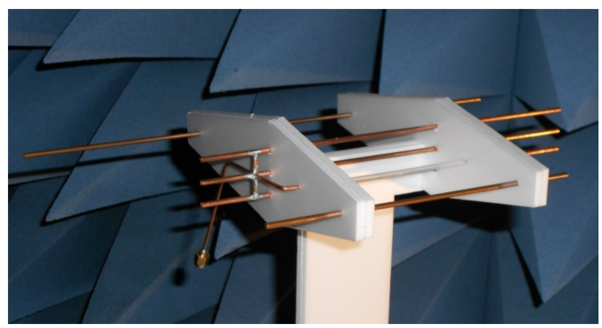


Fig. 13. Photograph of fabricated antenna.

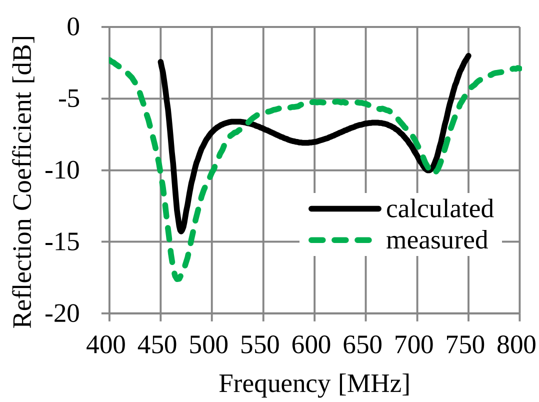


Fig. 14. Reflection Coefficient characteristics normalized by 50 Ω.

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