GA Optimized S-Band Quadrafilar Antenna with the Lowest Back Radiation for a Communication Satellite

Sungtek Kahng[1] · Joongpyo Kim[2]

Abstract

In this paper, a quadrafilar antenna is designed to have a lower profile as an essential part of the size reduction technique and lower back radiation(i.e. higher forward radiation) for the S-band telemetry/telecommand(TM/TC) function of a communication satellite. Particularly, to meet the challenging requirements on the higher isolation between the TM/TC antennas and simultaneously a smaller size, the lowest back radiation and lowest cross-polarization, the optimal physical dimensions of the quadrafilar antenna are found by using the Genetic Algorithm(GA). To prove the validity of the proposed antenna design, its 3D electromagnetic analysis and measured results are compared, showing good agreement.

Key words: Quadrafilar Antenna, Optimization, Genetic Algorithm.

I. Introduction

Showing its unique features compared to other antenna-using applications, the satellite is required to be equipped with a variety of antennas for different multiple functions, but calls for strict and complex specifications for high quality performance, including the environment qualification. The waveguide horn antennas represent the antennas used for satellite communication.

However, helical antennas are also adopted[1]. The helical antennas are easy to design and handle. But this is true for easy-to-realize cases occurring in ground wireless communication, and it is quite complicating and difficult to meet the satellite telemetry and telecommand functions, which, usually drive the antenna design in order to have the lowest interference possible between the telemetry and telecommand antennas with low 'back-radiation'(or high 'forward radiation') and a low cross-polarization level. This stems from the fact that a helical antenna has a relatively smaller number of design parameters[1].

When it comes to the application to telemetry and telecommand, the circular polarization(CP) is recommended; one type of CP antenna(i.e. right-handed CP or RHCP) is assigned to the telemetry and the other type of CP antenna(i.e. left-handed CP or LHCP) is for the telecommand to maximize the cross-polarization performance and isolation between the TM and TC functions. They are separated from each other by 180 degrees in order to minimize the interference between them. However, assuming the RHCP antenna is positioned in the top region with respect to the horizontal bisection-line of a satellite and the LHCP is in the bottom area, the cross-polarization component of the RHCP turns into the LHCP, which is the back radiation from the top region to the bottom region and will interfere with the LHCP of the original antenna for the bottom. To avoid this, Kilgus suggested a method to lower the back radiation and maximize the forward radiation by the quadrafilar helical antenna which shows a very flat forward pattern in either RHCP or LHCP[2]~[4], but it usually requires several turns which will end up with the increment of the antenna height.

In this paper, we use the GA(Genetic Algorithm)[5]~[10] to find the optimal values of the quadrafilar antenna design parameters for a smaller structure, not limited to the Kilgus' design guideline. Through the GA optimization process, we find a way to lower the back radiation and to have flatness in terms of the RHCP antenna residing on the top area of the satellite, and reveal the optimized performance.

II. Basis for the Proposed Design

2-1 Quadrafilar Antenna to be Used for the Communication Satellite

The quadrafilar antenna is placed on the top or bottom area of a satellite, working in an S-band.

The quadrafilar antenna takes the compound of four helical antennae with a sequential 90° phase difference between the two neighboring helixes. This antenna is

(a) Satellite
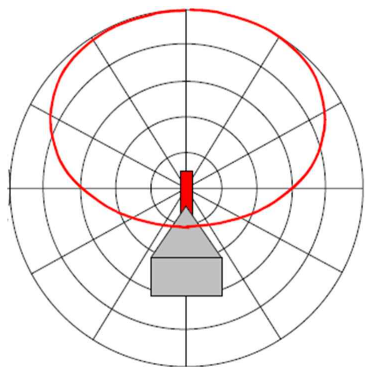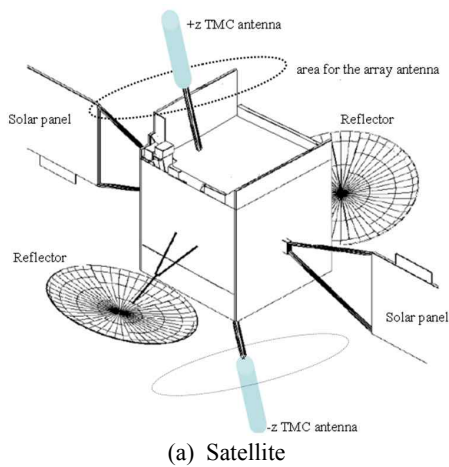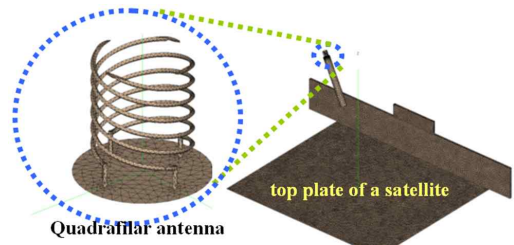

(b) Forward radiation required for TM/TC functions

Fig. 1. Sketch of a communication satellite with multiple antennas mounted on its surface, including wire antennas for the purpose of TM/TC(Telemetry/Tele-command).

(a) 3D quadrafilar antenna mounted on the vehicle

(b) Quadrafilar antenna for the proposed design

Fig. 2. Illustration of the quadrafilar antenna on the top area of a satellite.

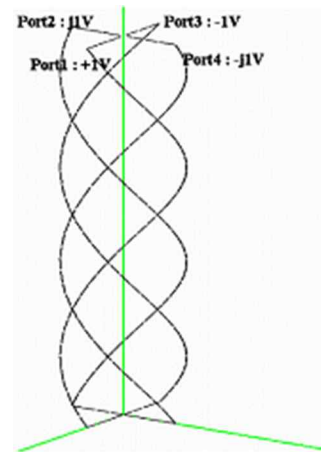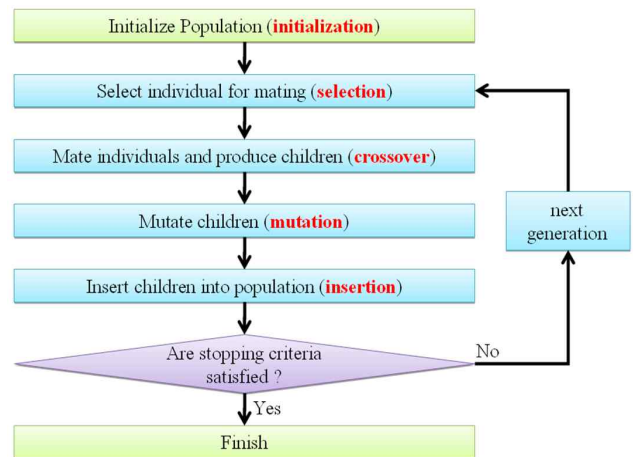Fig. 3. The optimization process of Genetic Algorithm.

assigned to the telemetry function in the top area of a satellite and will be designed to have the RHCP propagation. To avoid the interference from the metal plates of the top region and the degrading interference to the antenna on the other side, this antenna should have the lowest and weakest back radiation possible. Here, the number of the turns, the radius and the height of the antenna are designated as the physical dimensions for the design. To predict the electromagnetic field of the antenna according to the geometrical, boundary and material conditions, the Method of Moment(MoM) solver of the FEKO is used. On a side note, in terms of the degree of freedom in design, due to the limited number of the physically changeable parameters, it is a tough call in satisfying the challenging requirements. This is why we need an optimization algorithm, such as a stochastic search, in the following section.

2-2 Genetic Algorithm

The GA is employed to get the design parameters'

values that are optimal in producing the required performances[5]~[10]. Below, we briefly address the GA it stochastically searches the global minimum in the variable space of the cost function, while performing selection, mating, crossover, mutation, and reproduction.

As always, this optimization starts with defining the cost function as

$$Cost_1 = \sum_{q=1}^{Nq} n_q |P(\Theta_q) - P(\Theta_{q-1})|^{Ne}$$

(1)

$$Cost_2 = \sum_{p=1}^{N_p} \xi_p |P(\Theta_p)(P_{Ref})|^{N_e} \qquad (2)$$

where the cost function 1 as eqn. (1), with weight η_q, considering the 1st portion in the total cost, is the error between the two immediate points of N_q samples along the elevation angle as the RHCP E-field, and used to make the flat RHCP pattern. At the same time, with another weight ξ_p and order N_e, the cost function 2 as eqn. (2) is the inverse of the summation of the differences between the field's magnitudes $P(\Theta_p)$ at N_p angular points and the level P_{Ref} of -25 dB(or empirically at highest -20 dB) as the reference threshold points for the cross-polarization or back radiation, i.e. LHCP. Once again, eqn (2) is intended to maximize the gap between the -25 dB (or empirically, at highest -20 dB) and back radiation level. These two cost functions make up one total cost function. The genes (or binary bits) of the GA are generated as random variables for the design parameters N_{turn}(number of turns), R_{qudra}(radius), and h_{qudra}(height), each of which has N_{bit} binary bits. Each of the N_{pop}(number of population) individuals comprizes 5 N_u genes, where N_u is the number of genes. Afterwards, the population undergoes Selection, Crossover with rate P_{Cr}, and Mutation with rate P_m over N_{genr} generations, with Elitism specifically for this work.

Ⅲ· Design, Realization and Validation

The working frequency is 2.09 GHz and the total gain is set at 3 dBi. In line with this, the following table shows the detailed specifications on the quadrafilar antenna design.

Although most of the specifications above are dependent on this particular satellite development, the gain, bandwidth and polarization look very similar to other helical-type of antennas. However, what makes the difference between the present design and most antenna designs is the isolation and cross-polarization level observed at the broadside angle, i.e. $\Theta=0°$. Even if neither the

Table 1. Specifications on the quadrafilar antenna performance.

Item	Specification
Center frequency	2.09 GHz
Bandwidth (reflection<-10 dB)	0.7 GHz
Gain	$\geq$ 3 dBi
Type of Co-polarization	RHCP
Half power beam-width(=HPBW)	$\approx$ 60 degrees
Cross-polarization level at the broadside	LHCP$=-55$ dB
Isolation at the broadside	≥ 55 dB

gain nor the HPBW seems very large, it does not matter in this case, where the TM antenna on the top and TC antenna beneath the bottom of the satellite should not interfere with each other, and this is determined by the highest isolation(≥ 55 dB) and lowest cross-polarization level. This is the forward-only radiation or lowest back radiation possible from each of the TM and TC antennas.

Note we define the radius, the height, etc as the genes (=variables or design parameters) of the GA's individuals(=sets of parameters). Prior to the presentation of the GA optimization results, the optimization is carried out with cost function 1 to have flat forward radiation(Sampled RHCP E-field over $-60°<\Theta<60°$ should have extremely small variation) and cost function 2 to have the lowest back radiation (Sampled LHCP E-field over $-60°<\Theta<60°$ should be lower than -20 dB or -25 dB) separately. To run the GA optimization code, we have given $N_{bit}=5$, $N_{pop}=200$, $N_{genr}=100$, $P_{Cr}=0.5$, and P_m
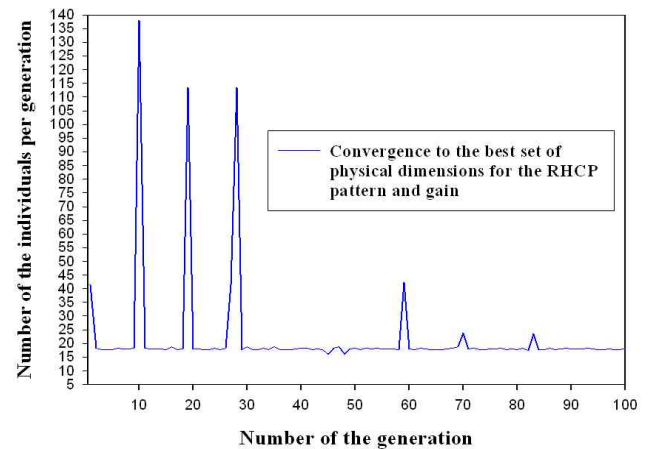
(a) Best number of individuals per generation
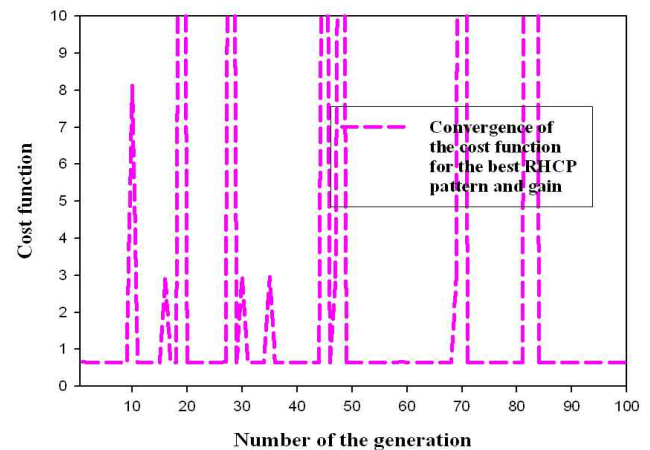
(b) Cost function

Fig. 4. Searching the optimal set of physical dimensions and minimizing the cost function to flatten the field radiation in the forward direction.

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=0.1 as the inputs. Also, η_p and ξ_p are set $1/N_p$ and $1/N_q$ for equal weighting over samples, where N_p and N_q are 20. Besides, we have set $N_e=1$. First, we choose 'P_{Ref} $=-20$ dB condition for cost function 2' and check convergence to find the optimal set of physical dimensions.

Fig. 4 shows how the optimal design parameter set is being found, and that the cost function is settling down. Actually, the average of the individuals or parameters per generation can be plotted, but its traces will cross one another and get tangled and confuse observers. Consequently, here we monitor the number(as the ID) of the parameter set(individual) best in each generation and plot it. Though the best few parameter sets, as the generation progresses, are very similar in terms of the cost function as well as the design parameters, the parameter sets' IDs as integers can be the same, close, or very far apart. Thus, Fig. 4 has some peaks, since the best sets of different generations have similar parameter values but different IDs. Fig. 4(a) tells us that numbers 22 and 17 are the best parameter sets among 200 individuals in generation 80 and generations 90, or 100, respectively. In Fig. 4(b), at first sight, the convergence of the cost function is not good, there being peaks right before the end of the generation. As a result, it provides us the following acceptable performance from the final best parameter set.

To check the forward-only radiation or lowest back-radiation as the key to the high isolation between the TM and TC antennas, it is worthwhile to note the difference between the RHCP and LHCP levels at $\Theta=0°$. It amounts to around 73 dB right at the center. It has acceptable isolation. However, the cross-polarization level goes beyond -20 dB at $\Theta=+60°$. Therefore, we desire to fix this problem by putting the LHCP under -20 dB.
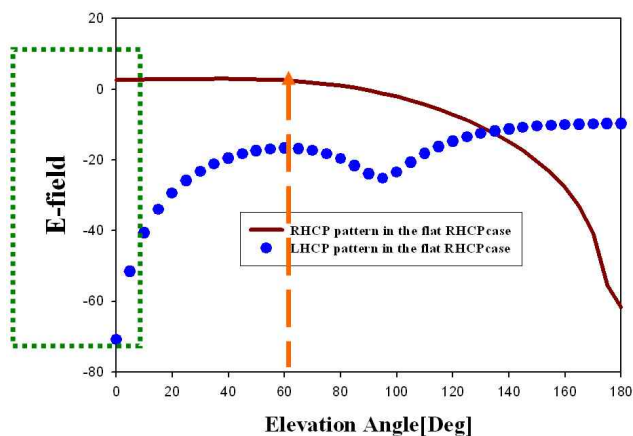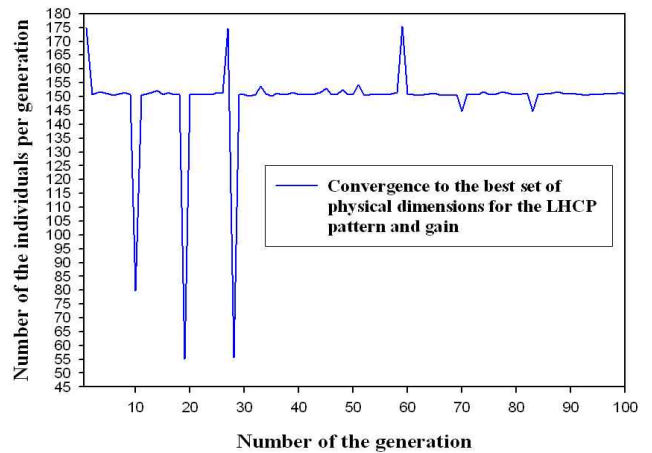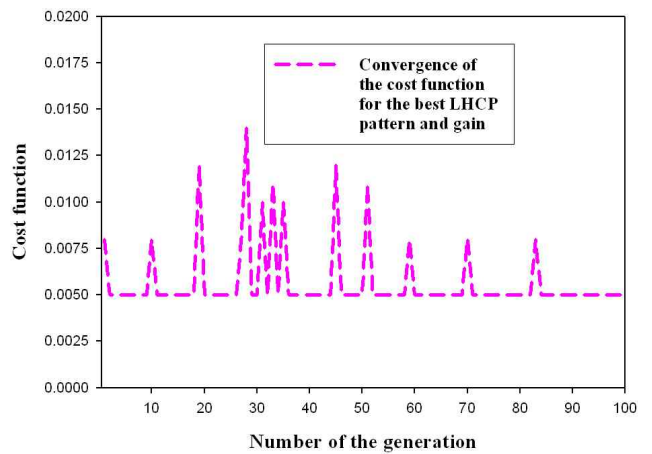
Second, we choose '$P_{Ref}=-25$ dB condition for cost

(a) Best individual per generation

(b) Cost function

Fig. 6. Searching the optimal set of physical dimensions and minimizing the cost function to lower the LHCP.

function 2' and watch the convergence for the optimal design to lower the LHCP comfortably below -20 dB, particularly at $\Theta=+60°$.

According to Fig. 6(a), while the generation progresses, the best parameter set becomes 150. With the new condition for cost function 2, the cost becomes much smaller than before to the order of 3, as shown in Fig. 6(b). Hence, we obtain the performance of the RHCP and LHCP as follows.

With Fig. 7 as the second design of the forward-only radiation or lowest back-radiation essential to the high isolation between the TM and TC antennas, it is worth noting the difference between the RHCP and LHCP levels at $\Theta=0°$. It is seen to be about 82 dB. It turns out to be another enormous isolation. Also, the cross-polarization level is under -20 dB over the HPBW. Through the above process of the work, we finalize the design. The optimized antenna has got physical dimensions, the radius of 11.5 mm, and the height of 65 mm in a half-

Fig. 5. The RHCP(solid line) shows the flat forward radiation, but LHCP(dotted line) is acceptable but not completely optimized.
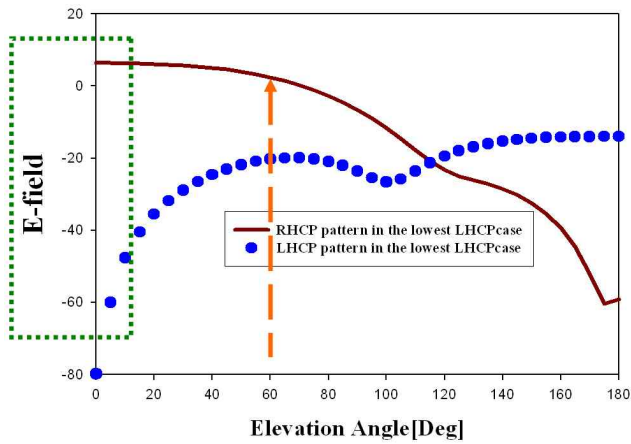
Fig. 7. The LHCP(dotted) and the RHCP(solid) improved by more steps of the optimization.
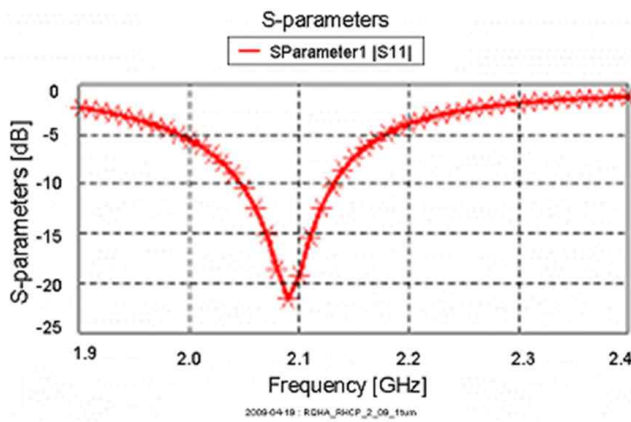

Fig. 8. Return loss of the proposed antenna.

turn geometry that are smaller than one-turn case with the radius of 11.5 mm and the height of 130 mm. Using this physical structure, the return loss of the optimized antenna is as follows.

As is targeted, the frequency band below the −10 dB-reflection coefficient has a center frequency of 2.09 GHz and bandwidth of 700 MHz. Finally, the E-field pattern is analyzed with respect to the proposed quadrafilar antenna.

The optimized antenna's pattern performance is addressed with the 3D electric field pattern and the comparison between co-polarization and cross-polarization levels as a check to the isolation. Both results show the wanted gain(3.3 dBi), the maximum radiation in the forward direction, and almost zero back radiation at Θ=180°. In particular, the predicted field pattern agrees well with the measurement. Despite the small discrepancy in Fig. 9(b), we can see the analyzed and measured patterns with low cross-polarization and maximized isolation for the TM and TC antennas. This proposed antenna has
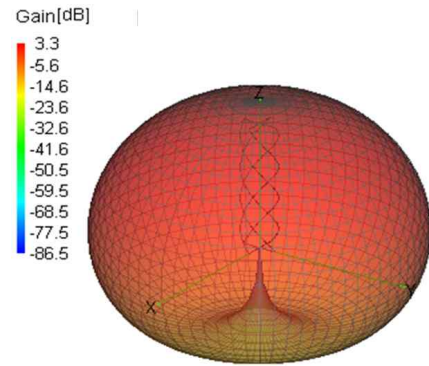
(a) 3D electric field pattern
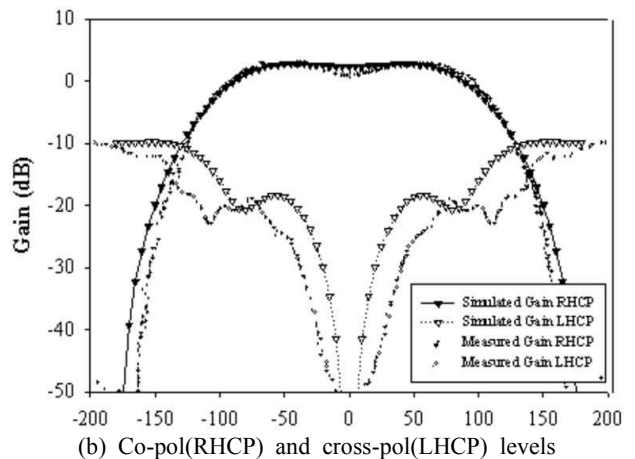
(b) Co-pol(RHCP) and cross-pol(LHCP) levels
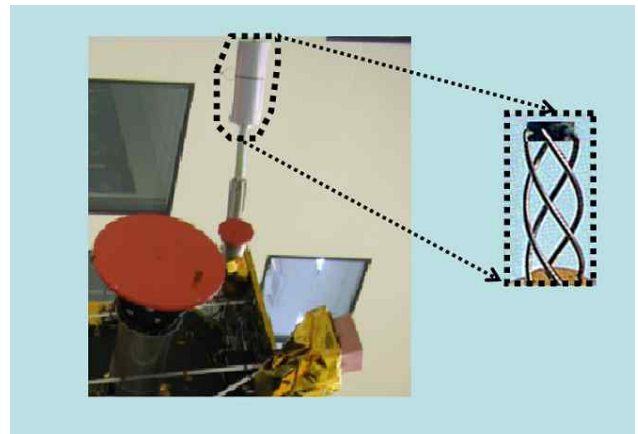
(c) Fabricated and mounted antenna

Fig. 9. Field patterns and photo of the realized antenna.

been fabricated and is shown in Fig. 9(C).

Ⅳ. Conclusions

We presented the design of the highest RHCP radiation and lowest LHCP(forward-only) radiation using a low-profiled S-band quadrafilar antenna on the satellite. The challenging requirements of the size and the tough specifications on the lowest back-radiation have been

met by the use of the GA optimization approach. The design has been validated by comparing the predicted and measured performances.

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