Radiation Pattern Optimization Using Quiescent Elements in Circular Array Antenna with Cylindrical Dielectric Load

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1. Introduction

Recently, the data transmission rate is increasing in the communication systems. In the millimeter wave (mm-wave) band, there are many potentially available bands that have not been used. Therefore, it is expected that a large capacity of the transmission rate are realized using mm-wave. Also, it is able to miniaturize the RF-system because wavelength of mm-wave is short, i.e., it is around 1 ~ 10 mm. For such reasons, the new systems like wireless HD (High Definition) and ultra high-speed WLAN (Wireless Local Area Network) have attracted much attention [1]. However, the higher transmit power is necessary to overcome the higher path loss at mm-wave. Therefore, a high-gain antenna is required to overcome this problem. The beam scanning antenna can be one of the solutions for achieving high gain to any direction. However, it is difficult to miniaturize the switched sector-beam antenna if the antenna consists of the individual antennas as many as the number of the beams.

In this paper, we propose a dielectric cylinder-loaded antenna and describe optimization of termination conditions at quiescent antenna elements. It is clarified that the proposed antenna is effective in achieving high-gain and miniaturizing the size of the antenna. Finite-Difference Time-Domain (FDTD) analysis is used for taking three dimensional dielectrics into account in this study.

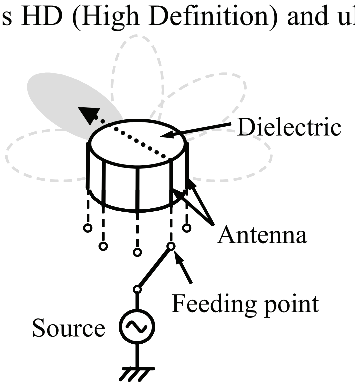


Fig. 1 Proposed antenna.

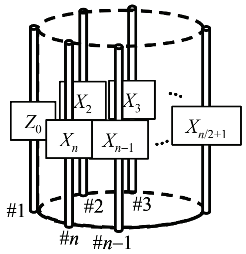


Fig. 2 Dielectric and elements.

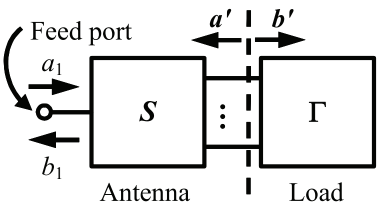


Fig. 3 Equivalent circuit.

2. Proposed Antenna and Optimization Method

2.1 Proposed Antenna

Figure 1 shows a dielectric cylinder-loaded antenna. The proposed antenna is constructed by several antenna elements and dielectric cylinder. The directivity can be controlled by switching feeding point. Dielectric has the two effects. One is able to focus radio wave such as lens, and the other is that shortening the wavelength. These effects achieve high-gain and miniaturized antenna. It can employ System-on-Package (SoP) because of the miniaturization [2].

2.1 Optimization Method

Figure 2 shows the model for this optimization method. A number of antenna elements are uniformly arranged along the cylinder sidewall. The loads are connected to parasitic elements, i.e., quiescent elements, as shown in Fig. 2. The radiation pattern characteristics are improved by optimizing termination conditions at the parasitic elements.

In the following optimization method, the iterative verification of the radiation pattern is required, but it will cost significant CPU time for the total process. In this study, the basic array element

patterns are calculated in advance, and the radiation patterns with certain loads are estimated by post processing with very small computation time.
The parasitic elements are connected to the reactive loads, $\boldsymbol{X} = \begin{pmatrix} X_2 & \cdots & X_n \end{pmatrix}$. #1 is connected to a 50 Ω feed line. Figure 3 shows equivalent circuit of the system. The circuit equations are expressed as,

$$\left.\begin{aligned} \begin{pmatrix} b_1 \\ \boldsymbol{b}' \end{pmatrix} &= \begin{pmatrix} S_{11} & \boldsymbol{S}_{12} \\ \boldsymbol{S}_{21} & \boldsymbol{S}_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ \boldsymbol{a}' \end{pmatrix} \\ \boldsymbol{a}' &= \boldsymbol{\Gamma} \boldsymbol{b}' \end{aligned}\right\}, \tag{1}$$

where $\boldsymbol{a}'$, $\boldsymbol{b}'$, and Γ are the incident waves, reflected waves, and reflection coefficients between antennas and loads, respectively. From (1), the incident waves $\boldsymbol{a}'$ can be solved as,

$$\boldsymbol{a}' = (\boldsymbol{I} - \boldsymbol{\Gamma}\boldsymbol{S}_{22})\boldsymbol{\Gamma}\boldsymbol{S}_{21}a_1, \tag{2}$$

where $\boldsymbol{I}$ is identity matrix. Γ can be expressed as a function of $\boldsymbol{X}$. Therefore, $\boldsymbol{a}'$ is a function of $\boldsymbol{X}$. The required $\boldsymbol{a}'$ and a_1 are expressed as $\boldsymbol{a} = \begin{pmatrix} a_1 & a_2 & \cdots & a_n \end{pmatrix}$. Directive function of the system is expressed as,

$$\boldsymbol{D} = \sum_{i=1}^{n} \boldsymbol{D}_i a_i, \tag{3}$$

where $\boldsymbol{D}_i$ is directive function which is obtained when each antenna is excited. The proposed antenna characteristics are calculated from (3).
Next, a maximum actual gain is evaluated using steepest gradient method. Now define $\boldsymbol{X}^k$ and $\boldsymbol{X}^{k+1}$ as the reactances at k and k+1 steps, respectively. The gradient can be calculated as $\boldsymbol{d}_k = \nabla \boldsymbol{G}_w^k(\boldsymbol{X}^k)$, where $\boldsymbol{G}_w^k(\boldsymbol{X}^k)$ means the actual gain with the reactance of step k. The reactance for step k+1 can be expressed as,

$$\boldsymbol{X}^{k+1} = \boldsymbol{X}^k + \alpha_k \boldsymbol{d}_k, \tag{4}$$

where α_k is the constant to climb the gradient. Thus, maximum actual gains will approach to a maximum value step by step.

3. Numerical Analysis

3.1 Characteristics for Single Element

Figure 4 shows the analysis model. This time, a dipole antenna constructed at the side of dielectric cylinder is used. r and h are radius and height of the dielectric cylinder, respectively. $2l$ is the antenna length. For simplification, we assumed $2l = h$ and neglected the radius of the antenna wire.

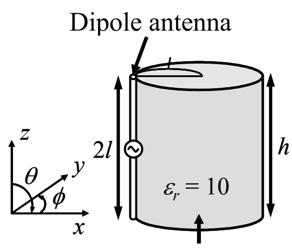


Fig. 4 Analysis model.

First, we analyzed the characteristics for h/λ_0. Here, r/λ_0 is assumed to be constant. Table 1 shows the analysis condition I. λ_0 is the wavelength in free space. Figure 5 shows the frequency characteristics of the actual gain for h/λ_0. At $h/\lambda_0 = 0.245$, it is seen that the antenna is resonated at center frequency. At this time the S_{11} of −13.92 dB is obtained. These results are represented that matching condition is determined by the shape of the dielectric cylinder.
Next, we analyzed the characteristics for r/λ_0. Table 2 shows the analysis condition II. h/λ_0 is determined by considering matching. Figure 6 shows the maximum actual gain and h/λ_0 versus r/λ_0. At $h/\lambda_0 = 0.182$ and $r/\lambda_0 = 0.403$, the maximum actual gain at center frequency becomes 7.27 dB as shown in Fig. 6. It is confirmed that the S_{11} of −10.65 dB at center frequency is obtained. Figure 7 shows the radiation pattern for various radiuses. A level of back lobes in the vertical plane ($\theta = 0$) and the horizontal plane ($\phi = 90$) are decreased by increase of r/λ_0. Table 3 shows the F/B (front-to-back ratio) and the −3 dB beam widths for various radiuses. Through the F/B doesn't become higher than 10 dB, the narrow beam can be formed, i.e., the −3 dB beam width is 49°.

Table 1 Analysis condition I.

Antenna elements	dipole
Dielectric cylinder (DC)	LTCC Relative permittivity : 10 $r/\lambda_0 = 0.316$ $h/\lambda_0 = 0.182, 0.214, 0.245$
Center frequency	60 GHz
Analysis frequency	55 ~ 75 GHz
Analysis region	5.32 x 5.32 x 5.32 mm
Cell size	$\Delta x=\Delta y=\Delta z=0.04$ mm
Time step	Δt = 0.072269 psec
Number of time step	3000
Feed model	Delta-gap feed
Exciting pulse	Gaussian pulse
Absorbing B.C	PML 6-layers

Table 2 Analysis condition II.

Antenna elements	dipole
Dielectric cylinder (DC)	LTCC Relative permittivity : 10 $r/\lambda_0 = 0.316 \sim 0.403$
Center frequency	60 GHz
Analysis frequency	55 ~ 75 GHz
Analysis region	Changed by shape of DC
Cell size	$\Delta x=\Delta y=\Delta z=0.04$ mm
Time step	Δt = 0.072269 psec
Number of time step	3000
Feed model	Delta-gap feed
Exciting pulse	Gaussian pulse
Absorbing B.C	PML 6-layers

Table 3 The F/B and the −3 dB beam widths.

r/λ_0	F/B [dB]	−3 dB beam widths [deg]	
		Vertical	Horizontal
0.316	0.84	50	50
0.356	2.19	50	50
0.395	3.42	49	49
0.403	3.96	49	49

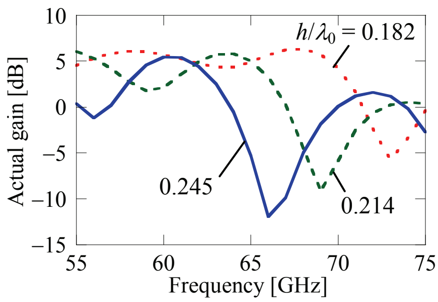


Fig. 5 Frequency characteristics of actual gain for h/λ_0.

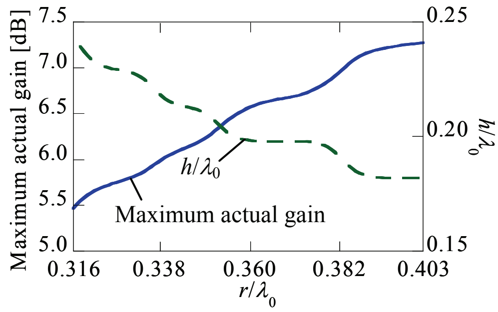
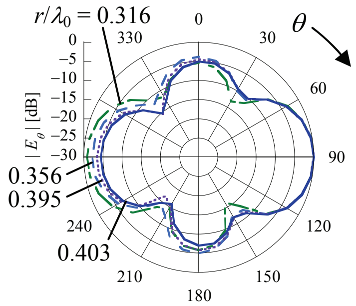
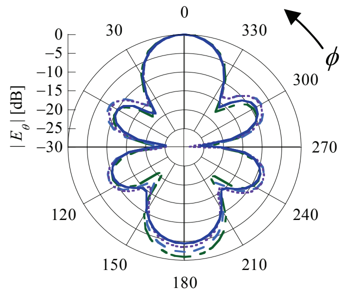


Fig. 6 maximum actual gain and h/λ_0 versus r/λ_0.



(a) Vertical plane (ϕ = 0)



(b) Horizontal plane (θ = 90)

Fig. 7 Radiation pattern for various radiuses.

3.2 Evaluation of Optimizing Termination Conditions at Parasitic Elements

Figure 8 shows the evaluation model. Table 4 shows the evaluation condition. We used the shape of the dielectric cylinder which obtained the maximum actual gain of 7.27 dB and used 6 elements considering the −3 dB beam widths of 49°. The elements were uniformly arranged along the cylinder sidewall. Initial reactance $\boldsymbol{X}$ is generated randomly. We employed reactance X that is obtained the best antenna characteristics when termination conditions at parasitic elements, i.e. quiescent elements, are optimized. Figure 9 shows the maximum actual gain versus the number of iterations. It can be seen that the maximum value of 14.14 dB is obtained by 26 time iterations. At this

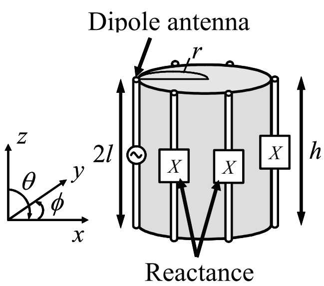


Fig. 8 Evaluation model.

time the S_{11} of −24.44 dB is achieved at center frequency. Figure 10 shows the radiation pattern. A level of back lobes in the vertical plane and the horizontal plane are lower than −10 dB. The F/B is 7.80 dB, the vertical −3 dB beam width is 80°, and the horizontal −3 dB beam width is 29°.
Compared to the radiation pattern characteristics for 1 element, we can observe the improvements in the maximum actual gain by 6.87 dB, the S_{11} by −10.52 dB, and the F/B by 3.85 dB. The narrower beam can be formed, i.e., the horizontal −3 dB beam width is 29°.
The size of the proposed antenna is compared to the size of the conventional antenna. The conventional antenna with height of λ_0, and diameter of $2\lambda_0$ is assumed. By this, it is found that the height and diameter of the proposed antenna are 1/5 and 2/5 of the conventional one, respectively.

4. Conclusion

In this paper, a dielectric cylinder-loaded antenna has been proposed. We analyzed antenna characteristics to consider the proposed antenna structure. With a single antenna element, the maximum actual gain becomes 7.27 dB at h/λ_0 = 0.182 and r/λ_0 = 0.403. Also, the sufficiently narrow beam can be formed. With the several antenna elements, the maximum actual gain of 14.14 dB is achieved by optimizing termination conditions at parasitic elements. These results proved that the proposed antenna is effective in achieving high-gain switched-beam antenna with the compact configuration.

References

[1] S.K. Yong and C.-C. Chong, "An Overview of Multigigabit Wireless through Millimeter Wave Technology: Potentials and Technical Challenges," EURASIP Journal on Wireless Communications and Networking, vol. 2007, 2007.

[2] K. Lim, S. Pinel, M. Davis, A. Sutono, C.-H. Lee, D. Heo, A. Obatoynbo, J. Laskar, E. M. Tantzeris, and R. Tummala, "RF system-on-package (SOP) for wireless communications," IEEE Microw. Mag. , pp. 88–99, Mar. 2002.

Table 4 Evaluation condition.

Antenna elements	dipole
Number of element	6 (uniformly)
Dielectric cylinder	LTCC Relative permittivity : 10 r/λ_0 = 0.403 h/λ_0 = 0.182
Center frequency	60 GHz
Number of iterative computation	100 times
Initial reactance	Random numbers in $X = -j100 \sim j100\ \Omega$
a_k	1000

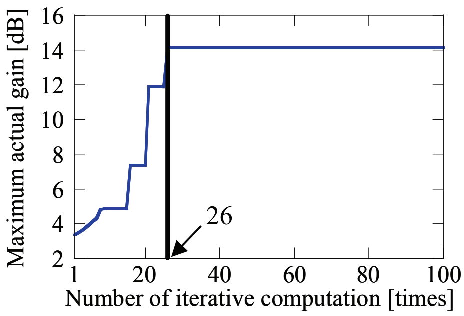
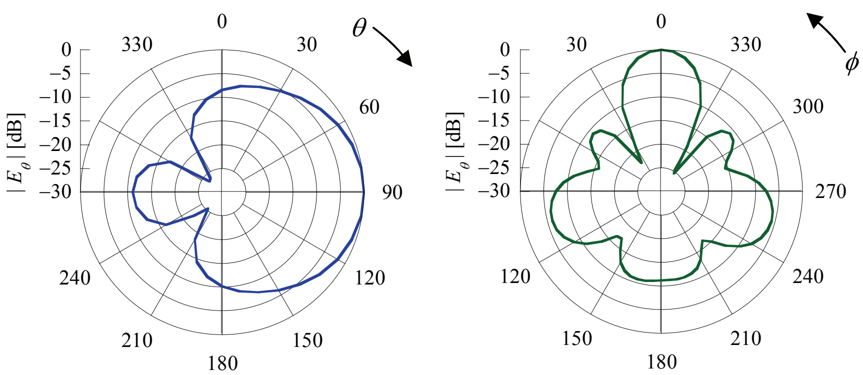


Fig. 9 Number of iterative computation versus maximum actual gain.



(a) Vertical plane (ϕ = 0)
(b) Horizontal plane (θ = 90)

Fig. 10 Radiation pattern.