A Mobile Communication Base Station Antenna Using a Genetic Algorithm Based Fabry-Pérot Resonance Optimization

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Abstract—We proposed a high-gain wideband resonant-type mobile communication base station antenna using a Fabry-Pérot cavity (FPC) technique. To overcome inherent narrow radiation bandwidth of FPC-type antennas while keeping relatively high gain, we introduced a new superstrate structure composed of square patches and loops, which satisfies an FPC resonance condition at a target frequency region. To do that, we optimized the superstrate geometry with the help of a real-value coding hybrid genetic algorithm (RHGA).

The optimized superstrate is very thin, and therefore, it can be fabricated with a single dielectric substrate, which is a fairly strong point in practical applications. Moreover, we enclosed four openings of the antenna in lateral directions to increase antenna gain with a limited aperture area. Therefore, a modified prediction method of an FPC resonance is used, which reduced the effort of complicated three-dimensional antenna optimization.

Consequently, our antenna is able to operate in a wide bandwidth with a relatively high realized gain. Furthermore, good agreement between measured results and prediction ones confirms the validity of our design approach.

Index Terms—Base station antenna, Fabry-Pérot cavity antenna, hybrid genetic algorithm, high-gain antenna, wideband antenna.

I. INTRODUCTION

RECENTLY, in accordance with the growth of mobile communication industry, the usage of a personal mobile phone has been explosively increased. For that reason, mobile base station antenna techniques also have been rapidly developed to keep up with the increased number of users within a service area using limited frequency resources [1], [2].

Many sorts of a base station antenna employ an array of a dipole antenna or a microstrip patch antenna, which is ready to increase overall antenna gain and to control a beam shape according to a frequency reuse plan [3]–[5]. However, signal feeding networks from a power input port to wave radiating structures are generally long and complicated, which might cause an unwanted energy loss during signal transportation.

Recently, highly directive antennas using resonance of a partially reflective surface (PRS) such as Fabry-Perot cavity (FPC) or electromagnetic band gap (EBG) structures have been introduced [6]–[12]. The FPC antenna makes use of resonance of a cavity generally consisting of a ground plane and a superstrate. By appropriately adjusting the cavity height and the reflection magnitude and phase of the superstrate, the FPC antenna can provide very high gain at and near the resonant frequency [13]. One strong point of the FPC antenna lies in its simple feeding structure. Practically, the FPC antennas provide high gain with a single feeding antenna such as a dipole or a microstrip patch antenna. It is matter of course that array signal feeding can more increase antenna gain compared to a single feeding case. In addition to a horizontally arranged PRS structure, cylindrical EBG structures have also been proposed for base station antenna applications [14], [15].

However, because the cavity resonance condition is satisfied only at one frequency, a radiation bandwidth of the FPC antenna is usually very narrow; in other words, the cavity resonates with a very high quality factor. Therefore, impedance matching and radiation bandwidths of FPC antennas are also inherently very narrow due to the nature of a cavity operation, which are not appropriate to commercial applications.

To overcome the narrow radiation bandwidth problem, an FPC antenna with a single-layer frequency selective surface (FSS) superstrate consisting of dissimilar size square conducting patches was proposed [16], [17]. In [16], [17], antenna bandwidth was increased by tapering cells printed on the superstrate, which spread resonant frequencies around a center frequency of a target bandwidth. In the meantime, some techniques of adjusting reflection phase of a superstrate unit cell to meet the resonance condition of a FP cavity were proposed in [18], [19]. Instead of tapering superstrate unit cells, they introduced two individual conductive patterns printed on a single or double dielectric layers, which provides relatively large reflection magnitude with reflection phase similar to an ideal phase response satisfying the FPC resonance.

In this paper, we provide a broadband high gain mobile base station antenna. Our antenna has a superstrate composed square patches and loops, which meets an FPC resonance condition in a target Korean personal communication service (PCS) band from 1 750 MHz to 1 870 MHz. The superstrate is very thin, and therefore, it is quite comfortable to fabricate and to apply for practical antennas. To optimize reflection behavior of the superstrate, we use a real-value coding hybrid genetic algorithm
Fig. 1. Photographs of (a) the inside and (b) the outside of the fabricated FPC antenna.

(RHGA) providing fast convergence with a relatively small size of population [20]–[23].

Initially, we design the superstrate based on a modified FPC resonance prediction formulation, which is able to consider the effect of four metallic side walls. And overall performance of the entire antenna structure is tuned by using a commercial 3-D full wave simulator of CST microwave studio (MWS) [24]. Experimental data show good agreement with the simulation result, which proves the validity of our design approach.

II. ANTENNA DESIGN AND MEASUREMENT

Photographs of a proposed FPC antenna are shown in Fig. 1. A 50 Ω coaxial probe-fed wideband patch antenna is located inside the FP cavity that is enclosed with four lateral metallic walls in the x- and y-direction, respectively. A ground plane of the patch antenna is the bottom face of the cavity. The superstrate consisting of 19 × 5 unit cells covers the entire upper opening of the FP cavity shown in Fig. 1(a), which is supported with eight acrylic posts. Overall dimension of the FPC antenna is 590 mm × 170 mm × 98 mm in the x-, y-, and z-direction.

A detailed description of the patch antenna and the unit cell geometry are shown in Fig. 2. To extend an impedance matching bandwidth of the patch antenna, we have inserted two rectangular slits as shown in Fig. 2(a) [25], [26]. An inner conductor of a signal feeding coaxial cable is directly connected to the patch. And an air gap has been placed between the substrate of the patch and the ground plane.

As for the unit cell of the superstrate, on one side of a dielectric substrate is printed with a square patch and the opposite side with a square loop. The lower side of the superstrate composed of square loops is confronting the bottom side of the cavity. Because our superstrate is very thin, where the thickness is about 1.5 mm, it is directly applicable to practical antennas.

We can determine the FP resonance condition by considering reflection phases of two faces of the cavity, which consist of the superstrate and the ground plane. However, with the help of a modified resonance prediction formula based on a dispersion relation of a classical metallic rectangular cavity, we can more accurately estimate FPC resonance including the effect of four metallic side walls [17]:

\[
f_{mnq} = \frac{c}{2\pi} \sqrt{k_x^2 + k_y^2 + k_z^2},
\]

\[
k_x = \frac{m\pi}{l_x}, \quad k_y = \frac{n\pi}{l_y}, \quad k_z = \frac{2\pi f_d}{c}, \quad \text{and}
\]

\[
f_q = \frac{c}{2h_c} \left( \frac{\phi_a + \pi}{2\pi} + q \right), \quad q = 0, 1, 2, \ldots ,
\]

where \(m, n\) are integer numbers corresponding to possible eigen-modes inside the cavity, and \(l_x\) and \(l_y\) are lengths of the cavity shown in Fig. 1(b), \(c\) is the speed of light in air, \(\phi_a\) is the reflection phase of the superstrate, and \(h_c\) is the resonant height from the ground to the bottom face of the superstrate.

It is well known that waves satisfying the FP resonance condition with relatively large magnitude of reflection can collimate outgoing waves toward a specific direction, and therefore, enhance the directivity and gain of antennas [6]–[10]. Generally, the large reflection can be easily obtained with various types of
conducting patterns within a certain frequency bandwidth. Consequently, the FP resonance condition is also readily acquired by changing the geometry of conducting patterns of a superstrate or by varying the distance between the superstrate and a ground plane. However, the FP cavity resonance condition is exactly satisfied at only one frequency, which restricts expansion of a radiation bandwidth of FPC antennas. Therefore, to obtain a wide radiation bandwidth and high gain properties at the same time, reflection phase of the superstrate should satisfy the FPC resonance condition at more than one frequency. To do that, we have optimized reflection behavior of the superstrate, which might provide an ideal phase-like response (see a broken line in Fig. 5) in a target PCS frequency region. From (1), the ideal phase response depicted in Fig. 5 is derived by

\[ \phi_{\text{ideal}} = \pm \frac{2\pi h_{c}}{c \cdot \ell_{p}} \sqrt{(2f \ell_{p})^2 - (nc)^2} - (2q + 1)\pi. \]  

(2)

In the frequency region of interest, the lowest mode inside the cavity is a TE_{011} mode, so we set \( m = 0 \) and \( n = q = 1 \), respectively [17].

To optimize the geometry of superstrate unit cell, we used a real-value coding hybrid genetic algorithm (RHGA) [20]–[23]. As shown in Fig. 3, the RHGA is equipped with a gradient-like selector based reproduction, modified simple crossover, and dynamic mutation. And, we applied elitism to prevent a loss of the best individual from the preceding generation, which might occur on account of inherent nature of a genetic algorithm. Four target optimization parameters are the height \( h_{c} \) of the FPC cavity, and lengths \( (l_{1}, l_{2}) \) and width \( (w_{1}) \) of the square patch and the square loop patterns. The population size of the RHGA is 10. The optimization process of the superstrate unit cell geometry is shown in Fig. 4. A fitness or cost function to be minimized is defined by

\[ \text{Fitness} = A_{1} \sum_{f=f_{1}}^{f_{2}} \left( |\phi_{\text{ideal}} - \angle S_{11,\text{cell}}| \right) + A_{2} \sum_{f=f_{1}}^{f_{2}} (1 - |S_{11,\text{cell}}|) \]  

(3)

where \( \phi_{\text{ideal}} \) and \( \angle S_{11,\text{cell}} \) are reflection phases of an ideal response and the proposed unit cell, \( S_{11,\text{cell}} \) is a reflection magnitude of the proposed cell, \( f_{1} \) and \( f_{2} \) are optimization starting and ending frequencies, \( A_{1} \) and \( A_{2} \) are weighting coefficients for each angular and magnitude component of the fitness function. We set \( f_{1} = 1750 \) MHz, \( f_{2} = 1870 \) MHz, \( A_{1} = 1 \) and \( A_{2} = 5 \), respectively. The total number of frequency points for the calculation of the fitness function is 25. To prevent the gain decrease, we selected the weighting coefficient of \( A_{2} = 5 \), which is five times larger than \( A_{1} \). Consequently, we could minimize the gain reduction caused by a small magnitude of \( S_{11} \) throughout the relatively wide target frequency range. Using the (1) and (2), and the optimized reflection behavior of the superstrate, the resonant height \( h_{c} \) is determined as 96.4 mm.

Computed reflection behaviors of the superstrate unit cell are shown in Fig. 5. In the figure, the broken line denotes an ideal reflection phase satisfying the FP resonance at each frequency. Therefore, it can be said that we could acquire the necessary
reflection phase values from 1.76 GHz to 1.88 GHz, which are very similar to the ideal phase response. But, a reflection magnitude is reduced to about 0.65, which may not be helpful to enhance antenna gain.

As shown in Fig. 1, we fabricated the wideband FPC antenna based on the optimization result of the superstrate geometry and the prediction of FPC resonance. Fig. 6 shows performance of the proposed antenna. As for the input reflection coefficient ($S_{11}$), −10 dB bandwidth is from 1.74 GHz to 1.84 GHz, which corresponds to a fractional bandwidth of about 5.6%. In regard to antenna gain, the maximum measured gain is 13.8 dB and the 3 dB radiation bandwidth is about 180 MHz, which corresponds to a fractional bandwidth of 10%. The antenna gain shown in Fig. 6 is realized gain in the superstrate surface normal direction including overall mismatch and efficiency parameters of the antenna. Hence, it is undoubtedly clear that our antenna well operates with relatively flat gain within the target PCS frequency band. The patch antenna behavior without the FPC is also shown in Fig. 6. The maximum gain of the patch antenna is about 9.4 dB. Accordingly, we could increase the overall antenna gain about 4.5 dB by introducing the FPC technique. In Fig. 6(a), we can see that there is another impedance matched frequency band near 2.06 GHz, which exists because of a generation of higher modes inside the cavity.

To more clearly show the existence of the higher mode, we compute the magnitude and phase distribution in the cavity, which are shown in Fig. 7. At a fundamental radiation mode, i.e., at 1.75 GHz and 1.85 GHz, the magnitude and phase distribution is approximately symmetric with respect to the center of the cavity. Moreover, the overall phase contrast shown in Fig. 7(b), namely, the maximum phase difference between the largest and the smallest values, does not exceed 100 degrees, which tells us that the signal distribution inside the cavity is not destructive. Therefore, the antenna stably and strongly radiates energy toward a normal direction (z-direction) in the fundamental mode frequencies. However, at the second radiation mode near 2.1 GHz, overall phase varies from 0 to 340 degrees, which is indicating the existence of destructive interference inside the cavity. In fact, we can see several magnitude peaks at 2.1 GHz resulting from the interference of waves at the higher mode. Accordingly, different from the radiation behavior in the fundamental mode, there exist several main beams distributing in the x-direction.

Measured radiation properties are compared with computed values, which are depicted in Fig. 8. To obtain practical beam shapes that are narrow in the elevation direction (the xz-plane) and wide in the azimuthal direction (the yz-plane), we intentionally make the aperture as a rectangular shape, which is narrower in the azimuthal direction. Consequently, the half-power beam width in the E-plane is more than 2 times narrower than that in the H-plane. As for the H-plane radiation pattern, the antenna structure including the feeding patch antenna is perfectly symmetric with respect to the xz-plane, so the radiation pattern in the azimuthal direction is also symmetric. However, the patch is not symmetric with respect to the yz-plane. That is the reason why the E-plane radiation pattern is not symmetric.
It is also important to note that a front-to-back radiation ratio (FBR) of the proposed antenna is relatively high, which is one significant design parameter required for base station and repeater antennas of today.

We can see that the measured and predicted radiation properties agree very well, which confirms the validity and accuracy of our design approach. The detailed antenna performance is described in Table I.

### III. CONCLUSION

A base station antenna for mobile communication was proposed. We chose an FPC-type antenna as our prototype antenna to obtain relatively high-gain property. A single wide band patch-antenna fed energy into the FP cavity, which is enclosed with four metallic side-walls. To get a wider beam width in an azimuthal direction, radiation aperture was made as a rectangular shape.

For wide beam width corresponding to a target personal communication service, we optimized the superstrate structure consisting of the square patches and loops, which satisfies an FPC resonance condition in the target frequency band. We used a hybrid genetic algorithm for the optimization of the superstrate geometry.

Our antenna radiates well in the target band with relatively high-gain. And, there exists only a fundamental mode inside cavity, which is important for high gain behavior radiating only toward the aperture-normal direction. Consequently, it was also shown that radiation behaviors at each frequency are also appropriate for the application of base station antenna.

Predicted antenna performance showed good agreement with experimental data gathered in a fully anechoic chamber, which confirms validity of our design approach.

### REFERENCES


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