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이중 대역 개구면 결합 공진기 급전 마이크로스트립 안테나 설계

(Dual Band Design of Aperture-Coupled Cavity-Fed Microstrip Antenna)

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요 약

개구면 결합 공진기 급전 마이크로스트립 패치 안테나의 단순하고도 정확한 등가 회로를 추출한다. 이 등가회로는 이상적인 트랜스포머, 어드미턴스 소자, 그리고 전송선으로 구성되고 각 소자 값들은 가역 정리와 스펙트럼 영역 이미턴스 방법에 기반한 복소 전력 개념으로부터 구할 수 있다. 기 게재된 논문의 연구 결과를 이용하여 제안한 등가회로의 타당성을 검증한 후 이중 대역 안테나를 유전 알고리즘과 Nelder-Mead 방법을 통한 이종 진화적 최적화 방법으로 설계하였다. 설계 목표치에 적합한 결과를 도출하였고, 이 결과는 이종 진화적 최적화 방법이 설계에 매우 효율적임을 확인해 준다.

Abstract

A simple but accurate equivalent circuit of an aperture-coupled cavity-fed microstrip patch antenna is developed. It consists of ideal transformers, admittance elements, and transmission lines, and the related circuit element values are computed by applying the reciprocity theorem and complex power concept with the spectral-domain immittance approach. After validating by the published design example, a dual-band antenna was designed with the help of a hybrid optimization method. For this purpose, the Genetic Algorithm is applied with the Nelder-Mead simplex method. The obtained good results show that this approach turned out to be a very efficient tool for the design of aperture-coupled cavity-fed microstrip patch antenna having various structural design parameters.

Keywords : Aperture-coupled, Cavity-fed, Microstrip antenna, Equivalent circuit, Computer-aided design Hybrid optimization

I. INTRODUCTION

Recently, a thick ground plane was added to the aperture-coupled microstrip patch antenna especially for active phased array antenna applications to serve as a heat sink for active TR modules and to provide structural support for thin substrates[1],[2]. However, the coupling to the patch decreases rapidly with increasing ground plane thickness since the thick slot behaves as a waveguide below cutoff[2]. The coupling can be restored by increasing the aperture length (above cut-off), but this in turn increases unwanted back radiation. In order to solve this problem, an aperture-coupled cavity-fed microstrip patch antenna was proposed[3]. The cavity can be made to be operated above cutoff to provide good coupling

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efficiency while maintaining a small slot in feed side for minimal back radiation.

The numerical method of moments has been used to determine the input impedance of the antennas[3] Even the customized numerical code is efficient compared to the commercially available numerical EM solvers, there is a limit in optimized design applications, where large number of design parameters are invoked. In this paper, a much more efficient optimized design scheme, which is based on a simple but accurate equivalent circuit model, is presented. After validating the equivalent circuit with the published design example, a dual-band antenna is designed with the hybrid optimization method, where the genetic algorithm (GA) is applied with the Nelder-Mead (NM) simplex method.

Ⅱ. ANALYSIS AND EQUIVALENT CIRCUIT

Fig 1 shows a structure of an aperture-coupled cavity-fed microstrip patch antenna. A rectangular microstrip patch antenna is located on the top plane of the upper substrate with a dielectric constant ε_{rp} and a thickness h_p. W_p and L_p are the width and the length of the antenna. A microstrip feed line is placed on the bottom plane of the lower substrate with a dielectric constant ε_{rf} and a thickness h_f. W_f is a width of feed line and L_{stub} is the stub length of microstrip line. Slot 1 is located on the ground plane of the feed with the width of W_{s1} and the length of L_{s1}. Slot 2 is placed on the ground plane of the patch antenna with the width of W_{s2} and the length of L_{s2}. And a and b are the width d the height of the cross-section of a rectangular waveguide with the length t. ε_{rw} is dielectric constants of dielectric materials in the waveguide cavity.

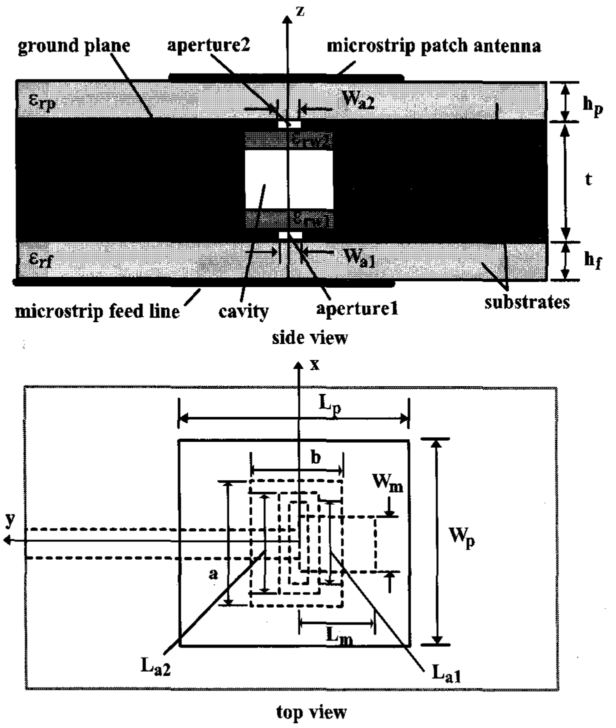

그림 1. 개구면 결합 공진기 급전 마이크로스트립 패치 안테나의 구조

Fig. 1. Geometry of an aperture-coupled cavity-fed microstrip patch antenna.

In order to accommodate the effects of aperture radiation and a thick ground plane accurately, the equivalent network model for an aperture-coupled microstrip patch antenna with a zero thickness ground plane[4] should be modified. For this purpose, the effects of the complex power flow into the lower and upper half spaces from apertures 1 and 2 are represented by admittances Y_f and Y_p, respectively. Since a cavity with two apertures is a two-port network, it can be modeled by an equivalent

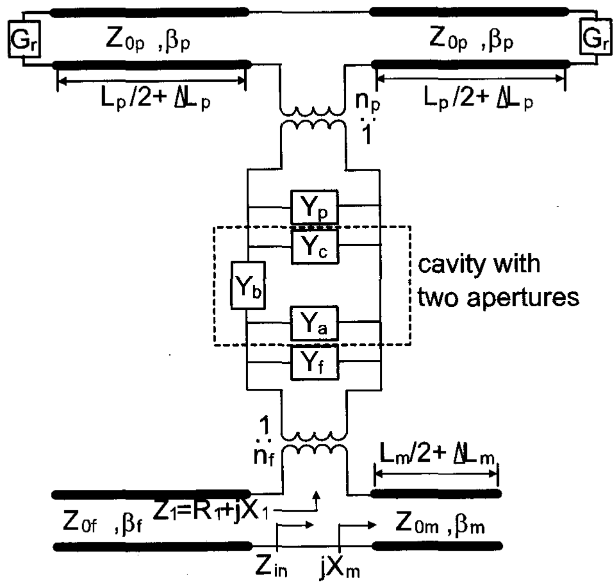

그림 2. 개구면 결합 공진기 급전 마이크로스트립 패치 안테나의 등가 회로

Fig. 2. equivalent circuit of an aperture-coupled cavity-fed microstrip patch antenna.

-network. Therefore the equivalent circuit of the antenna shown in Fig. 2 is obtained, and the remaining work is to find the related circuit parameters.

It is well known that coupling between the microstripline and aperture in the ground plane can be modeled by an ideal transformer, and turns ratio n_f can be calculated efficiently[4] with the following assumed aperture electric field:

$$e_y = \frac{\cos(\pi x / L_{a1})}{\pi \sqrt{(W_{a1}/2)^2 - y^2}} \qquad (1)$$

Since a complex power can be calculated from an equivalent magnetic current[5], the admittance looking into the lower half space from the aperture 1, Y_f, is expressed as

$$Y_f = \frac{-1}{4\pi^2 |V_s|^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \widetilde{G}_{xx}^{HM} |\widetilde{M}_x|^2 dk_x dk_y \qquad (2)$$

where $\widetilde{G}_{xx}^{HM}$ denotes the spectral-domain Green's function of magnetic field h_x due to the equivalent magnetic current density m_x, and $\widetilde{M}_x$ is the Fourier transform of m_x. With the spectral-domain immittance approach[6] and the Fourier transform relation, $\widetilde{G}_{xx}^{HM}$ and $\widetilde{M}_x$ are obtained as

$$\widetilde{G}_{xx}^{HM} = -\frac{k_x^2 Y_{TE} + k_y^2 Y_{TM}}{k_x^2 + k_y^2} \qquad (3)$$

$$\widetilde{M}_x = \frac{2\pi}{L_{a1}} \frac{\cos(k_x L_{a1}/2)}{(\pi/L_{a1})^2 - k_x^2} J_0\left(\frac{W_{a1}|k_y|}{2}\right) \qquad (4)$$

where Y_{TE} and Y_{TM} are the input wave admittances for the TE_z and TM_z modes, respectively, and $J_0(.)$ denotes the zero order Bessel function of the first kind. Applying the rectangular-to-polar coordinate transformation and the symmetry property of $\widetilde{G}_{xx}^{HM}$ and $|\widetilde{M}_x|^2$, Y_f can be numerically evaluated without difficulty with the help of the singularity extraction and the asymptotic extraction techniques. n_p and Y_p for patch side can be calculated similarly.

The rectangular cavity with two apertures in the antenna can be regarded as two aperture-to-waveguide sections in a back-to-back configuration. Considering the behavior of magnetic field in the waveguide h_{wx}, the Fourier series is chosen as

$$f(x,y) = \sum_{m=1}^{\infty} \sum_{n=0}^{\infty} F_{mn} \sin k_{xm}(x + a/2) \cos k_{yn}(y + b/2) \qquad (5)$$

where $k_{xm}=m/a$, $k_{yn}=n/b$, and F_{mn} is the Fourier coefficient of $f(x,y)$. With this choice and applying Parseval's theorem and some algebraic manipulations, Y_w, the input admittance looking into the waveguide from the aperture, is expressed as

$$Y_w = \sum_{m=1}^{\infty} \sum_{n=0}^{\infty} \left\{ (n_{mn}^{TE})^2 Y_{mn}^{TE} + (n_{mn}^{TM})^2 Y_{mn}^{TM} \right\} \qquad (6)$$

where

$$(n_{mn}^{TE})^2 = \frac{ab}{2\epsilon_n} |(\widetilde{M}_x)_{mn}|^2 \frac{k_{xm}^2}{k_{xm}^2 + k_{yn}^2} \qquad (7)$$

$$(\widetilde{M}_x)_{mn} = \frac{2\epsilon_n}{ab} \frac{2\pi}{L_{a1}} \frac{\cos(k_x L_{a1}/2)\sin(k_{xm}a/2)}{(\pi/L_{a1})^2 - k_x^2} J_0\left(\frac{W_{a1}|k_y|}{2}\right) \cos\left(\frac{k_{yn}b}{2}\right) \qquad (8)$$

and the expression of $(n_{mn}^{TM})^2$ is the same that of $(n_{mn}^{TE})^2$ with k_{xm} and k_{yn} interchanged. n=1 for n=0 and n=2 for n≠0. Because n_{mn}^{TE} and n_{mn}^{TM} can be considered as the turns ratios of the corresponding modes of the transformer, characteristics of each

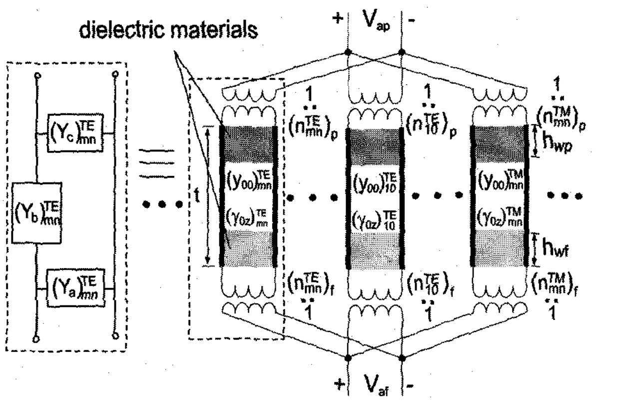

그림 3. 두 개의 개구면을 갖는 도파관의 등가회로
Fig. 3. Equivalent circuit of a cavity with two apertures.

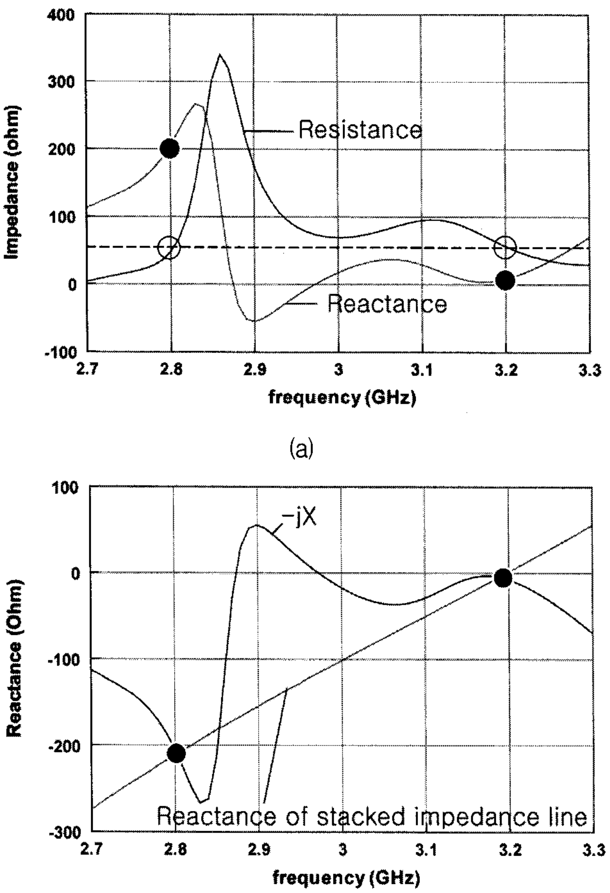

그림 4. 스터브 설계를 통한 이중 대역 임피던스 정합 개념

Fig. 4. Concept of dual-band impedance matching with stub design.

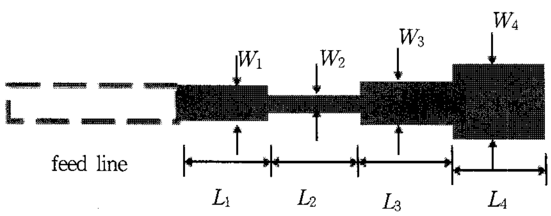

그림 5. 다 계단형 임피던스 선로

Fig. 5. Multi-section stepped impedance line.

mode of a waveguide can be modeled by the corresponding equivalent transmission line. Since the opposite section can be modeled similarly, the equivalent circuit of a cavity with two apertures shown in Fig. 2 is obtained.

The characteristics of the circuit with transformers and transmission lines in the box shown in Fig. 3 can be analyzed using the ABCD matrix formulation. From the obtained ABCD matrix, the admittance parameters of the equivalent -network shown in Fig. 3 are obtained by the network parameter conversion [7]. After applying this procedure to the other transmission line sections, all the parallel-connected π -networks obtained can be represented by one π -network. Therefore the equivalent circuit of the antenna shown in Fig. 2 is obtained. The related circuit parameter values can be found from the network analysis[4].

As a first step for the simple impedance matching of antenna, series impedance Z_1 (= R_1 + jX_1) is calculated, and the related structure dimensions are adjusted appropriately such that $R_1 = 50\,\Omega$. Then the remaining X_1 is canceled by reactance of feed-line stub X_f by adjusting its length as shown in Fig. 4. Especially on matching conditions at dual band frequencies, for design flexibility, multi-section stepped impedance line is good candidate. (Fig. 5)

Ⅲ. OPTIMIZED DESIGN METHOD

Many structural parameters are involved in the design of the aperture-coupled cavity-fed microstrip patch antenna.

The genetic algorithm[6] is well-known to be one of the powerful global optimization tools for the electromagnetic design works. Since it is based on the statistical search, it can provide not an optimal solution, but a close one. On the other hand, the NM method[8], a geometrical search method of minimax, is efficient in finding a local minimum of function of variables with the given initial values. Therefore the hybrid optimization method combining these algorithms as depicted in Fig. 6 is considered to be much efficient for the optimized design of the aperture-coupled cavity-fed microstrip patch antenna.

This algorithm starts with an initial set of randomly generated population, which consists of chromosomes whose elements are genes, that is, the population values to be optimized. Next, fitness values, which will be properly defined with the cost function, are computed for population. In this paper, these are defined as

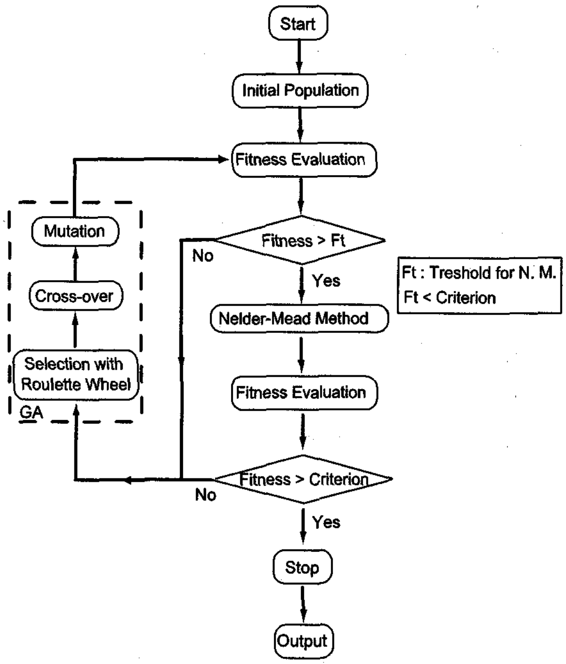

그림 6. 이종 GA의 흐름도

Fig. 6. Flow-chart of the hybrid genetic algorithm.

$$Cost = \sum_{f_1, f_2} \left(\frac{R_1}{50} - 1 \right)^2, \tag{9}$$

$$Fitness = \frac{1}{\sqrt{1 + Cost}}. \tag{10}$$

If the best fitness value does not meet the termination condition, the population is generated with crossover and mutation for the next generation in the conventional GA. Due to the statistical property of the conventional GA, a lot of generations are generally needed to meet the termination condition. In order to solve this kind of problem, the NM method is invoked for the efficient finding of the solution with the endorsed chromosomes with fitness value larger than the NM threshold as shown in the flow-chart (Fig. 5).

Ⅳ. Results and Discussion

To check the validity of the theory, the antenna treated in the published paper[3] was considered. The rectangular cavity is filled with a dielectric material with ε_{rw} = 10.2. The other parameters of the antenna are L_p = 32.50 mm, W_p = 27.50 mm, h_p = 1.60 mm, ε_{rp} = ε_{rf} = 2.2, L_{a1}= 12.00 mm, L_{a2} = 20.00 mm, W_{a1} = W_{a2} = b = 1.27 mm, a = 37.00 mm, t = 14.80 mm, W_f = 2.47 mm, h_f = 0.79 mm, and L_f = 17.40 mm. After the circuit parameters calculated, the input impedance was computed. The result is shown in Fig. 7 along with the published measured and calculated data[3]. Good agreements are observed.

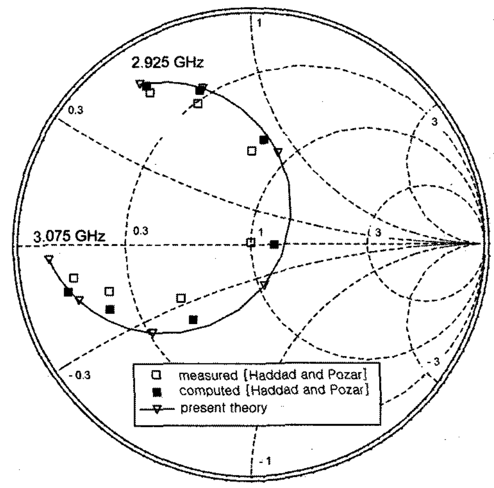

그림 7. 안테나의 입력 임피던스

Fig. 7. Input impedance of the antenna.

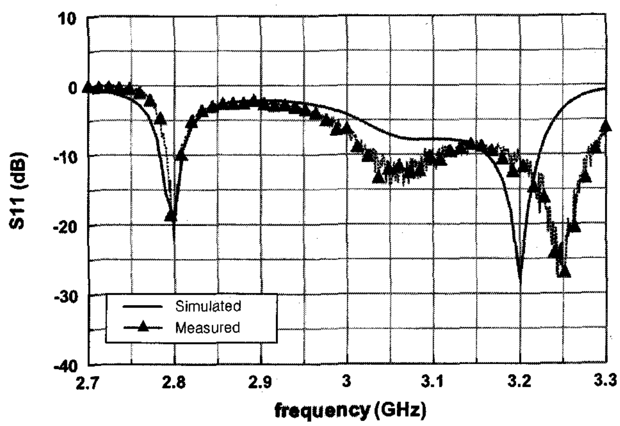

그림 8. 이중 대역 개구면 결합 공진기 급전 마이크로스트립 패치 안테나의 특성

Fig. 8. Characteristics of the dual-band aperture-coupled cavity-fed microstrip patch antenna.

Now with the above mentioned optimized design scheme, dual-band antenna was designed at 2.8 and 3.2 GHz. Substrate parameters are h_f = 31 mils, ε_{rp} = 2.2, h_p = 250 mils, and ε_{rf} = 2.2. The fixed and obtained design parameter values are shown in Table I. Fig. 8 shows the measured return loss of the designed antenna along with the calculated by the network model. A reasonable agreement was

표 1. 안테나 구조 변수
Table 1. Antenna parameters.

Fixed parameter [mm]		Design parameter [mm]	
W_f	2.40	L_p (=W_p)	27.80
W_{sf}	1.00	t	18.60
		L_{sp}(=a)	28.20
		L_{sf}	17.80
		b	25.00
		L_1	6.90
		L_2	10.30
		L_3	12.90
		L_4	6.90
		W_1	0.70
		W_2	4.00
		W_3	2.00
		W_4	6.00

observed, ant it shows the validity and efficiency of the proposed theory, equivalent circuit, and optimized design scheme.

V. Conclusions

With the developed equivalent circuit, an efficient and optimized design scheme of aperture-coupled cavity-fed microstrip patch antenna was proposed. For the verification of the equivalent circuit, the published design example was considered. The computed antenna input impedance from the proposed theory was compared with the measured, and good agreements were observed. For the further validation, a dual-band antenna was designed with the hybrid genetic algorithm, and the measured results agreed well with the given specifications. All the obtained results from the design examples show the accuracy and efficiency of the presented equivalent circuit and optimized design scheme.

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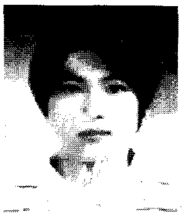
저 자 소 개



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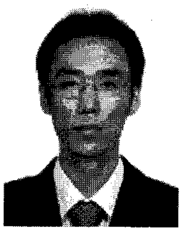

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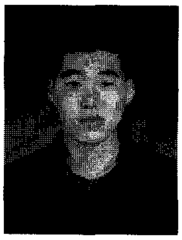

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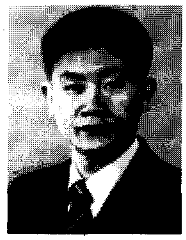

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