An Efficient Design Method of Microstrip Filtering Antenna Suitable for Circuit Synthesis Theory of Microwave Bandpass Filters

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***Abstract*—This paper proposes an efficient design method of filtering antennas, enabling to apply a well-established filter design theory to the antenna design. In the design of filtering antenna, an external Q factor at input port, coupling coefficients, and a radiation Q factor of antenna need to be evaluated. However, conventional design methods have a time-consuming procedure, since a time domain response from the overall structure is required for the evaluation of coupling coefficient between resonator and antenna. For an efficient design, we propose a parameter extraction technique using only amplitude property of input reflection responses for the evaluation of both the coupling coefficient and the radiation Q factor. As an example, a third-order filtering antenna is synthesized, designed, and tested, which numerically and experimentally validates the effectiveness of the proposed design method.**

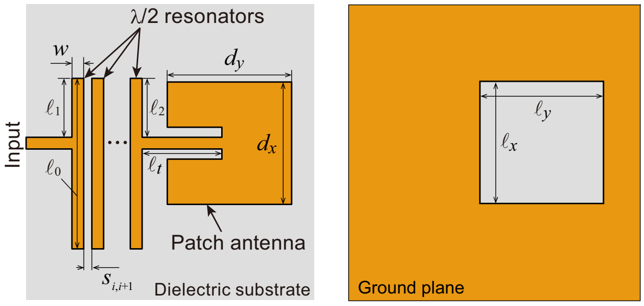
Keywords*—Filtering antenna, radiation Q factor, coupling coefficient, input reflection response.

I. INTRODUCTION

The filtering antenna is constructed by replacing the Nth resonator of an Nth-order bandpass filter with an radiation element [1]–[6]. In a specified frequency band, the filtering antenna has a radiation with a gain from the antenna, and can suppress return loss under a predetermined level. Thus, an antenna having a given frequency bandwidth can be designed without trial and error by enormous simulations that have been repeated in conventional antenna designs for bandwidth enhancement.

The difficulty of the design of filtering antennas lies in the evaluation of antenna characteristics in order to apply a well-established design theory of bandpass filters to filtering antenna designs. This is attributed to the fact that the antenna is a one-port device, unlike a two-port circuit of bandpass filter. To this end, several design methods of filtering antennas have been reported in recent years [3]–[6]. However, they are inefficient since a bandpass filter needs to be designed prior to a filtering antenna. In addition, a time domain response from the overall structure is required for the evaluation of coupling coefficient between the resonator and the antenna, thereby taking much calculation time.

To solve the problem, a simple and efficient design method of the filtering antenna is proposed in this paper. The key technique of the proposed design method is to extract the radiation Q factor of the antenna, and the coupling coefficient between the resonator and the antenna from only amplitude information of input reflection response. As a design example, we show here a 2.45-GHz microstrip filtering antenna, which realizes a flat gain, a good impedance matching in a specified 8% bandwidth, and radiation suppression out of the band. Finally, the designed filtering antenna is fabricated and tested for experimental verification.



(a) (b)

Fig. 1. Structure of a microstrip filtering antenna. (a) Top view and (b) bottom view.

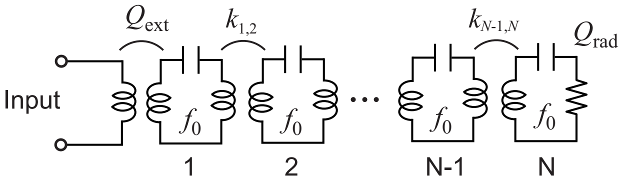


Fig. 2. Equivalent circuit model using coupling coefficients, external Q factor, and radiation Q factor.

II. STRUCTURE OF FILTERING ANTENNA

The microstrip filtering antenna in this paper is composed of a patch antenna and $(N{-}1)$ half-wavelength microstrip resonators on a dielectric substrate with the relative permittivity ε_r and the thickness t. The structure of the Nth-stage filtering antenna is illustrated in Fig. 1. The antenna has a rectangular patch of $d_x \times d_y$ with an aperture of $\ell_x \times \ell_y$ at the ground plane to control the radiation Q factor. The antenna is coupled to the $(N-1)$th resonator via a microstrip line with the length ℓ_t. Two adjacent microstrip resonators are coupled to each other with a gap $s_{i,i+1}$ $(i = 1, 2, \cdots, N-2)$.

The filtering antenna can be expressed with an equivalent circuit shown in Fig. 2. The antenna is represented by an LCR resonant circuit with the radiation Q factor Q_{rad} at the resonant frequency f_0, while the half-wavelength resonators are given by coupled LC resonant circuits with coupling coefficients $k_{i,i+1}$ and external Q factor Q_{ext}.

III. DESIGN METHOD OF FILTERING ANTENNA

A. Circuit Synthesis based on Filter Theory

As found from the equivalent circuit model, the filtering antenna can be designed by the evaluation of external Q factor Q_{ext} at the input port, coupling coefficients $k_{i,i+1}$ $(i = 1, 2, \cdots, N-2)$ between resonators, coupling coefficient $k_{N-1,N}$ between the $(N-1)$th resonator and the antenna, and radiation Q factor Q_{rad} of the antenna. These design parameters can be synthesized with a well-known theory for the design of bandpass filters in the following equations [7]:

$$Q_{\mathrm{ext}} = \frac{\Omega_c}{\mathrm{FBW}} g_0 g_1 \tag{1}$$

$$k_{i,i+1} = \frac{\mathrm{FBW}}{\Omega_c \sqrt{g_i g_{i+1}}} \quad (i=1,2,\cdots,N-1) \tag{2}$$

$$Q_{\mathrm{rad}} = \frac{\Omega_c}{\mathrm{FBW}} g_N g_{N+1} \tag{3}$$

where Ω_c is a normalized cutoff frequency in a lowpass frequency domain, normally set to 1; FBW represents a fractional bandwidth of a filtering antenna to be designed; g_i $(i = 1, 2, \cdots, N+1)$ are normalized circuit parameters determined from a specified in-band response.

B. Proposed Parameter-Extraction Technique

In the filtering antenna design, it is important to evaluate $k_{N-1,N}$ and Q_{rad} involved in the antenna. The proposed technique allows us to direclty extract $k_{N-1,N}$ and Q_{rad} from only amplitude property of input reflection response S_{11}.

First, the radiation Q factor Q_{rad} of the antenna is calculated from the loaded Q factor Q_{L} by

$$Q_{\mathrm{rad}} = Q_{\mathrm{L}}\,(1 + r_1) \tag{4}$$

In (4), the loaded Q factor Q_{L} of a single antenna, as shown in Fig. 3, is evaluated by

$$Q_{\mathrm{L}} = \frac{\omega_0}{\Delta\omega} \tag{5}$$

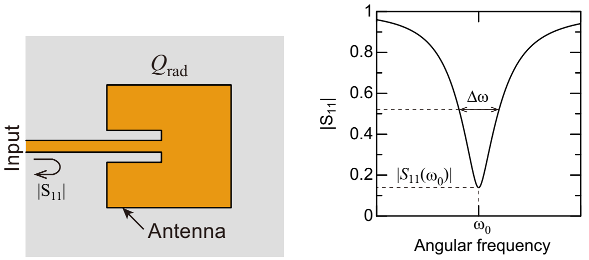
where ω_0 and $\Delta\omega$ denote a resonant angular frequency and a half-power bandwidth of $|S_{11}(\omega)|$, respectively. Also, r_1 in (4) is obtained from $|S_{11}(\omega_0)|$ of a single antenna as follows:

$$r_1 = \begin{cases} \dfrac{1+|S_{11}(\omega_0)|}{1-|S_{11}(\omega_0)|} & \text{(overcoulple)} \\[2ex] \dfrac{1-|S_{11}(\omega_0)|}{1+|S_{11}(\omega_0)|} & \text{(undercoulple)} \end{cases} \tag{6}$$

Next, the coupling coefficient $k_{N-1,N}$ between the $(N-1)$th resonator and the antenna can be calculated by

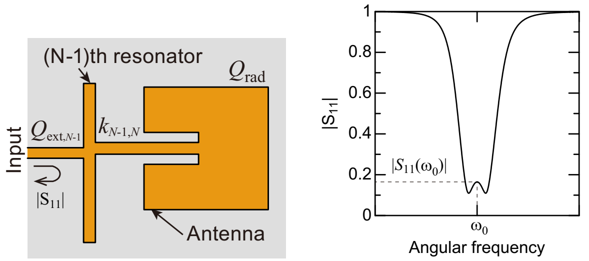
$$k_{N-1,N} = \frac{1}{\sqrt{r_2 Q_{\mathrm{rad}} Q_{\mathrm{ext},N-1}}} \tag{7}$$

which is analytically derived from the equivalent circuit model at the resonant frequency f_0. In (7), Q_{rad} is already obtained with (4). $Q_{\mathrm{ext},N-1}$ is an external Q factor to express the coupling between the $(N-1)$th resonator and the input line. This external Q factor is calculated in advance, and is used only for the calculation of (7). r_2 is given in the same expression as (6), but is for $|S_{11}(\omega_0)|$ of the structure shown in Fig. 4.



(a) (b)

Fig. 3. Evaluation of radiation Q factor Q_{rad}. (a) Structure for parameter extraction. (b) Example of input reflection response.



(a) (b)

Fig. 4. Evaluation of coupling coefficient $k_{N-1,N}$ between antenna and $(N-1)$th resonator. (a) Structure for parameter extraction. (b) Example of input reflection response.

The rest of design parameters are Q_{ext} and $k_{i,i+1}$ $(i = 1, 2, \cdots, N-2)$, which are evaluated with the same manner as the design of conventional microstrip bandpass filters [7].

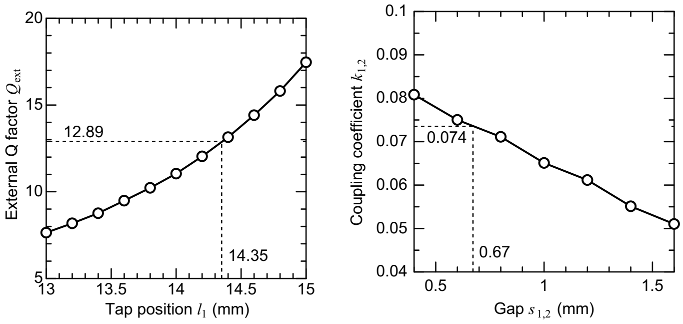
C. Design of Structural Parameters

The structural parameters of the filtering antenna can be designed using the abovementioned parameter-extraction technique. The patch antenna size $d_x \times d_y$ and the length ℓ_0 of microstrip resonators are determined to resonate at the center frequency f_0. The aperture size $\ell_x \times \ell_y$ is adjusted to acquire a required radiation Q factor Q_{rad}. Then, the coupling coefficient $k_{N-1,N}$ between the antenna and the $(N-1)$th resonator is controlled with the tap position ℓ_2 and the length ℓ_t so as to have a specified value. The coupling coefficient $k_{i,i+1}$ $(i = 1, 2, \cdots, N-2)$ and the external Q factor Q_{ext} are designed with the gap $s_{i,i+1}$ and the tap position ℓ_1, respectively. When a specified impedance-matching response can be realized, the design of the filtering antenna is finished.

IV. DESIGN EXAMPLE

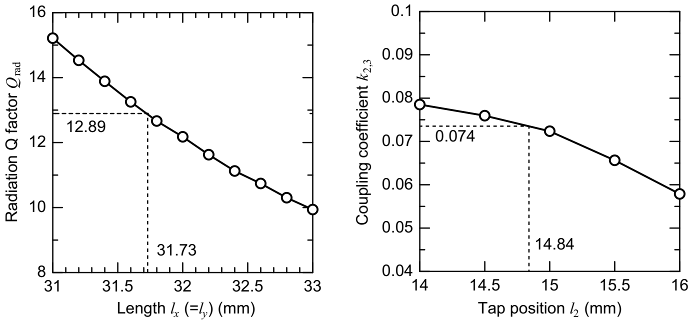
A. Design Specifications

As an example, a microstrip filtering antenna is designed with the proposed design method under the following specifications.



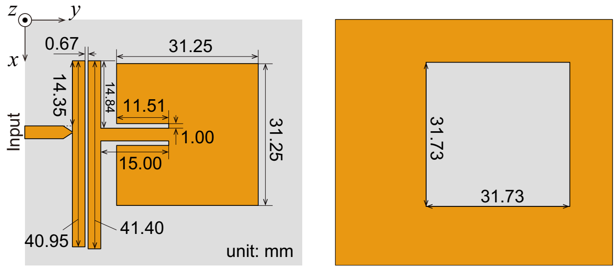
(a) (b)

Fig. 5. Design of structural parameters for microstrip resonators. (a) External Q factor $Q_{\rm ext}$ and (b) coupling coefficient $k_{1,2}$ between two microstrip resonators.



(a) (b)

Fig. 6. Design of structural parameters related to the antenna. (a) Radiation Q factor $Q_{\rm rad}$. (b) Coupling coefficient $k_{2,3}$ between resonator and antenna.



(a) (b)

Fig. 7. Structure of the designed filtering antenna (unit: mm). (a) Top view and (b) bottom view.

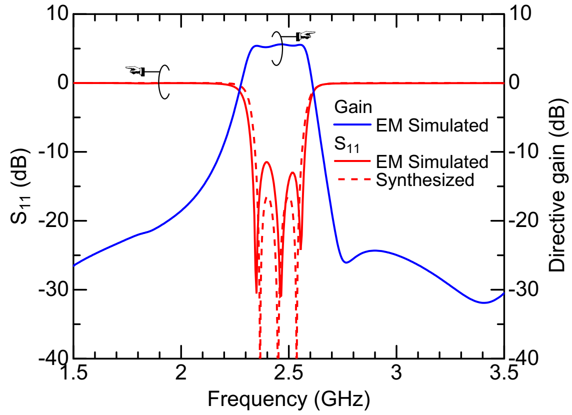


Fig. 8. Frequency characteristics of gain considering only a mismatch loss and S_{11} of the designed filtering antenna (material losses are not included).

- Center frequency: $f_0 = 2.45$ (GHz)
- Fractional bandwidth: FBW= 8 %
- Transfer function: third-order 0.1dB-ripple Chebyshev response

The external Q factor $Q_{\rm ext} = 12.89$, the coupling coefficients $k_{1,2} = k_{2,3} = 0.074$, and the radiation Q factor $Q_{\rm rad} = 12.89$ are obtained from the above design specifications based on the filter theory. The structural parameters of the filtering antenna shown in Fig. 1 are designed on the dielectric substrate with $\varepsilon_r = 2.6$ and the thickness $t = 1.0$ (mm) so that these ideal values can be obtained.

B. Design Results

Based on a filter design technique, the structural parameters of microstrip resonators 1 and 2 are designed as shown in Fig. 5. The tap position of the input line with respect to the microstrip resonator 1 is determined to realize the external Q factor $Q_{\rm ext} = 12.89$, while the gap between the two resonators 1 and 2 is found to be 0.67 mm for $k_{1,2} = 0.074$.

The structural parameters related to the antenna are designed by the proposed technique described in Section III-B. As demonstrated in Fig. 6, The radiation Q factor $Q_{\rm rad}$ can be adjusted by the aperture size $\ell_x (= \ell_y)$ at the back of the antenna. The coupling coefficient $k_{2,3}$ between the resonator 2 and the antenna can also be controlled with the tap position ℓ_2. It can be found from Figs. 6(a) and (b) that the ideal values of $Q_{\rm rad} = 12.89$ and $k_{2,3} = 0.074$ are obtained when $\ell_x = 31.73$ (mm) and $\ell_2 = 14.84$ (mm), respectively.

Figure 7 shows the designed structure of filtering antenna after a fine tuning of the resonator length ℓ_0. The frequency characteristics of the maximum directive gain of co-polarization and the reflection response $|S_{11}|$ are plotted in Fig. 8. Note that the gain in Fig. 8 includes a mismatch loss, but excludes material losses. In the specified frequency band, three reflection zeros are clearly observed in the electromagnetic (EM) simulation results obtained by a commercially available EM simulator HFSS. The frequency characteristic of the gain shows a sharp filtering response like a bandpass filter by introducing a bandpass filter technology to the antenna design.

C. Measurements

To verify experimentally the effectiveness of the designed method, the filtering antenna is fabricated and tested. The photograph of the fabricated antenna is given in Fig. 9.

In Fig. 10, the frequency characteristics of the measured absolute gain and the reflection coefficient are compared to the EM simulated ones taking into account material losses (copper conductivity $\sigma = 58 \times 10^6$ (S/m) and dielectric loss $\tan\delta = 1.4 \times 10^{-3}$). The both results show good agreement in the measured frequency range, although the frequency shift toward a lower frequency side is caused by a difference of dielectric constant between actual and nominal values. The

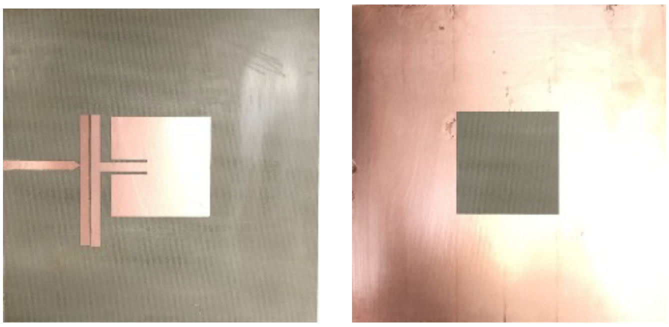

(a) (b)

Fig. 9. Photograph of the fabricated microstrip filtering antenna. (a) Top view and (b) bottom view.

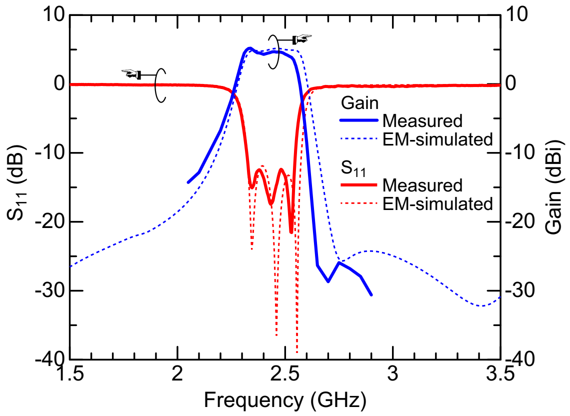


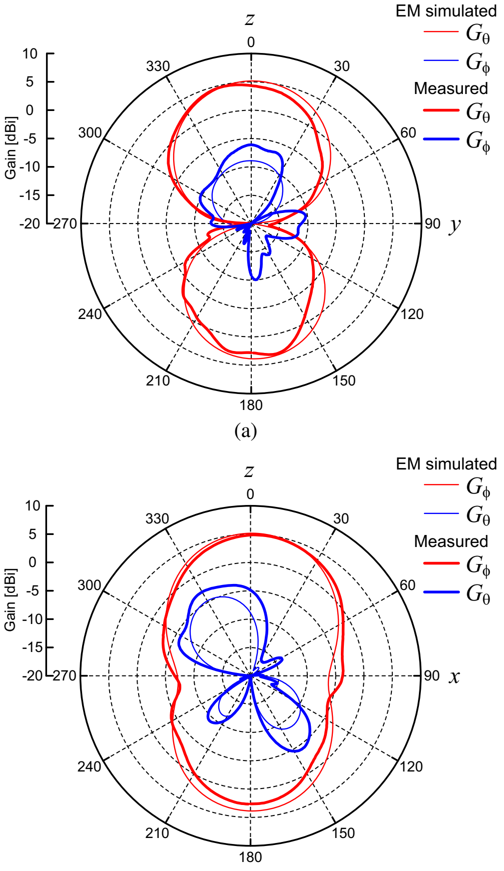
Fig. 10. Measured frequency characteristics of gain and S_{11} of the fabricated filtering antenna in comparison with EM-simulated ones including material losses.

measured gain is 4.6 dBi at the center frequency f_0, and the gain in band is kept almost constant within an acceptable small deviation. In addition, the measured gain achieves a rapid roll-off characteristic out of the band, which leads to the suppression of unwanted radiation.

Finally, the measured radiation patterns of E- and H-planes are compared to EM simulation results at 2.45 GHz. The good agreement between both results are also confirmed in Fig. 11. It can be concluded from the comparison in Figs. 10 and 11 that the proposed design method are effective for the design of filtering antennas.

V. CONCLUSIONS

In this paper, a new and efficient design method using only amplitude property of input reflection responses has been proposed so that a filtering antenna can be designed based on a design theory of bandpass filters. A 2.45 GHz filtering antenna having 8% bandwidth and a flat in-band gain of 4.6 dBi in the measured results has been successfully realized. Finally, it has been shown that the measured frequency characteristics of the gain and the reflection coefficient agree well with the EM simulated ones, thereby proving the validity of the proposed design method.



(a)

(b)

Fig. 11. Comparison of radiation patterns between EM simulated and measured results at 2.45 GHz. (a) E-plane and (b) H-plane.

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