정보통신설비학회 논문지 2권 1호 (2003. 2)

Circuit Modeling of Transition from Stripline to Dual Slotline for the Notch Antenna

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ABSTRACT

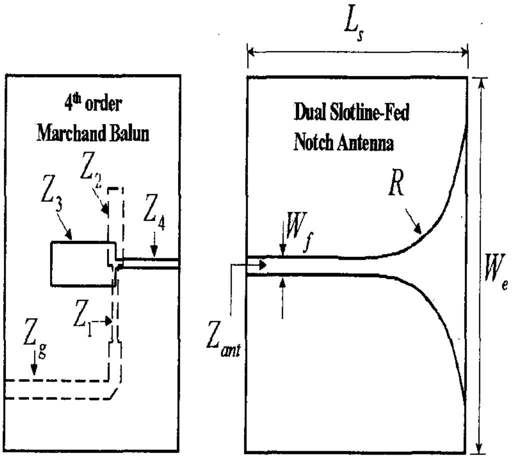
A circuit model for the transition of stripline to dual slotline and a segmented method to analyze a notch antenna are presented. For the circuit model of the transition, the characteristic impedance, dispersions, and the shorted impedance of dual slotline are calculated and approximated with the closed-form expressions. The segmented analysis method allows to get readily an optimized results for the dual slotline-fed notch antenna. As a design example, a notch antenna is segmented into a 4th order Marchand balun and a dual slot fed notch antenna, and tested to show the validity of the proposed circuit model.

요 약

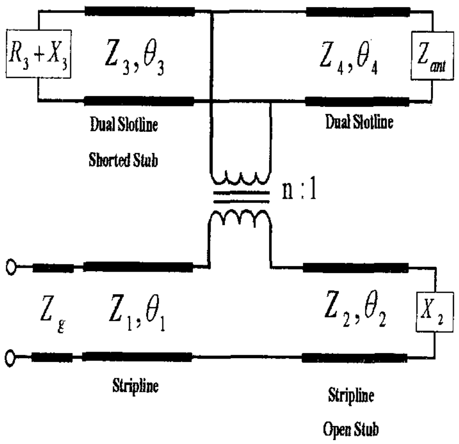
스트립라인/이중슬롯라인 변환구조에 대한 등가회로모델과 넛치 안테나를 해석하기 위한 segmented method를 제시하였다. 변환구조에 대한 등가회로 모델을 구축하기 위하여 이중슬롯라인에 대한 특성 임피던스, 분산특성과 단락 임피던스에 대한 계산을 통하여 해석적인 해로 근사화하였다. Segmented method는 이중슬롯라인 급전 넛치 안테나의 최적 설계를 구현하기 용이하게 해준다. 설계 예제로 넛치 안테나를 4차 Marchand 밸룬과 이중슬롯라인 급전 넛치 안테나로 분할하여 해석하였으며, 제안된 등가회로모델과 비교하여 타당성을 검증하였다.

I. Introduction

Notch antenna has long been studied and used as a wideband radiator with a single element or array elements [1], [2]. Since a microstrip-to-slotline transition has the disadvantage of having a radiating microstrip feeder, the strip-to-dual slotline transition with a non-radiating strip feeder has usually been used for the notch antenna. The dual slotline has relatively less dispersion and lower characteristic impedance than single-sided slotline for the same slot width, which gives an advantage for the fabrication of narrow slot [3], [4]. The circuit model for the microstrip-to-slotline transition is well known in [5] with analytical formulas, however not yet for the strip-to-dual slotline transition.



[Fig. 1] Segmented notch antenna consisting of a 4th order Marchand balun and a dual slotline-fed notch antenna



[Fig. 2] Equivalent circuit for the segmented notch antenna

In order to design the notch antenna systematically not by a cut-and-trial method, a segmented analysis method and a circuit model for the transition of stripline to dual slotline are presented in this paper. For the circuit model of the transition, the characteristic impedance, dispersions, and the shorted impedance of dual slotline are calculated and approximated with the closed-form expressions. The 4th order Marchand balun as a segmented two-port circuit is analyzed using those analytic equations. To get the synthesized element values of the balun, the antenna impedance should be a real constant [6]. Therefore, the dual slotline-fed notch antenna was optimized to have the constant real values of the antenna impedance with a small variation in the design frequency range.

Ⅱ. Characterization of Transition

The segmented notch antenna consisting of a 4th order Marchand balun and a notch antenna fed dual slotline is shown in [Fig. 1] The equivalent circuit for the segmented notch antenna is shown in [Fig. 2] The balun circuit as a two-port circuit consists of two striplines with Z_1 and Z_2, an open-ended strip reactance X_2, and two dual slotlines with Z_3, Z_4, a shorted slotline impedance R_3 and X_3, turns-ratio of transformer n, and has an antenna input impedance Z_{ant} as a load. The dual slotline-fed notch antenna as one port circuit has the exponentially tapered slot shape. Here, R is the exponential opening rate, L_s is the length of the tapered slotline, and W_f and W_e are the widths of the dual slotline feeder and the antenna aperture as defined in [2].

In order to characterize the circuit elements, the time domain solver was used. The dispersion characteristics of dual slotline and stripline, and the end effect of a shorted slotline and an open-ended stripline are calculated, varying the width of strip or slot from 0.1mm to 20mm. In this work, the parameters for the substrate are fixed with thickness d = 3.2mm and its dielectric constant ε_r = 2.2.

[Fig. 3](a) shows the characteristic impedance of dual slot increases with the slot width as well known in [3], [4], but that of strip decreases with the strip width.

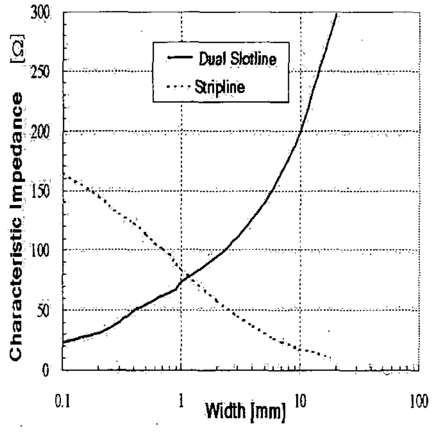
[Fig. 3](b) shows the dispersion characteristic of dual slot where the effective dielectric constant decreases with the slot width. In [Fig. 3](c), we can see the short end in a dual slot is not purely reactive, and the resistance and reactance are the same order as those of single-sided shorted slotline [5]. It was found that the resistance increases with the slot width, and have the linear frequency dependency. In this work, the resistance value is calculated at the design center frequency of 4GHz, and the frequency dependency is considered Since the strip line has a non-dispersive characteristic and the open-ended strip has a nearly non-radiative characteristic, the effective dielectric constant for the strip is fixed at ε_r = 2.2, and only the reactance of the open-ended strip is considered, but these numerical results are not shown here in this figure. The turns-ratio n of the transformer between stripline and slotline can be decided using the closed form equations in [7], which has a frequency dependency with the widths of strip and slot.

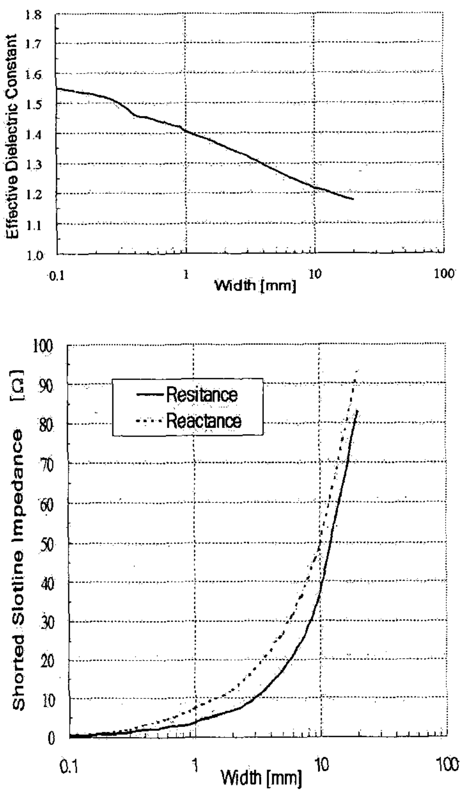
Ⅲ. Analysis of Balun

Using the numerical results for the circuit elements of the balun in [Fig. 2], these parameters are approximated by synthesis and analysis formula as following exponential polynomials.

$$W_{DS,ST} = e^x, \text{ where } x = \sum_{i=0}^{4} X_i\{\ln(Z_0)\}^i \quad (1)$$

$$Z = e^y, \text{ where } y = \sum_{i=0}^{4} Y_i\{\ln(W_{DS,ST})\}^i \quad (2)$$





[Fig. 3] (a) Characteristic impedance of stripline and dual slotline.

(b) Dispersion characteristics of dual slotline.

(c) Resistance and reactance of shorted dual slotline; $\varepsilon_r = 2.2$ and d = 3.2mm.

In the synthesis formula (1), $W_{DT,\,ST}$ denotes the width of dual slot or strip, and Z_0 the characteristic impedance of slot or strip, and with these closed-form expressions, the physical width of strip or slot can be determined. In the analysis equation (2), Z represents the resistance or reactance or effective dielectric constant according to the strip or slot width. These polynomial coefficients for the circuit elements are summarized in <table 1>.

In order to design the 4th order Marchand balun in [Fig. 2], the load impedance should be real and constant, but the antenna impedance of notch has a variation with the frequency due to the finite taper length and aperture size. However if we get the antenna impedance which is real and nearly constant with a small variation, the values Z_1, Z_2, Z_3, and Z_4 in the equivalent circuit can be decided using the synthesis formula in [6].

Using the $ABCD$ transmission parameter, the overall T_B matrix of the balun as a two-port circuit can be obtained by following expression:

$$T_B = T_1 \cdot T_2 \cdot T_3 \cdot T_4 \tag{3}$$

where $T_{1,4} = \begin{bmatrix} \cos\theta_{1,4} & jZ_{1,4}\sin\theta_{1,4} \\ jY_{1,4}\sin\theta_{1,4} & \cos\theta_{1,4} \end{bmatrix}$

$$T_n = \begin{bmatrix} n & 0 \\ 0 & n \end{bmatrix},\ T_2 = \begin{bmatrix} 1 & Z_2^{in} \\ 0 & 1 \end{bmatrix},\ T_3 = \begin{bmatrix} 1 & 0 \\ Y_3^{in} & 1 \end{bmatrix}$$

The serial and parallel impedance Z_2^{in}, Y_3^{in} for the open end and shorted stubs are expressed as follows:

$$Z_2^{in} = Z_2 \frac{-jX_2 + jZ_2 \tan\theta_2}{Z_2 + X_2 \tan\theta_2} \tag{4}$$

$$Y_3^{in} = Y_3 \frac{Z_3 + j(R_3 + jX_3)\tan\theta_3}{(R_3 + jX_3) + jZ_3 \tan\theta_3} \tag{5}$$

In the above equations, θ is the electrical length of each element at the operating frequency.

The overall Scattering matrix S_B for the balun which has different two-ports impedance is then readily obtained as follows:

$$S_B=\sqrt{Y_o}(Z_B-Z_o)(Z_B+Z_o)^{-1}\sqrt{Z_o} \qquad (6)$$

where $Z_B=\begin{bmatrix} A/C & (AD-BC)/C \\ 1/C & D/C \end{bmatrix}$,

$Z_o=\begin{bmatrix} Z_g & 0 \\ 0 & Z_f \end{bmatrix}$, $Y_o=Z_o^{-1}$, Z_0 and Z_f are the characteristic impedances of the generator and antenna feeder ports.

Ⅳ. Performance Evaluation

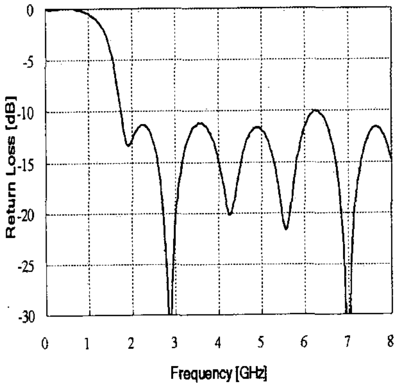
The segmented analysis method with the circuit model discussed in the previous section is applied to the design of a wideband notch antenna with the 4th order Marchand balun that has the 4:1 bandwidth at the center frequency of 4GHz.

<Table 1> Polynomial Coefficients for the Equations of Analysis (1) and Synthesis (2) Formula.

i	0	1	2	3	4
X$_i$ (W$_{DS}$)	-26.458	22.580	-8.5354	1.5144	-0.0970
X$_i$ (W$_{ST}$)	-15.306	24.886	-11.953	2.4096	-0.1812
Y$_i$ (ε_{eff})	0.3422	-0.0555	-0.0055	0.0006	0.0002
Y$_i$ (X$_2$)	7.206	-0.6726	-0.0807	0.0031	-0.0001
Y$_i$ (R$_3$)	1.3268	0.9617	-0.0339	0.0083	0.0041
Y$_i$ (X$_3$)	1.9814	0.9457	-0.1048	0.0072	0.0062

<Table 2> the Characteristic Impedance and their Physical Values for the 4^{th} Order Marchand Balun; BW=4:1, f_c= 4GHz, Z_{ant}= 60Ω, and Z_g= 50Ω

i	1	2	3	4
Z_i [Ω]	52.6	16.2	184.9	56.9
W_i [mm]	2.39	11.47	9.01	0.58
L_i [mm]	12.64	11.87	14.42	15.58
δL_i [mm]	-	0.77	2.49	-



[Fig. 4] Return loss of the optimized dual slotline-fed notch antenna; W_e = 62 mm, L_s = 72.6 mm, R = 0.113 mm^{-1}, W_f = 1.2 mm, ε_r = 2.2 and d = 3.2mm.

In order to design the balun as a feeder of notch antenna, the antenna impedance should be real and constant. Therefore, the dual slotline-fed notch antenna was optimized with a design goal where the return loss of antenna is less than -10dB above 1.8GHz, and the result was shown in the [Fig. 4] And the optimal shape of antenna was obtained where the antenna aperture W_e is 62mm, the taper length L_s

is 72.6mm, the exponential opening rate R is 0.113 mm^{-1}, and the slot width W_f of the antenna feeder is 1.2mm.

To get the variation of antenna impedance as a load impedance of the balun, the antenna input impedance Z_{ant} is given by the following equation:

$$Z_{ant} = Z_f \frac{1+\Gamma_{ant}}{1-\Gamma_{ant}} \tag{7}$$

In [Fig. 5], the antenna resistance is nearly constant about 60±20 Ω and the reactance is about 0±20 Ω above 1.8GHz in case the port characteristic impedance Z_f is 72.5 Ω. The element characteristic impedances for the 4th order Marchand balun are obtained using the synthesis equations in [6], the averaged antenna impedance Z_{ant} of 60 Ω and a generator impedance of 50 Ω. To get the physical values for the circuit elements, each width W_i and quarterwave length L_i of stripline and dual slotline is obtained by the formulas (1) and (2), and these results are summarized in the <table 2>.

In order to compensate the extended length of the open-ended stripline stub due to the fringing field at the end of strip and that of the shorted dual slotline stub due to the current flows around the end of the slot, the physical lengths in the <table 2> are calculated as following equations:

$$L_{2,3} = \lambda_o/\sqrt{\varepsilon_{eff}^{W_{2,3}}}/4 - \delta L_{2,3} \tag{8}$$

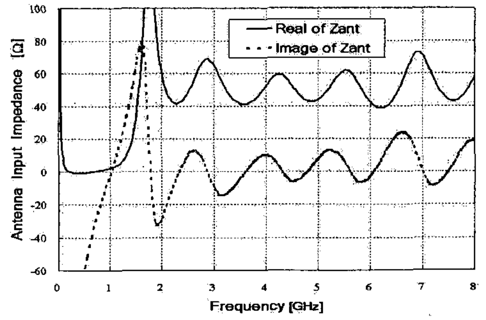
where $\delta L_2 = \dfrac{1}{\beta_2 \tan^{-1}(X_2 Z_2)}$,

$$\delta L_3 = \frac{1}{\beta_3 \tan^{-1}(X_3/Z_3)}$$

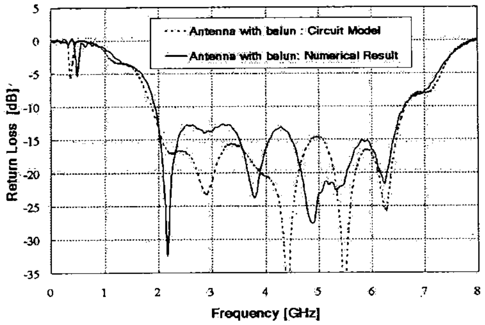
Using the scattering parameters in (6) and the reflection coefficient of the antenna Γ_{ant}, the overall scattering parameter S_{11}^T for the notch antenna with the balun can be represented by

$$S_{11}^T = S_{11}^B + \frac{S_{12}^B S_{21}^B \Gamma_{ant}}{1 - S_{22}^B \Gamma_{ant}} \tag{9}$$

The results obtained from the circuit model and the numerical simulation for the physical parameters in the <table 2> are shown in [Fig. 6]. Comparing the results, the equivalent circuit model provides a reasonable result in return loss and bandwidth, but there are some disagreements in the passband due to the tapered shape of the strip and slot stubs at the junction of the transition. From the above results, it was found that the shorted resistance R_3 causes the null points at about 0.5GHz, and the bandwidth is very sensitive to the lengths of δL_2 and δL_3.



[Fig. 5] The optimized result of antenna input impedance.



[Fig. 6] Return loss of the notch antenna with balun.

V. Conclusion

A segmented analysis method with a circuit model for the transition from stripline to dual slotline has been presented. Using the numerical results for the dual slotline and discontinuities, the synthesis and analysis formula are accomplished. The proposed circuit model has been applied to the study of segmented notch antenna with the 4th order Marchand balun. The results show the good agreement with the numerical simulation. With this circuit model and its related formulas, the notch antenna can be easily designed without tediously long numerical simulations. Application of this segmented analysis method to the notch array antenna is currently under development.

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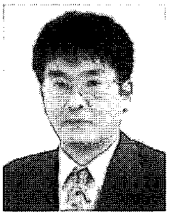

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