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# Perfectly-Matched DC Blocks Terminated in Arbitrary Impedances

# 임의의 종단 임피던스를 갖는 DC Block의 완전 정합

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## Abstract

Design equations of DC blocks terminated in arbitrary impedances are newly suggested and a microstrip DC block is tested for the perfect matching. The DC block is a two-port passive component and the power excited at a port is transmitted into another port. However, all the excited power at the input can not be delivered to the output and therefore most of the conventional DC blocks can not be perfectly matched with arbitrary termination impedances. To solve the matching problem, its one-port equivalent resonant circuit model, from which design equations can be derived, is newly suggested. Using the derived design equations, any DC block can be designed, perfectly matched without any restriction of coupling coefficients. To verify the derived design equations, measurements were carried out and the results are in good agreement with prediction, showing insertion and return losses at 4.1 GHz are 0.82 dB and −31 dB, respectively.

## 요 약

임의의 종단 임피던스를 갖는 DC block을 정합하기 위한 새로운 설계식이 소개되었으며, 이 설계식을 이용한 microstrip DC block이 제작, 측정되었다. 기존의 DC block은 완전히 정합되지 않았기 때문에, 한 단자에서 여기된 power가 다른 단자로 모두 전달되지 않는 문제점이 있었다. 이런 문제점을 해결하기 위하여, 한 단자의 등가 공진기 회로를 제시하였으며, 이 등가회로를 이용하여, coupling coefficient에 관계없이, 어느 경우에도 완전 정합을 이룰 수 있는 설계식을 유도했다. 이 설계식을 이용하여 측정된 microstrip DC block의 삽입, 반사 손실은 중심 주파수 4.1 GHz에서 0.82 dB, −31 dB를 보였으며, 이 측정 결과는 예상된 결과와 잘 일치함을 보여주고 있다.

Key words : DC Blocks Terminated in Arbitrary Impedances, Impedance-Transforming Directional Couplers, Equivalent Resonant Circuit Model of DC Blocks, Impedance-Transforming DC Blocks

## Ⅰ. Introduction

The parallel coupled transmission lines have been applied for microwave components like directional couplers, filters, wideband ring hybrids, phase shifters, power samplers and multiplexers.

The first directional coupler was reported in 1922[1] and significant progress was made during the 1940s and 1950s[2],[3]. In the 1960s and 1970s, numerous papers[4]~[11] extended the theory, and their application and development have continued[12]. However, all the conventional theories and developments can be applied only for equal termination impedances even with asymmetric structures[11],[12]. Very recently, design equations of impedance-transforming directional couplers were first derived[13]. If the passive components are terminated in

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arbitrary impedances, the total size of microwave integrated circuits can be reduced.

The study of asymmetric passive components with arbitrary termination impedances first started with asymmetric ring hybrids in 1994[14] and other asymmetric components including branch-line hybrids, three-port power dividers, phase shifters, attenuators and impedance transformers were investigated during the last 10 years[15]~[20].

In this paper, the distributed type of DC block terminated in arbitrary impedances will be discussed as an additional asymmetric passive component. DC blocks are used to isolate the bias voltages applied to various circuits as well as to block DC(Direct Current) and low-frequency voltages while permitting RF(Radio Frequency) signal to flow through the DC block with minimal loss. At microwave frequencies, both a high-quality capacitor and a distributed type of DC block consisting of a pair of coupled-transmission lines are used for blocking DC and low-frequency voltages.

The distributed type of DC blocks terminated in arbitrary impedances have been discussed in two references[21],[22]. However, in [21], the coupling coefficient is proportional to square root of the impedance transformation ratio, by which the coupling coefficient can be greater than unity. In [22], Chebysheve-like and Butterworth-like responses of the DC blocks were suggested. However, even though both responses are effective only for equal termination impedances, the Chebysheve-like response was mentioned for the application to arbitrary termination impedances. This will be discussed later in more detail.

The DC blocks terminated in arbitrary impedances can be obtained by terminating two of four ports of impedance-transforming directional couplers in opens. Therefore, the DC block is a two-port component and the power excited at one port is transmitted into another port and how much power can be delivered depends on the coupling structure. Due to the reason, most of conventional DC blocks with arbitrary termination impedances can not be perfectly matched even at a design center frequency. To solve the matching problem, an equivalent resonant model, from which design equations can be derived, is newly suggested. Using the derived design equations, any DC block can be designed, perfectly matched without any restriction of coupling coefficients. To verify the design equations, a microstrip DC block is fabricated and measured at a center frequency of 4 GHz.

## Ⅱ. Impedance-Transforming Directional Couplers

Fig. 1 shows an impedance-transforming directional coupler symmetrically terminated in arbitrary real impedances. When $\Theta$=90°, the power excited at port ① is coupled to port ② with a certain coupling power, while the remainder of the input power is delivered to port ④. Theoretically, no power is delivered to port ③, which is called an isolated port. In this case, the even- and odd-mode impedances[13] are

$$Z_{0e} = \sqrt{Z_r Z_L}\sqrt{\frac{1+C}{1-C}}, \tag{1a}$$

$$Z_{0o} = \sqrt{Z_r Z_L}\sqrt{\frac{1-C}{1+C}}, \tag{1b}$$

where $C$ is a coupling coefficient.

For the impedance-transforming directional couplers, the following relations hold:

$$C = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}}, \tag{2b}$$

$$Z_{0e} Z_{0o} = Z_r Z_L, \tag{2b}$$

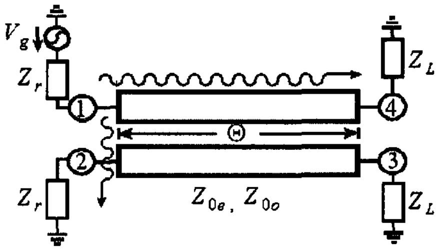


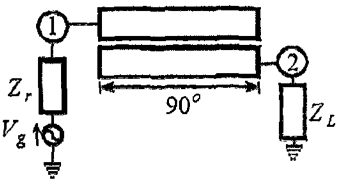
Fig. 1. Impedance-transforming directional coupler with arbitrary termination impedances $Z_r$ and $Z_L$.

If $Z_L=Z_r=Z_0$ in (1) and (2), they are well known design equations of directional couplers terminated in equal impedances, $Z_0$[2],[5],[21].

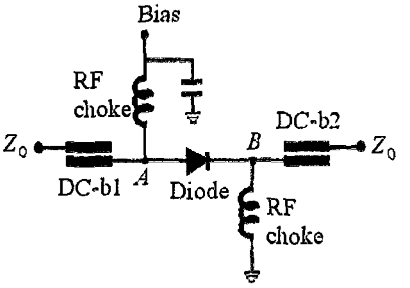
## Ⅲ. Application and Importance of DC Blocks with Arbitrary Termination Impedances

The distributed type of DC block terminated in arbitrary impedances is obtained from the impedance-transforming directional coupler in Fig. 1 by terminating ports ② and ④ in opens and used to block DC(Direct Current) in various active components comprising diodes or transistors. At the operating frequency, the length of the DC block is 90° for the minimum insertion loss. The DC block and its application to a single-pole, single-throw RF switch are shown in Fig. 2(a) and (b), respectively.

The RF switch Fig. 2(b) consists of input and output DC blocks(DC-b1 and DC-b2), at least one diode and bias circuits. The RF diode operates as a RF on-off switch when switched between a fixed forward bias and a reverse bias. Under the forward bias, the diode offers a very low impedance, thus approximating a short circuit(on state), and under reverse bias, it offers a very high impedance, approximating an open circuit(off state). Under the on-state, the input impedance of the diode at point $A$ in Fig. 2(b) is very small and generally complex, which should be transformed into the termination impedance of the DC block(DC-b1) at point $A$. In this case, if the DC-b1 can transform a real impedance into another real impedance, only one stub is needed more for the perfect input matching between diode and DC-b1 and the stub can be used as a RF-choke. Therefore, if the DC blocks are terminated in arbitrary impedances, the RF-switch is designed with very simple circuitry and big advantage to reduce total size of an electronic equipment, which requires many switches, can be expected.



(a) DC block



(b) RF switch

Fig. 2. DC block and its application to a RF switch.

If the termination impedances of the DC blocks are fixed at 50 Ω, additional matching network between the diode and the DC-b1 are needed and its resulting total circuit becomes complex.

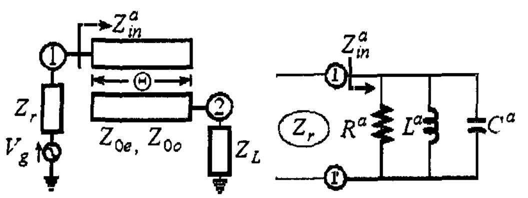
## Ⅳ. DC Blocks Terminated in Arbitrary Impedances

Terminating two ports of the directional coupler in Fig. 1 in two opens results in the DC block shown in Fig. 3(a), where the input impedance $Z_{in}^{a}$, looking into the coupled transmission lines terminated in $Z_L$ at port ②, is indicated.

To discuss conventional DC blocks in [22], Table 1 gives the normalized even- and odd-mode impedances, $z_e$ and $z_o$ of the Chebysheve-like response presented in [22]; $S$, $B_r$, $\Omega_C$ are the standing wave ratio, the bandwidth and its cotangent value, respectively. Based on Table 1, three DC blocks were designed at a design center frequency of 1 GHz and simulated using an ADS(Advanced Design System) circuit simulator. The

Table 1. Design example of Chebysheve-like response suggested in [22].

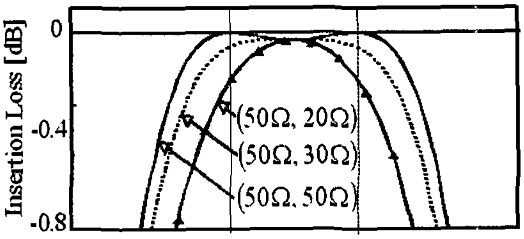
| $S$=1.19, $B_r$=0.4,<br>$\Omega_c$=cot[$\pi$/2(1 − $B_r$/2)] | | | |
|---|---|---|---|
| $z_e$=3.3<br>$z_o$=1.119 | $Z_r$=50 Ω<br>$Z_L$=50 Ω | $Z_r$=30 Ω<br>$Z_L$=50 Ω | $Z_r$=20 Ω<br>$Z_L$=50 Ω |
| $Z_{0e}$ | 165.0 Ω | 127.80 Ω | 104.36 Ω |
| $Z_{0o}$ | 55.95 Ω | 43.34 Ω | 35.39 Ω |



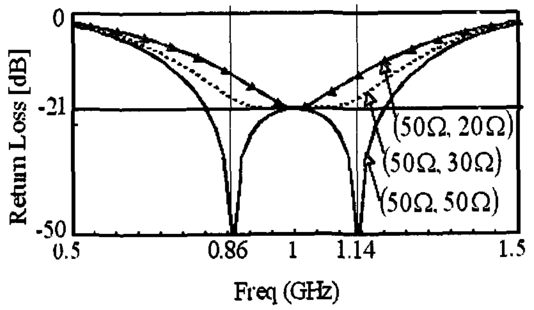
(a) DC block terminated in arbitrary impedances

(b) One-port equivalent resonant circuit

Fig. 3. DC blocks.



(a) Insertion losses



*(b) Return losses(Matching performances)*

Fig. 4. Simulation results of the Chebysheve-like responses[22] that depend on the termination impedances.

simulation results are plotted in Fig. 4, where insertion and return losses are in Fig. 4 (a) and (b), respectively, and termination impedance pairs are indicated in the parentheses. Fig. 4 demonstrates that the DC block with equal termination impedances shows ripples and perfect matching but that the others with different termination impedances do not. Therefore, the Chebysheve-like responses suggested in [22] are also effective only for equal termination impedances.

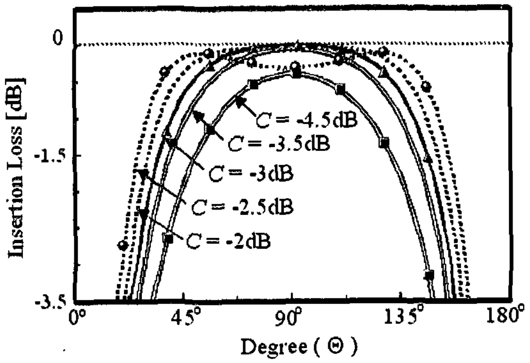
The two-port DC block can be obtained by terminating ports ② and ④ of the directional coupler in Fig. 1 in opens. Therefore, applying the open boundary condition to the directional coupler in Fig. 1, the impedances parameters of the DC block are derived as

$$[Z]^a=\begin{bmatrix} -j\frac{(Z_{0e}+Z_{0o})}{2}\cot\Theta & -j\frac{(Z_{0e}-Z_{0o})}{2}\csc\Theta \\ -j\frac{(Z_{0e}-Z_{0o})}{2}\csc\Theta & -j\frac{(Z_{0e}+Z_{0o})}{2}\cot\Theta \end{bmatrix} \quad (3)$$

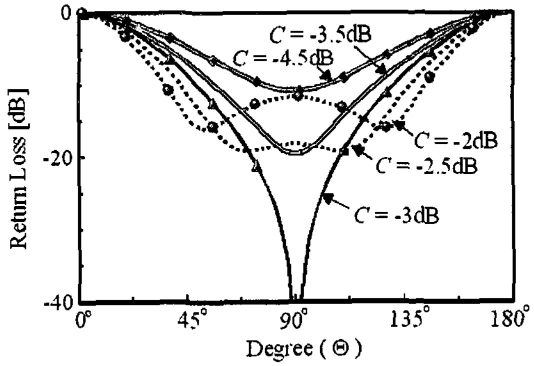
where $Z_{0e}$ and $Z_{0o}$ are the even- and odd-mode impedances before any modification.

Since the termination impedances are different from each other, normalized scattering parameters are needed for the analyses of the DC block and derived by use of (3.29) given in [20]. The normalized scattering parameters are expressed as:

$$S_{11}=\frac{1}{D^a}[(Z_{0e}+Z_{0o})^2\cos^2\Theta-(Z_{0e}-Z_{0o})^2 \\ +4Z_LZ_r\sin^2\Theta+j(Z_L-Z_r)(Z_{0e}+Z_{0o})\sin 2\Theta], \quad (4)$$



(a) Insertion losses(Matching performances)



(b) Return losses

Fig. 5. Simulation results of the DC blocks with an impedance transformation ratio, $I_R=Z_r/Z_L=1.5$.

$$S_{22} = \frac{1}{D^a}[(Z_{0e}+Z_{0o})^2\cos^2\Theta - (Z_{0e}-Z_{0o})^2$$
$$+4Z_LZ_r\sin^2\Theta - j(Z_L - Z_r)(Z_{0e}+Z_{0o})\sin 2\Theta] \ ,$$

$$S_{12} = S_{21} = \frac{1}{D^a}[j4(Z_{0e}-Z_{0o})\sqrt{Z_rZ_L}\sin\Theta] \ ,$$

where $D^a = (Z_{0e}+Z_{0o})^2\cos^2\Theta - (Z_{0e}-Z_{0o})^2$

$$-4Z_LZ_r\sin^2\Theta + j(Z_r+Z_L)(Z_{0e}+Z_{0o})\sin 2\Theta \ .$$

Based on (4), several DC blocks were simulated by use of mathematical software of Matlab 6.1, and the simulations were carried out as the coupling coefficients varied and an impedance transformation ratio, $I_R=Z_r/Z_L$, is fixed at 1.5; the results are plotted in Fig. 5. Depending on the coupling coefficients, coupling characteristics are classified as critical coupling($C=-3$ dB), over coupling($C>-3$ dB) and under coupling($C<-3$ dB)[23]. Fig. 5 shows that perfect matching appears only with the critical coupling, and ripples with no perfect matching exist in the over-coupling case. The excited power at port ① of the DC block in Fig. 3(a) is transmitted into port ②, and the amount of transmitted power is dependent on the coupling structure. Therefore, the equivalent circuit can be a parallel resonant circuit, as depicted in Fig. 3(b)[23], and three behaviors of the input impedance $Z_{in}^a$ are plotted depending on the coupling coefficients. The input impedance[20] is computed using

$$Y_{in}^a = Y_{11}^a - \frac{Y_{12}^aY_{21}^a}{Y_{22}^a + Y_L} \ , \tag{5}$$

where $Y_{11}^a = Z_{22}^a/\Delta_Z$, $Y_{22}^a = Z_{11}^a/\Delta_Z$,

$Y_{12}^aY_{21}^a = (Z_{12}^aZ_{21}^a)/\Delta_Z$, $Y_L = Z_L^{-1}$ and

$$\Delta_Z = \frac{(Z_{0e}-Z_{0o})^2 - (Z_{0e}+Z_{0o})^2\cos^2\Theta}{4\sin^2\Theta} \ .$$

This gives the frequency dependent values of $R_a$, $L_a$, $C_a$ in Fig. 3(b) as

$$R_a = \frac{\left[(\Delta_ZY_L)^2 + \left(\frac{(Z_{0e}+Z_{0o})}{2}\cot\Theta\right)^2\right]}{Y_L\left[\frac{(Z_{0e}-Z_{0o})}{2}\csc\Theta\right]^2} \ , \tag{6a}$$

for $\cot\Theta/\Delta_Z > 0$,

$$\omega C_a = \frac{1}{\Delta_Z}\frac{\left(\frac{Z_{0e}-Z_{0o}}{2}\csc\Theta\right)^2\frac{Z_{0e}+Z_{0o}}{2}\cot\Theta}{\left[(\Delta_ZY_L)^2 + \left(\frac{Z_{0e}+Z_{0o}}{2}\cot\Theta\right)^2\right]} \ ,$$

$$\frac{1}{\omega L_a} = \frac{1}{\Delta_Z}\left(\frac{Z_{0e}+Z_{0o}}{2}\cot\Theta\right) , \tag{6b}$$

for $\cot\Theta/\Delta_Z < 0$,

$$\frac{1}{\omega L_a} = -\frac{1}{\Delta_Z}\frac{\left(\frac{Z_{0e}-Z_{0o}}{2}\csc\Theta\right)^2\frac{Z_{0e}+Z_{0o}}{2}\cot\Theta}{\left[(\Delta_ZY_L)^2 + \left(\frac{Z_{0e}+Z_{0o}}{2}\cot\Theta\right)^2\right]} \ ,$$

$$\omega C_a = -\frac{1}{\Delta_Z}\left(\frac{Z_{0e}+Z_{0o}}{2}\cot\Theta\right) . \tag{6c}$$

The input impedance $Z_{in}^a$ of the DC block can be displayed on a Smith chart and coupling to a parallel resonant circuit is illustrated in an admittance Smith chart in Fig. 6 where the input impedance $Z_{in}^a$ with the critical coupling is $Z_r$ at a design center frequency, or, $\Theta$=90°, but the two others have more or less than $Z_r$. Only when $Z_{in}^a$ is equal to $Z_r$ at a center frequency,

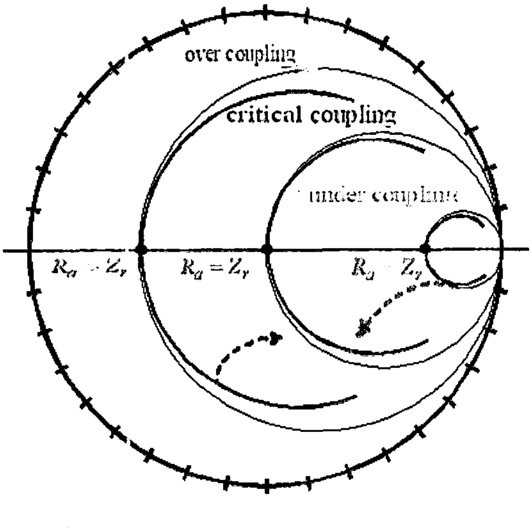


Fig. 6. Input impedances of the DC blocks on an admittance Smith chart with three different coupling cases(over coupling; critical coupling; under coupling).

can perfect matching appear; these results coincide with those in Fig. 5.

For any DC block to have perfect matching regardless of the coupling coefficients, the even- and odd-mode impedances need to be modified in such a manner that the input impedances of the over-coupled DC blocks are reduced and those of the under-coupled ones are increased, as indicated with dotted arrows in the lower part of the Smith chart in Fig. 6. When $\Theta$=90° in (6), only $R_a$ appears as the input impedance of $Z^a_{in}$, and its value is

$$R_a = Z_r\left(\frac{C^2}{1-C^2}\right). \tag{7}$$

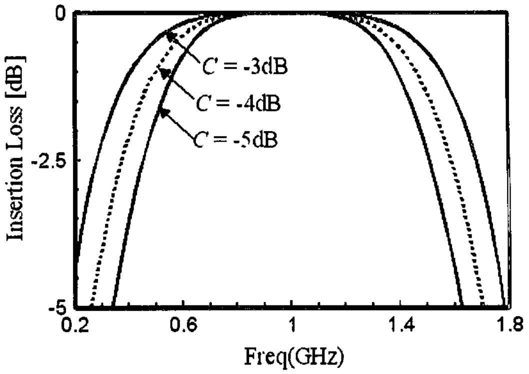
From (7), $R_a$ is $Z_r$ when $C = 1\sqrt{2}$(critical coupling), which agrees with the simulation results in Figs. 5 and 6. For the DC blocks with any coupling coefficient to be perfectly matched at a design center frequency, the even- and odd-mode impedances should be modified so that the value of $R_a$ is always $Z_r$ regardless of the coupling coefficients. The $Z_r$ in (7) comes from the even- and odd-mode impedances in (1) and can be modified to have a constant value of input impedance. The solution for this is to replace $Z_r$ in (1) by $Z_r[(1-C^2)/C^2]$.

In such a manner, the modified even- and odd-mode impedances $Z^a_{0e}$ and $Z^a_{0o}$ are derived as

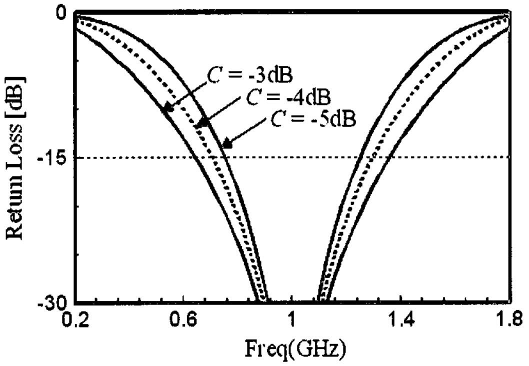
$$Z^a_{0e} = \frac{1+C}{C}\sqrt{Z_r Z_L} \tag{8a}$$

$$Z^a_{0o} = \frac{1-C}{C}\sqrt{Z_r Z_L}, \tag{8b}$$

Using $Z^a_{0e}$ and $Z^a_{0o}$, the input impedance $Z^a_{in}$ always becomes $R_a$=$Z_r$ at resonant frequency regardless the coupling coefficients. The modified even- and odd-mode impedances $Z^a_{0e}$ and $Z^a_{0o}$ were used to simulate three DC blocks with fixing the impedance transformation ratio $Z_r/Z_L$ at 1.2 and varying the coupling coefficients. The simulation insertion and return losses are plotted in Fig. 7(a) and (b), respectively. The results show that perfect matching appears at the center frequency regardless of the coupling coefficients, and that the bandwidths are proportional to the coupling powers.



(a) Insertion losses



(b) Return losses(Matching performances)

Fig. 7. Simulation results of DC blocks with compensated design equations.

## V. DC Block Measurements

The modified even- and odd-mode impedances( $Z^a_{0e}$ and $Z^a_{0o}$) were verified by measuring a microstrip DC block at a center frequency of 4 GHz. When a DC block is terminated in 35 Ω and 25 Ω, several sets of modified even- and odd-mode impedances and their realizable design data on a substrate( $\varepsilon_r$=4.0, $h$=0.57 mm) are given in Table 2 where $Z_{T1}$ and $Z_{T2}$ are characteristic impedances of impedance transformers to transform the termination impedances $Z_r$ and $Z_L$ into 50 Ωs. Since the gap of the coupled transmission lines is limited to 0.15 mm to fabricate, the maximum coupling

Table 2. Fabrication data for a DC block with −10 dB coupling.

<table>
<tr><td colspan="6">$Z_r$=25 Ω, $Z_L$=35 Ω, $f_0$=4 GHz<br>$Z_{T1}$=41.83 Ω, $Z_{T2}$=35.35 Ω</td></tr>
<tr><td>$C$</td><td>−6</td><td>−7</td><td>−8</td><td>−9</td><td>−10</td></tr>
<tr><td>$Z_{0e}^a$</td><td>88.6</td><td>95.80</td><td>103.8</td><td>112.9</td><td>123.1</td></tr>
<tr><td>$Z_{0o}^a$</td><td>29.44</td><td>36.64</td><td>44.72</td><td>53.7</td><td>63.96</td></tr>
<tr><td>$w$</td><td colspan="2" rowspan="3"></td><td>0.45</td><td>0.35</td><td>0.259</td></tr>
<tr><td>$s$</td><td>0.142</td><td>0.209</td><td>0.285</td></tr>
<tr><td>$l$</td><td>11.53</td><td>11.54</td><td>11.58</td></tr>
<tr><td colspan="3">$Z_{T1}$:$w$=1.504 mm<br>$l$=10. 60 mm</td><td colspan="3">$Z_{T2}$:$w$=1.937 mm<br>$l$=10.46 mm</td></tr>
</table>

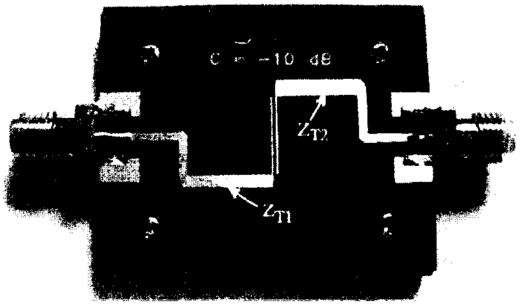


Fig. 8. A DC block with −10 dB coupling coefficient.

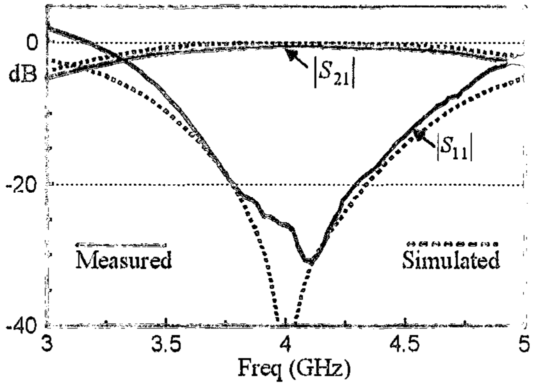


Fig. 9. Results measured and simulated are compared.

coefficient is −9 dB. A microstrip DC block with −10 dB coupling coefficient was fabricated and shown in Fig. 8. Fig. 9 compares the measured and simulated results where the measured return and insertion losses at 4.1 GHz are −31 dB and 0.82 dB, respectively.

## Ⅵ. Conclusions

As an application of the impedance-transforming directional couplers symmetrically terminated in arbitrary impedances, DC blocks terminated in arbitrary impedances were introduced. They were obtained by terminating two of four ports of the directional couplers in two opens. Therefore, the power excited at a port is transmitted into the other port and how much power can be delivered depends on the coupling structures. However, most of conventional DC blocks with arbitrary termination impedances can not be perfectly matched. To solve the matching problem, one-port equivalent resonant circuit model was newly suggested, by which design equations were derived. Based on the derived design equations, simulation and measurements were carried out and their results confirmed the DC blocks could be designed, perfectly matched without any restriction of coupling structures. Since the DC blocks are terminated in arbitrary impedances, any advantage to reduce total size of microwave integrated circuits can be gained. Since perfectly matched DC blocks can be designed without any restriction of coupling powers, more applications can be expected in various microwave circuit applications.

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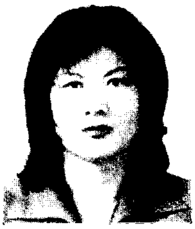
### 안 희 란



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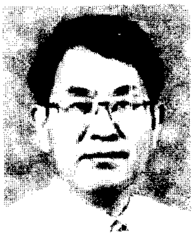

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