A New Directional Coupler Design with High Directivity for PCS and IMT-2000

Il-Gu Ji and Jong-Wha Chong

This paper proposes a new design of directional couplers with high directivity for personal communication services (PCS) and International Mobile Telecommunications-2000 (IMT-2000). The directional coupler is used to check and verify the power, frequency, and antenna reflection of a signal at transmission stations for mobile communications. The performance requirements of directional couplers are a strong coupling to reduce the effect on the transmitted power and high directivity to suppress the interference of the reflected signals and reduce the errors in communication. So far, various architectures have been proposed to gain high directivity, and there have been many studies used to obtain a strong coupling. However, conventional architectures for high directivity and strong coupling have a directivity of only about 20 dB, and there have been difficulties to achieve the higher directivity of 30 dB suitable for PCS and IMT-2000. This paper proposes a new architecture of directional couplers based on a grounding composed of strip lines, and compares the test results of this directional coupler with conventional ones. The results show that the proposed directional coupler has a directivity of more than 30 dB and is adequate for PCS and IMT-2000.

Keywords: High directivity directional coupler, IMT-2000, grounding area, compensate.

Manuscript received Sept. 9, 2004; revised July 27, 2005.

This work was supported by the research fund of Hanyang University (HY-2005-T).

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I. Introduction

The directional couplers used to distribute a signal or combine signals can have a 3-port or 4-port architecture with the directivity of power coupling. The transmission station for mobile communications uses the directional coupler to check and verify the power, frequency, and antenna reflection of a signal. Directional couplers need strong coupling to reduce the effect on transmitted power and high directivity to suppress the interference of reflected signals and improve communication quality.

The coupler in microwave systems is also used as a passive component to split or combine a signal, and is available for various purposes. In particular, a directional coupler is applied to a linear amplifier to improve inter-modulation properties between stations of recent mobile communication systems. The performance of directional couplers can be evaluated by indices that include coupling, directivity, and reflection loss. On the bases of the evaluation results, a directional coupler with wide bandwidth and high directivity can be used as the main module of communication systems or testing instruments. Architectures to achieve higher directivity have been proposed, and there have been many studies on how to achieve a stronger coupling.

The directional couplers in microwave systems can be classified into the hybrid and strip-line structured types. The hybrid type has a good coupling property, but its frequency range is narrow for the directivity. On the other hand, the directivity of the strip-line structured type has a wider bandwidth in frequency. However, it is difficult to get more than 25 dB for directivity and coupling properties. Therefore, this paper is focused on a study showing that the proposed architecture based on the strip-line structure can achieve more than 30 dB for directivity. The proposed strip-line structure composed of the same materials can make equal mode phase velocities in the coupler. In order to evaluate the performance of the proposed strip-line structure, its directivity has been monitored with simulations and experiments, and the factors to directivity are analyzed in this paper. The change and degradation of directivity by the impedance mismatching are also evaluated by simulations. Furthermore, this paper will suggest a new design method to add a ground between the discontinuous band and step in the coupler by comparing the simulation results to the properties of output frequency from the directional coupler with parallel coupled strip-line. A comparison between the experimental results for the coupler applied with the proposed design with conventional couplers is shown in this paper.

In summary, the objective of this paper is to propose a design method and architecture of the directional coupler with high directivity of about 30 dB suitable for PCS and IMT-2000, an objective that has been difficult to attain thus far [18], [19]. The study results of this paper can be applied to base and relay stations for mobile communications and testing equipment for communication terminals. Also, these can be used for signal generators and spectrum and network analyzers.

II. Design Theory of Directional Coupler with Parallel Coupled Strip-Line

The design of directional couplers with a parallel coupled strip-line can begin with the theory of the coupled line through edge-coupled architecture. Figure 1 shows a symmetric and uniform coupler with edge-coupled architecture. One strip-line on the dielectric substance in the coupler is adjacent to the other strip-line at an interval of constant S. Figure 2, which shows the capacitances for two strip-lines, is an equivalent circuit of the coupler shown in Fig. 1. In Fig. 2, the capacitances C_{11} and C_{22} are reasonable factors because they represent the electric fields between each strip-line and the substance, that is, the ground. What does capacitance C_{12} describe? This has been the theme of many studies and papers in relation with directional couplers.

Processes to explain the capacitance C_{12} are the even and odd modes. The even mode shown in Fig. 3 has a magnetic wall, that is, an H-wall. In the odd mode, reversely, an electric wall, that is, an E-wall, is used as shown in Fig. 4 [1].

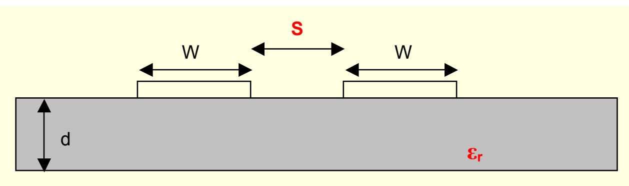


Fig. 1. Symmetric and uniform coupler with edge-coupled architecture.

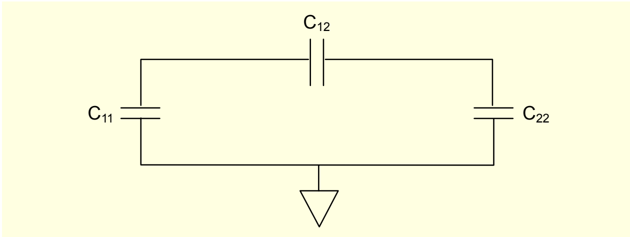


Fig. 2. Equivalent circuit of edge-coupled architecture.

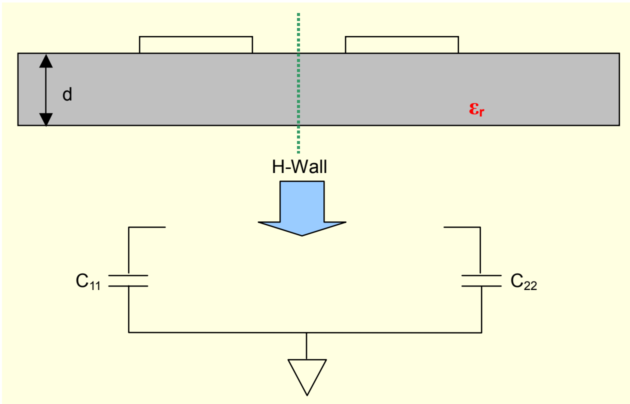


Fig. 3. Equivalent circuit for even mode.

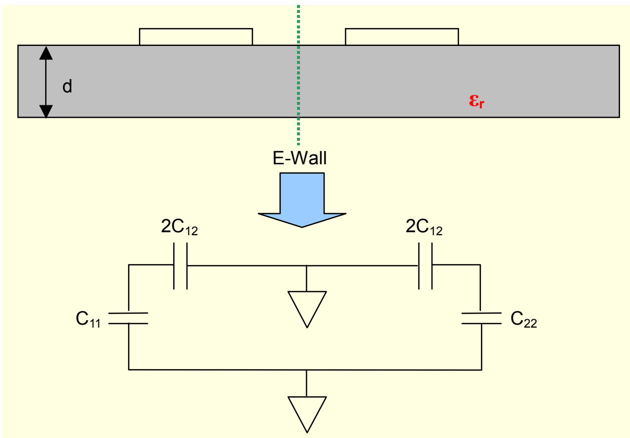


Fig. 4. Equivalent circuit for odd mode.

The characteristic impedance using the capacitances for the even mode as in [1] is

$$C_e = C_{11} = C_{22},$$
$$Z_{0e} = \sqrt{\frac{L}{C_e}} = \sqrt{\frac{LC_e}{C_e}} = \frac{1}{\upsilon C_e}. \qquad (1)$$

Equation (2) shows the characteristic impedance using the capacitances for the odd mode.

$$C_o = C_{11} + 2C_{12} = C_{22} + 2C_{12}$$
$$Z_{0o} = \frac{1}{\upsilon C_o} \quad (2)$$

In a case where the distance between two transmission-lines is as close as the occurrence of the coupling, each of the even and odd modes has a characteristic impedance different from the other one, as shown in (1) and (2). On the other hand, the characteristic impedances of the even and odd modes come to be the same in relatively far enough distances. The relation between the different characteristic impedances between even and odd modes is explained with the coupling coefficient. The coupling extent K between the strip-lines is defined as in [1] and [2] as

$$K = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}}. \quad (3)$$

Figure 5 shows the fundamental architecture and its equivalent circuit to analyze the directional coupler with parallel coupled strip-line [1], [2].

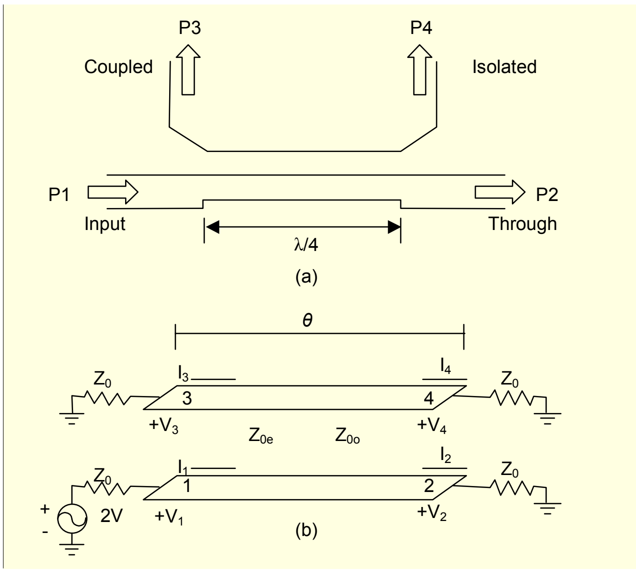


Fig. 5. (a) Fundamental architecture and (b) equivalent circuit of a directional coupler.

Voltages of the ports in Fig. 5 are as follows:

$$V_1 = 1, \quad V_2 = \frac{\sqrt{1-K^2}}{\sqrt{1-K^2}\cos\theta + j\sin\theta},$$
$$V_3 = \frac{jK\sin\theta}{\sqrt{1-K^2}\cos\theta + j\sin\theta}, \quad V_4 = 0. \quad (4)$$

As shown in (4), the only port isolated is port 4, while the others are matched. Then, the coupler has an output power that is dependent on K and on distributed power from ports 2 and 3. Equation (4) also shows that the maximum coupling is generated when the coupler is λ/4. When θ = π/2 and the coupler is λ/4, the port voltages are as follows:

$$V_1 = 1,\ V_2 = -j\sqrt{1-K^2},\ V_3 = K,\ V_4 = 0. \quad (5)$$

The coupling extent in dB, K_{dB}, is as follows:

$$K_{dB} = -10 \cdot \log_{10} \frac{1}{|K^2|} \ \text{[dB]}. \quad (6)$$

The coupling extent K can be obtained with Z_{0e}, Z_{0o} in (1). And the design equation for the characteristic impedances of even and odd modes is derived from (1), as shown in (7), on the specified characteristic impedance Z_0 and voltage coupling coefficient K [1], [2].

$$Z_{0e} = Z_0\sqrt{\frac{1+K}{1-K}}, \quad Z_{0o} = Z_0\sqrt{\frac{1-K}{1+K}} \quad (7)$$

In summary, a coupling or isolating coefficient can be described as (8), with output against input to the coupling or isolating port of a directional coupler with parallel coupled strip-line, as shown in Fig. 5.

$$C = -10 \cdot \log_{10}\left|\frac{P_3}{P_1}\right| \ \text{[dB]}, \quad I = 10 \cdot \log_{10}\left|\frac{P_4}{P_1}\right| \ \text{[dB]},$$
$$T = -10 \cdot \log_{10}\left|\frac{P_2}{P_1}\right| \ \text{[dB]}. \quad (8)$$

In (8), T represents the transmission coefficient. The directivity, which is the most important of the performance indices, is defined as the relative power of the isolating port for power of the coupling port. Then, the directivity in dB is described as follows:

Directivity = Isolating coefficient (I) – Coupling coefficient (C). (9)

Equation (9) shows that the power of the isolating port should be zero in the given frequency-band for ideal implementation of the directivity with a specified coupling coefficient. However, in the case of practical coupled-line couplers, physical changes in the transmission line causes discontinuity, which results in degrading the directivity. But, in the case of general coupled line couplers, the discontinuity caused by the physical change of transmission line brings a decline of directivity. In addition, there are some important factors that closely affect the directivity as an important performance parameter of the coupling coefficient.

a. Radio wave speed ($v_e = v_o = v$) in the coupler for the even-odd mode
b. Mismatching of the junction of step and band due to line separation to transmission lines from two terminals of the coupled line
c. Voltage standing wave ratio (VSWR) when connecting a load to the output port
d. Inter-matching ($Z_0 = \sqrt{Z_{0e} Z_{0o}}$) of the coupler as a balance function of mode impedance

Because the radio wave speed of a mode in the strip coupled line having a parallel transmission line within the flat dielectric material is the same, the directivity, compared to the micro-strip coupled line coupler where the radio wave speed is different, is basically superior. But, the discontinuity in the port connection and the band, which is the separation part between the coupling line and 50 Ω transmission line, remains as a reactance component and causes the decline in directivity.

In this paper, a parallel coupled strip-line architecture with transverse electro-magnetic wave transmission mode has been applied to improve the directivity and widen the bandwidth. In general, it is hard to get high directivity in a directional coupler having a weakened coupling coefficient. Therefore, a directional coupler having a stronger coupling coefficient has been designed and tested. We used a Teflon board of h = 3.175 mm, t = 0.03 mm, and ε_r = 2.33, which can be used in amplification for high electric power. As for the range of the measurement frequency, the central frequency has been set at 2.05 GHz experimented with a range of 150 MHz.

In this paper, a physical dimension of the coupler was obtained by a simulator for ultra high frequency. Table 1 shows the physical dimensions of the strip coupled-line directional coupler obtained by each coupling coefficient.

Table 1. Physical dimensions of directional coupler. (unit : mm)

Coupling coefficient (dB)	B	W	d	λ/4 length
30	6.35	4.97	4.23	23.97

(50 Ω width of the transmission line : h = 3.175 mm, t = 0.035 mm, ε_r = 2.33)

Two boards (B=2h) of the same dielectric substance material are used to form a strip structure. We made a pattern on one board and completely removed the copper from one side of another board, stacking it on the first [9], [13].

In the directional coupler that is not cut to the pattern, the directivity is remarkably deteriorated because of the discontinuity from the bend part. So, the directivity can be improved by cutting the bend properly. Although there are various suitable bend cutting methods in a strip line and micro-strip line, in this research, we cut a bend part with various angles using a cut-and-try method and observed the trend of directivity. Finally, we reached a result showing that about 45 degrees is the most proper bend and that the directivity is more improved than at any other angles with the exception of 45 degrees. Figure 6 displays a pattern drawing of a directional coupler cut at a 45° angle.

Fig. 6. Pattern drawing of a general directional coupler.

III. Design of Directional Coupler with High Directivity

The high directivity generally indicates directivity by more than 25 dB. The conventional directional couplers with parallel coupled strip-line have a directivity of about 20 dB. Improving the directivity by the bend-cutting method described in the previous sub-section has a limitation. Therefore, a new architecture or design method is required to implement a directivity of more than 25 dB.

First, capacitance, inductance, and impedance representing properties of a transmission line are easily obtained for a single transmission line. However, practical circuits are composed of transmission lines with a complex structure. In this case, the property of each transmission line is made up by complex relationships among line materials according to signal layer; isolation materials between signal layers; shape, including thickness, area, and length of the transmission line; and the disposition state of adjacent transmission lines. In summary, the characteristic of the directional coupler is determined by the characteristic parameters of such capacitance and inductance that are dependent on the structure of the transmission lines [14].

This paper began with an objective to reduce the signal quantity at the coupling port by preventing a coupling effect between 50 Ω transmission lines, and resulted in a design method that compensates the impedance mismatching due to the discontinuous reactance components by the capacitance generated between line and ground. In summary, this paper

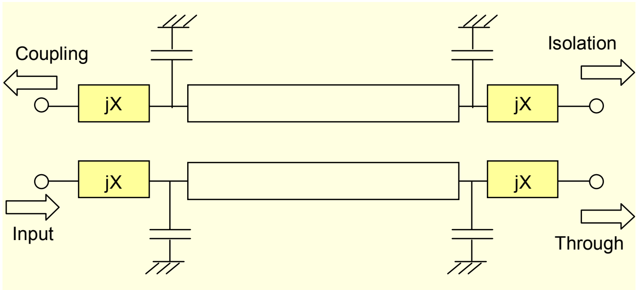


Fig. 7. Equivalent circuit of a directional coupler.

proposes an architecture to compensate impedance mismatching, as shown in Fig. 7, with capacitance between line and ground. The capacitance formed on the grounding area is as follows:

$$C = \frac{8.85\times10^{-12}\times\varepsilon_r\times S}{d}, \tag{10}$$

where ε_r is a dielectric coefficient, S is the grounding area (m^2), and d is the distance between transmission line and ground. The grounding area is derived from (10) as follows:

$$S = \frac{C\times d}{8.85\times10^{-12}\times\varepsilon_r}. \tag{11}$$

In the first step to compensate capacitance by about 0.0001 pF, each ε_r, d, and C in (11) is substituted with 2.32, 2.23, and 0.0001 [pF] as follows:

$$S = \frac{2.23\times0.0001\times10^{-12}}{8.85\times10^{-12}\times2.32} \fallingdotseq 0.000011\ \text{m}^2 = 11\ \text{mm}^2. \tag{12}$$

Equation (12) describes a new design method that deposits an 11 mm^2 triangle grounding area instead of the capacitance on the bend position. Then, the proposed architecture to achieve high directivity in the first step has the pattern diagram in which the triangle grounding area is deposited as shown in Fig. 8.

What would happen if we make the capacitance larger? In the second step, to achieve a higher directivity than that in the first step, we increased the compensation capacitance to about 0.00025 pF. In this case also, the grounding area is obtained from (11). Like (12), each ε_r, d, and C in (11) is substituted with 2.32, 2.23 [m], and 0.00025 [pF] as follows:

$$S = \frac{2.23\times0.00025\times10^{-12}}{8.85\times10^{-12}\times2.32} \fallingdotseq 0.000027\ \text{m}^2 = 27\ \text{mm}^2. \tag{13}$$

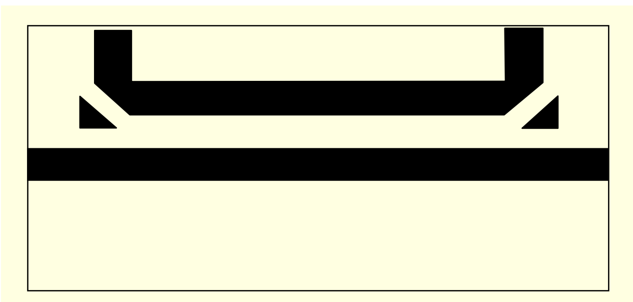


Fig. 8. Pattern diagram of directional coupler with triangle grounding area.

Based on (12), this paper proposes another architecture to achieve higher directivity, in which a larger grounding area is deposited than that of the architecture proposed first as shown in Fig. 9.

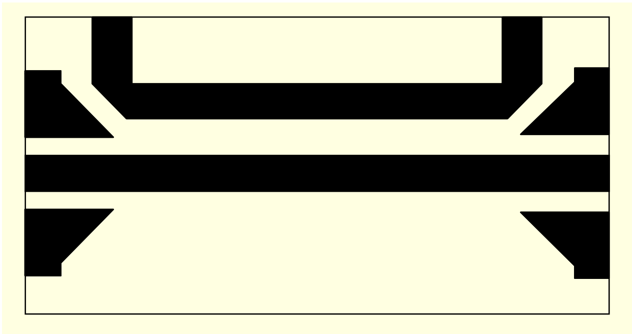


Fig. 9. Pattern diagram of the proposed architecture for a directional coupler.

IV. Simulation

Figure 10 shows the simulation results for the directional coupler with a cutting bend of 45°. In concrete terms, Fig. 10(a) describes reflection and insertion losses at the coupling port. This shows that a –29.5 dB coupling is generated. Figure 10(b) shows a 44.9 dB isolation coefficient when measured at isolating ports. From Fig. 10, the conventional directional couplers that have a strip-line architecture with a cutting bend of 45° can gain a directivity of about 15 to 20 dB. And it is shown that each insertion loss and reflection loss at the passing port of the directional coupler is 0.05 and 32 dB.

We also performed simulations to monitor the effects of discontinuous reactance components, which are generated at a bend by connecting 50 Ω transmission lines with a 90° angle for the line separation, on the directivity. First, the frequency characteristics of the directional coupler with parallel coupled strip-line were observed. For an ideal directional coupler with perfect matching between impedances of the ports, each center frequency and bandwidth of the directional coupler is set to 2.05 GHz and 300 MHz as a simulation environment. Figure 11 shows the simulation results. The ideal directional coupler naturally has a wide bandwidth.

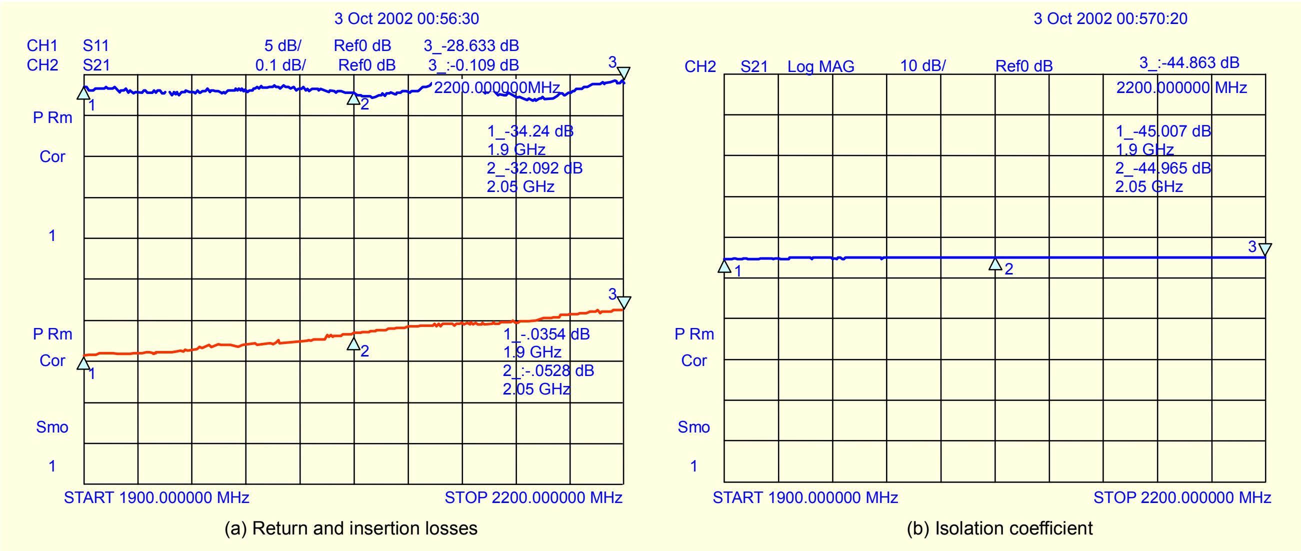


Fig. 10. Simulation results for a directional coupler with a cutting band of 45°.

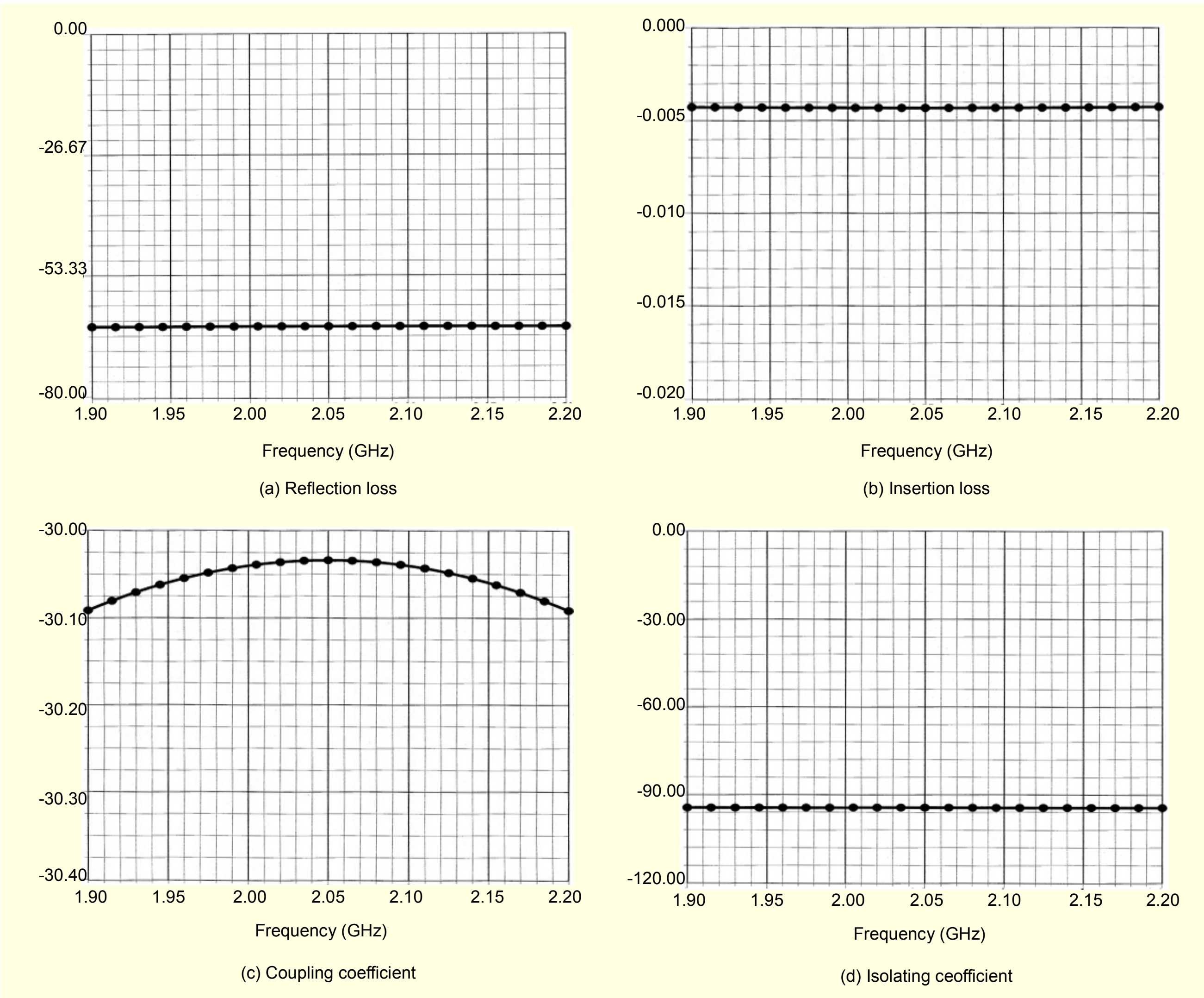


Fig. 11. Frequency characteristics of ideal directional coupler.

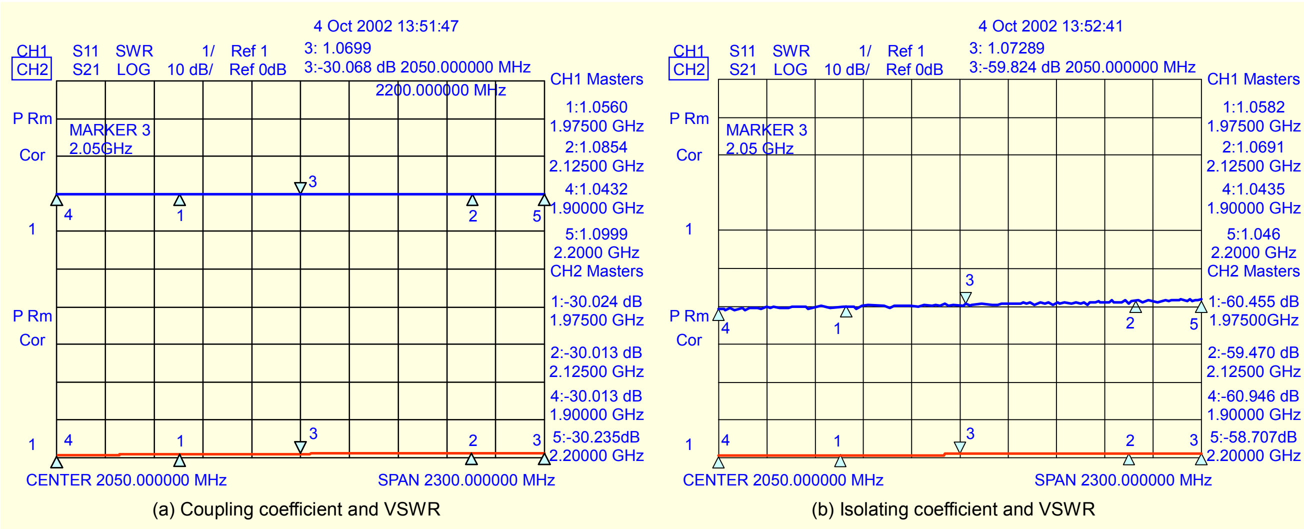


Fig. 12. Simulation results for directional coupler with grounding area.

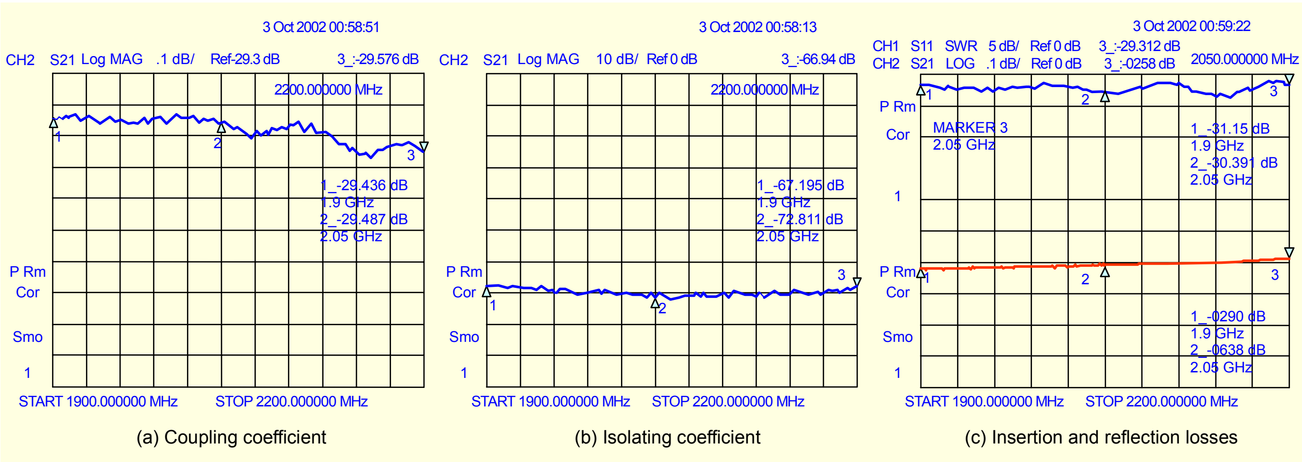


Fig. 13. Simulation results for the proposed direction coupler.

Table 2. Simulation summary for directional couplers (unit: dB).

	Conventional directional couplers	Proposed directional couplers (simulation results)
Directional couplers	30	30
Insertion loss of through port	0.05	0.06
Coupling coefficient	29.5	29.4
Isolating coefficient	44.9	72.8
Directivity	15.4	43.4
Return loss of a port	32	30.4

Figure 12 shows the simulation results for the directional coupler with the grounding area described in Fig. 10. From Fig. 12, each coupling coefficient and isolating coefficient at the coupling port is 30.1 and 59.47 dB. This shows that the directional coupler in which the grounding area is deposited can get a directivity of about 29 dB. It is also shown in Fig. 12 that the insertion loss at the passing port is 0.07 dB and reflection losses at all ports are 30 dB.

The simulation results for the architecture finally proposed are described and shown in Fig. 13. From Fig. 13, you can see that the insertion loss (S_{21}) at the isolating port of the proposed architecture is reduced to noise level. This shows that the proposed directional coupler has an isolation effect superior to that of the conventional directional couplers. The measured isolating coefficient of 72.8 dB indicates a relatively higher directivity of about 43 dB. Figure 13 also shows that the measured reflection loss is less than 30 dB, which is relatively low, and that the insertion loss at all ports is measured to be 0.06 dB.

Table 2 summarizes the simulation results discovered by this paper. As shown in the table, the proposed directional coupler can achieve a higher directivity compared with the conventional directional couplers.

V. Experiment Results of the Designed Product

1. The Experiment Results of the PCS Directional-Coupler Designed in This Paper

Table 3 shows the experiment results for the design specification of the proposed directional-coupler for PCS communication.

Table 3. Experiment results for the performance of the designed directional-coupler.

Items	30 dB		40 dB	
	Specification	Experiment results	Specification	Experiment results
Freq. range	1810-1870 MHz	1700-1900 MHz	1810-1870 MHz	1700-1900 MHz
Insertion loss (max)	0.15 dB	0.15 dB	0.11 dB	0.1 dB
Coupling value (dB)	30±0.7	30±0.5 dB	40±1 dB	40±0.7 dB
Coupling flatness (dB)	±0.2	±0.2	±0.2	±0.2
Directivity	30 dB	34 dB	30 dB	32.1 dB
Return loss (min)	26 dB	28 dB	26 dB	28 dB
Input power (max)	200 W	200 W	200 W	200 W
Impedance (Ω)	50	50	50	50
Dimension (mm)	TBD	56.5×26×43	TBD	61×26×37
Weight	TBD	235(g)	TBD	218(g)
I/O port connector	TBD	N(f)	TBD	N(f)
Coupling	TBD	SMA(f)	TBD	SMA(f)

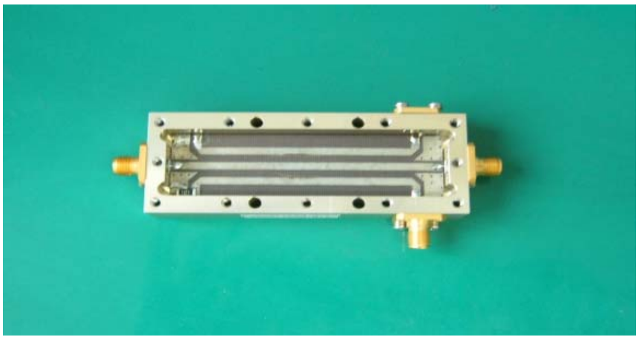


Fig. 14. Architecture of 30 dB directional coupler for PCS.

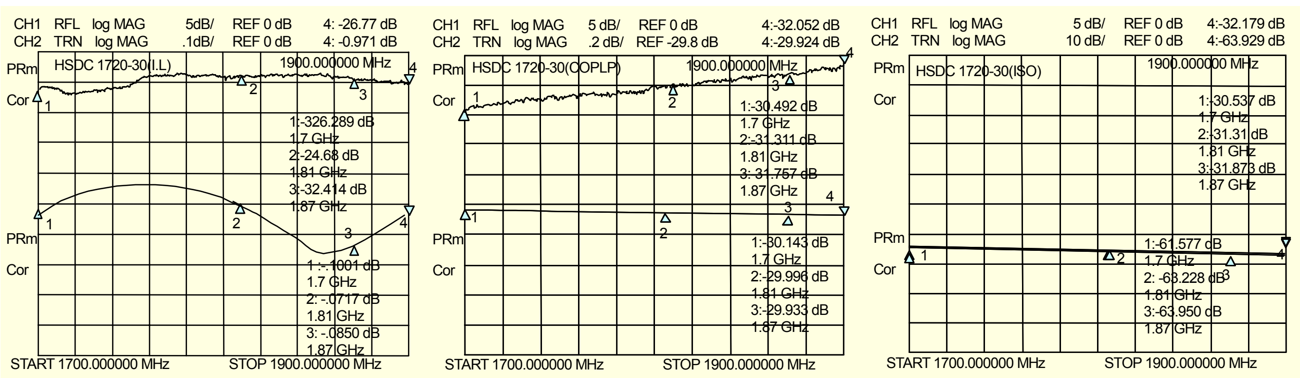
The shape of the 30 dB directional-coupler for the PCS designed in this paper is shown in Fig. 14. The insertion loss property, coupling coefficient, and isolating coefficient obtained by the experiments on the designed directional-coupler are described in (a), (b), and (c) of Fig. 15.

In addition, the shape of the 40 dB directional-coupler for the PCS designed in this paper is shown in Fig. 16. The insertion loss property, coupling coefficient, and isolating coefficient obtained by the experiments of the designed directional-coupler are described in (a), (b), and (c) of Fig. 17.

2. The Experiment Results of the IMT-2000 Directional-Coupler Designed in This Paper

Table 4 shows the experiment results for the design specification of the proposed directional-coupler for IMT-2000 communication. In Fig. 18, the shape of the directional-coupler for IMT-2000 designed in this paper is shown. The insertion loss property, coupling coefficient, and isolating coefficient obtained by the experiments of the designed directional-coupler are described in (a), (b), and (c) of Fig. 19.

Two results are analyzed: one obtained from the directional coupler designed and assembled as shown in Tables 3 and 4, and the other obtained from the simulation as shown in Table 2.



(a) Insertion loss (b) Coupling coefficient (c) Isolating coefficient

Fig. 15. 40 dB directional-coupler for PCS.

The directivities of the former are 34, 32.1, and 35 dB as compared to 43.1 dB of the latter. The directivity indicated by the simulation result is approximately 9 dB higher than the actual coupler because it was obtained through a simulator and graphics. However, all directional couplers assembled and tested achieved higher than 30 dB, which was the goal.

VI. Conclusions

In this paper, we watched and discovered through simulation that impedance mismatching due to discontinuity of bend affect the directivity of a directional coupler. We also designed the proposed directional couplers to improve impedance mismatching in band and verified the improved performance by comparing them with conventional directional couplers. The proposed architectures are not the micro-strip type, but are rather the strip type so that higher directivity than that of the conventional architectures can be obtained. Also, the proposed directional couplers do not have a hybrid branch-line architecture, but a parallel coupled strip-line so that the bandwidth of the directivity is relatively wide.

This paper proposed the architecture of a directional coupler that inserts the grounding area as a capacitance to offset the reactance caused by the discontinuity in the bend connected to 50 Ω transmission lines. It was shown in Tables 2, 3, and 4 that the directivity of the proposed architectures is superior to that of conventional ones. This proves that the directional coupler with a relatively high directivity of more than 30 dB, compared with 25 dB of conventional directional couplers, can

Table 4. Experiment results for the performance of the designed directional-coupler.

ITEMS	Measurement results		
	10 dB	20 dB	30 & 40 dB
Pass band frequency	1900 ~ 2200 MHZ		
Insertion loss (Max.)	0.6 dB	0.15 dB	0.1 dB
Return loss (Min.)	25 dB		
Coupling value	10 ± 0.5 dB	20 ± 0.5 dB	30 ± 0.5 dB
Coupling flatness	± 0.2 dB		
Directivity	35 dB		
Impedance	50 Ω		
Dimension (mm)	48×25×14		
Temperature r	−30 ~ +75°C		

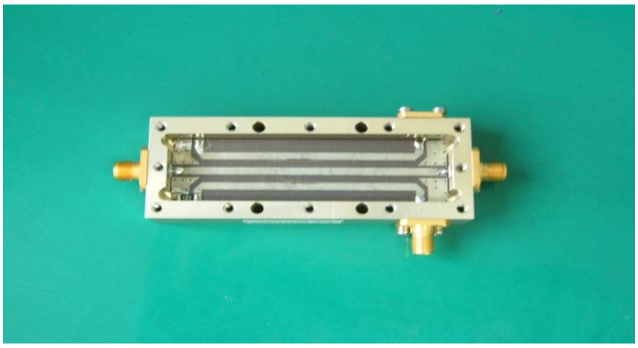
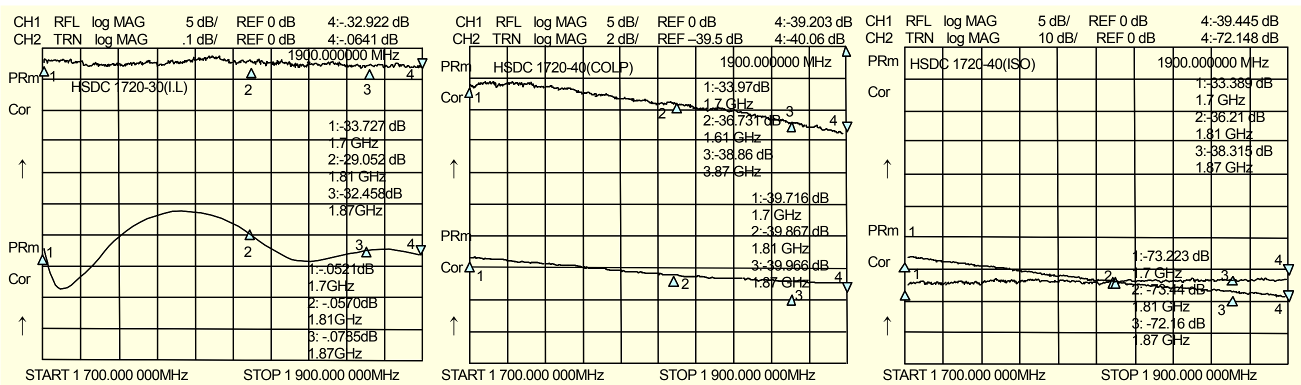


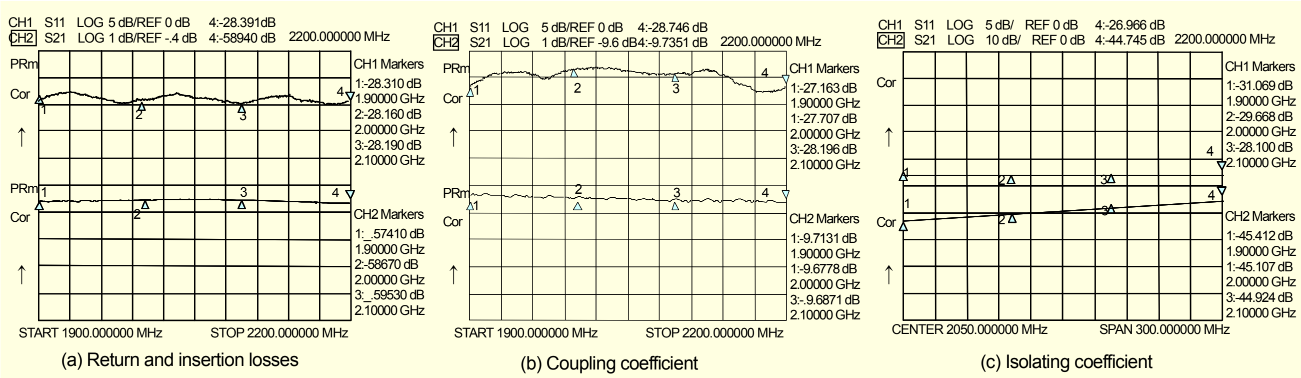
Fig. 16. Architecture of 40 dB directional coupler for PCS.

Fig. 18. Architecture of directional coupler for IMT-2000.



(a) Insertion loss (b) Coupling coefficient (c) Isolating coefficient

Fig. 17. 40 dB directional-coupler for PCS.



(a) Return and insertion losses (b) Coupling coefficient (c) Isolating coefficient

Fig. 19. Experiment results of the designed directional-coupler for IMT-2000.

be obtained by the proposed design method. Therefore, the proposed directional couplers with a directivity of 30 dB, which is substantially higher than 20 dB, as the practical index can be sufficiently suitable for communication systems such as microwave systems and IMT-2000. More studies are required to additionally improve the directivity of the proposed architectures or apply the proposed architectures to practical hardware.

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