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Reduced Hybrid Ring Coupler Using Surface Micromachining Technology for 94-GHz MMIC Applications

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Abstract

In this study, we developed a reduced 94 GHz hybrid ring coupler on a GaAs substrate in order to demonstrate the possibility of the integration of various passive components and MMICs in the millimeter-wave range. To reduce the size of the hybrid ring coupler, we used multiple open stubs on the inside of the ring structure. The chip size of the reduced hybrid ring coupler with multiple open stubs was decreased by 62% compared with the area of the hybrid ring coupler without open stubs. Performance in terms of the loss, isolation, and phase difference characteristics exhibited no significant change after the use of the multiple open stubs on the inside of the ring structure. The reduced hybrid ring coupler showed excellent coupling loss of 3.87±0.33 dB and transmission loss of 3.77±0.72 dB in the measured frequency range of 90–100 GHz. The isolation and reflection were −48 dB and −32 dB at 94 GHz, respectively. The phase differences between two output ports were 180°±1° at 94 GHz.

Index Terms: DAML, Hybrid ring coupler, MMIC, 94 GHz

I. INTRODUCTION

Nowadays, conventional planar transmission line structures such as microstrip line and coplanar waveguide (CPW) are widely used in microwave and millimeter-wave integrated circuits. However, the geometric structure of these conventional transmission lines has dielectric loss and dispersion characteristics due to the semiconductor substrate, which degrades the circuit performance in the high-frequency range. Recently, micro-electro-mechanical (MEMS)-based low-loss transmission lines have been reported with various structures [1-6]. The improvement in their performance has been drastic. In particular, membrane-supported transmission lines have been proven to be one of the most promising candidates for millimeter-wave applications [6]. However, these transmission lines including membrane-supported transmission lines have some critical drawbacks such as difficulty for fabrication, large size, and problems with their integration on monolithic microwave integrated circuits (MMICs), resulting in high costs per unit area. In order to solve these problems, we proposed a dielectric-supported air-gapped microstrip line (DAML) structure in which signal lines are elevated from ground plates to reduce the substrate dielectric loss and obtain low losses in the millimeter-wave range [7]. The fabrication of DAMLs can be easily realized using a microstrip structure without a complex backside process because in this structure, the signal line and the ground plate are on the same plane. In

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fact, this structure has various advantages for MMIC applications.

An important consideration in DAML applications is the electrical wavelength. The electrical wavelength of the DAML is longer than that of a conventional planar transmission line. This implies that passive components using DAMLs require a large chip size. Therefore, reducing the electrical wavelength of DAML is very important for integrating passive components with active devices on the same substrate.

In this study, we have developed a reduced 94-GHz hybrid ring coupler on a GaAs substrate. To reduce the size of the hybrid ring coupler, we used multiple open stubs on the inside of the ring structure.

II. DAML CHARACTERISTICS

The SEM photograph of the fabricated DAML is shown in Fig. 1. The signal line was elevated in air from the ground plates on the GaAs substrate by using a surface micromachining technology. When the metal thickness was 5 μm, the signal line height was 10 μm, and the signal line widths were 30 μm, 50 μm, and 70 μm, we obtained an insertion loss of 4.3 dB/cm, 3.5 dB/cm, and 2.2 dB/cm, respectively, at 110 GHz. The changes in impedance were shown to be in the range of 29–112 Ω [8].

DAMLs have considerable advantages as compared to established low-loss transmission lines, such as the ease of fabrication and integration on MMICs. Fig. 2 shows a comparison of the attenuation characteristics of other MEMS-based transmission lines reported previously. DAMLs do not show the lowest loss characteristics among the reported works. However, these transmission lines [5, 6], which have a lower loss than our DAML, have some critical drawbacks such as fabrication problems and large size, resulting in the difficulty of integration on MMICs. On the other hand, the DAML fabrication process is very simple and compatible with the standard MMIC techniques. Moreover, this process is carried out at a low temperature (T < 120°C) without any steps that cause a performance degradation of the MMICs, such as a dry etching step. In fact, our DAMLs are very useful for application in integrated millimeter-wave circuits, even when they do not have the lowest loss characteristics.

Further, for transmission line applications, the transmission-line wavelength must be considered. This wavelength is defined in Eq. (1), where λ_0 denotes the wavelength and the length of free space and ε_{eff} represents the effective dielectric constant of the substrate material. The effective dielectric constant is defined in Eq. (2). Here, w denotes the signal line width, h indicates the distance between the signal line and the ground, and ε_r represents the dielectric constant of the substrate. The width-to-height ratio (h/w) is a function of ε_r. When h/w is more than 1.3.

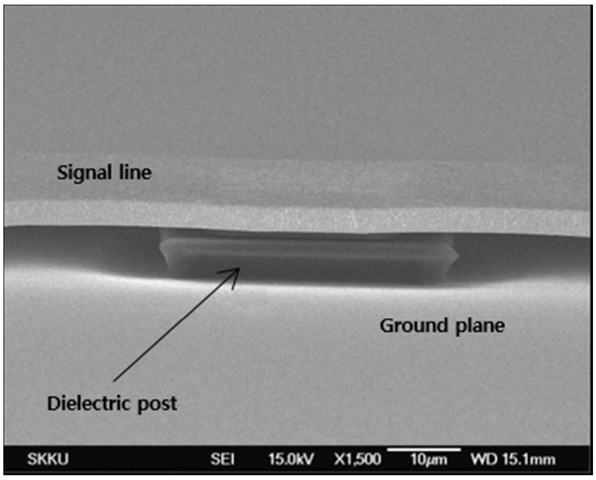

Fig. 1. SEM photograph of the fabricated dielectric-supported air-gapped microstrip line (DAML).

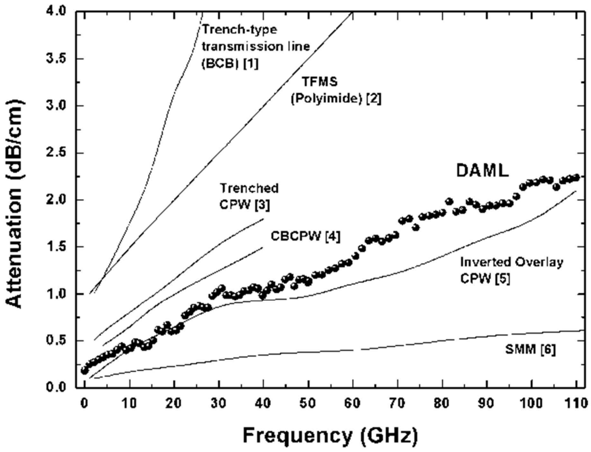

Fig. 2. Comparison of the attenuation characteristics of other MEMS-based transmission lines reported previously.

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}}, \quad (1)$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+10\frac{h}{w}\right)^{-0.5}. \quad (2)$$

Eq. (2) gives accurate results [9]. The analysis of the wavelength evaluation in the quasi-TEM mode is fairly accurate at low frequencies. At high frequencies, the effective dielectric constant begins to change as the frequency increases, making the transmission line dispersive [10]. The ratio of the longitudinal-to-transverse electric field components becomes significant, and the propagating mode can no longer be considered quasi-TEM. The analysis of the hybrid mode is far more rigorous.

The wavelength of the DAML was simulated using an electromagnetic simulation tool called HFSS from Ansoft. When the metal thickness was 5 μm, the signal line height was 10 μm, the signal line width was 50 μm, the distance between the dielectric posts was 500 μm, and the length of one side of the dielectric post was 40 μm, we obtained $\lambda_0/4$ = 766 μm at 94 GHz. The simulated results agree well with the measured results. The measured $\lambda_0/4$ of the fabricated DAML was 769 μm at 94 GHz.

III. REDUCED HYBRID RING COUPLER

As previously mentioned, the wavelength of the transmission line is an important factor for circuit design. The wavelength of the DAML is longer than that of the conventional planar transmission line because most of the substrate dielectric is in air. This implies that passive components using DAMLs require a large chip size compared with passive components using conventional transmission lines. Thus, reducing the wavelength of DAML is very important for high integration.

The quarter-wavelength of the transmission line can be reduced by connecting two open stubs [11]. Z_0, Z_a, and Z_b denote the characteristic impedances, and 45°, θ_a, and θ_b indicate the wavelength of the center frequency. Z_a and Z_b are defined in Eqs. (3) and (4) [11]. The simulated result obtained using the Ansoft HFSS shows that the reduced quarter-wavelength of the DAML is 478 μm at 94 GHz. Table 1 shows a comparison of the quarter-wavelength of the transmission line at 94 GHz.

$$Z_a = \frac{Z_0}{\sqrt{2}\sin\,\theta_a}, \quad (3)$$

$$Z_b = \frac{Z_0 \tan\theta_b}{\sqrt{2}\cos\theta_a - 1}. \quad (4)$$

To verify the reduced DAML with open stubs, we designed a hybrid ring coupler operating at the center frequency of 94 GHz. A general hybrid ring coupler is made of 1.5-λ_g DAMLs. In order to reduce the size of the hybrid ring coupler, the DAMLs on the circumference of the hybrid ring coupler are divided into a series of DAMLs. Then, each piece of DAML is replaced by a shorter DAML with two shunted open stubs.

The designed hybrid ring coupler was fabricated on a 680-μm-thick GaAs substrate by using the standard MMIC process of MINT, Dongguk University. The MINT MMIC process steps include mesa isolation, evaporation of an ohmic metal, resistor, first metal, deposition of Si_3N_4, and air-bridge formation. Fig. 3 shows an SEM photograph of the reduced hybrid ring coupler. The diameter of the fabricated hybrid ring coupler was 0.888 mm. The chip size of the reduced hybrid ring coupler with multiple open stubs was decreased by 62% compared with the area of the hybrid ring coupler without open stubs. The diameter of the hybrid ring coupler using DAMLs without open stubs was 1.46 mm [8].

Table 1. Comparison of the quarter-wavelength of the transmission line at 94 GHz

Type	Quarter-wavelength at 94 GHz (μm)
Microstrip	304
Coplanar waveguide	266
DAML	769
Reduced DAML with open stubs	478

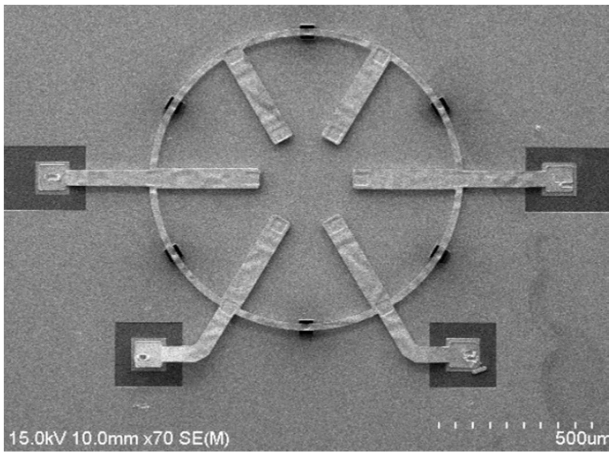

Fig. 3. SEM photograph of the fabricated hybrid ring coupler using reduced DAML with open stubs.

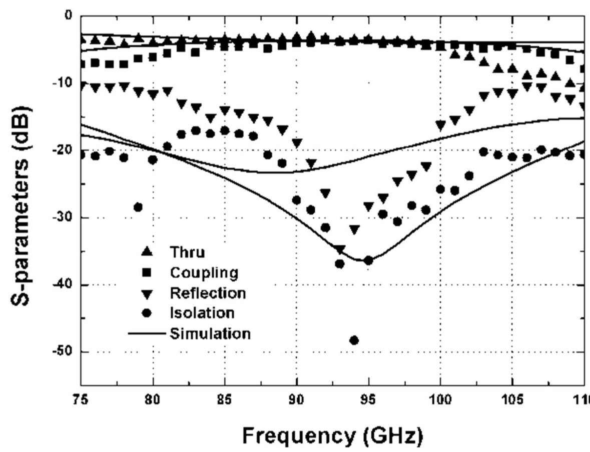

Fig. 4. Measured and simulated *S*-parameters of the fabricated hybrid ring coupler using reduced DAMLs with open stubs.

Table 2. Comparison of the hybrid ring coupler with other published data

Reference	Type	Transmission loss (dB)	Coupling loss (dB)	Reflection (dB)	Isolation (dB)	Diameter (mm)	Center frequency (GHz)
[12]	CPW	−5.50	−4.70	-	−29	0.70	94
[8]	DAML	−3.72	−3.35	−22	−34	1.46	94
This work	Reduced DAML	−3.78	−3.58	−32	−48	0.888	94

The *S*-parameters of the reduced hybrid ring coupler with multiple open stubs were measured using an Anritsu ME7808A vector network analyzer in the frequency range of 75–110 GHz. A through-short-line (TRL) calibration was performed using the on-wafer Anritsu calibration standard.

The simulated and measured results for the reduced hybrid ring coupler are shown in Figs. 4 and 5, respectively. The measured results agreed well with the simulated ones. Fig. 4 shows the *S*-parameters of the fabricated hybrid ring coupler, and Fig. 5 illustrates the phase differences between the direct port and the coupled port. The reduced hybrid ring coupler showed excellent coupling loss of 3.87±0.33 dB and transmission loss of 3.77±0.72 dB in the measured frequency range of 90−100 GHz. The isolation and reflection characteristics were −48 dB and −32 dB at 94 GHz. The phase differences between two output ports were 180°±1° at 94 GHz.

There are a few papers reporting the loss characteristics of a conventional hybrid ring coupler in this high frequency, 94 GHz. Table 2 shows a comparison of the hybrid ring coupler with other published data. The comparison revealed that the performance of our DAML-based hybrid ring coupler was superior to that of the conventional CPW-based hybrid ring coupler. The hybrid ring coupler with multiple open stubs was reduced by 62% in area. The measured results revealed that almost the same transmission and coupling loss characteristics as those of the hybrid ring coupler without open stubs were obtained in spite of the 62% size reduction. Therefore, the reduced hybrid ring coupler developed in this study is expected to be useful in 94-GHz MMIC applications.

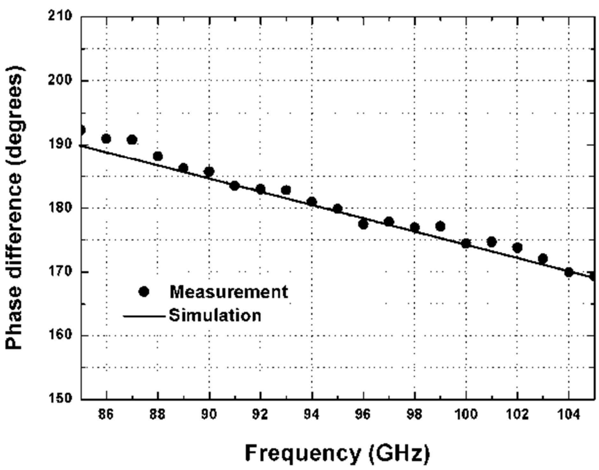

Fig. 5. Measured and simulated phase differences of the fabricated hybrid ring coupler using reduced DAMLs with open stubs.

IV. CONCLUSION

In this study, we developed a reduced hybrid ring coupler on a GaAs substrate in order to demonstrate the possibility of the integration of various passive components and MMICs in the millimeter-wave range. The reduced 94-GHz hybrid ring coupler was fabricated using surface micromachining technologies, which adopted our DAML structure. To reduce the size of the hybrid ring coupler, we used multiple open stubs on the inside of the ring structure. The chip size of the reduced hybrid ring coupler with multiple open stubs was decreased by 62% compared with the area of the hybrid ring coupler without open stubs. Performance in terms of the loss, isolation, and phase difference characteristics exhibited no significant change after using the multiple open stubs on the inside of the ring structure. The reduced hybrid ring coupler showed excellent coupling loss of 3.87±0.33 dB and transmission loss of 3.77±0.72 dB in the measured frequency range of 90–100 GHz. The isolation and reflection characteristics were −48 dB and −32 dB at 94 GHz, respectively. The phase differences between two output ports were 180°±1° at 94 GHz.

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