High-Performance Air-Gap Transmission Lines and Inductors for Millimeter-Wave Applications

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***Abstract*—The air-gap transmission lines and inductors are developed by new multilayer process. The developed transmission lines are air-gap coaxial line, air-gap strip line, air-gap coplanar waveguides (CPW), and air-gap buried microstrip line (BMSL). The air-gap transmission lines show very low signal loss and very high isolation performances. The transmission line loss of the coaxial line is less than 0.08 dB/mm up to 40 GHz. Those of the CPW, strip line and BMSL are about 0.07, 0.15, and 0.13 dB/mm, respectively. The isolation characteristics of the coaxial line and BMSL are measured. In case of the coaxial line with 2-mm coupling length and 60-μm distance between signal lines, the coupling is less than −52 dB up to 40 GHz. In case of the BMSL with the same conditions, the coupling is less than −43 dB. Therefore, the air-gap transmission line is very suitable structure for high performance and high-density RF application. Additionally, the air-gap inductors are monolithically fabricated using the same process of the transmission line. The fabricated inductors have very high quality factors, the maximum Q factor of 1.46-nH air-gap inductor is about 130. Using the developed multilayer process, we can realize various types of air-gap transmission lines (coaxial line, CPW, strip line and BMSL) and air-gap inductors simultaneously.**

***Index Terms*—Air-gap transmission line, multilayer RF passive device, RF micromachining device.**

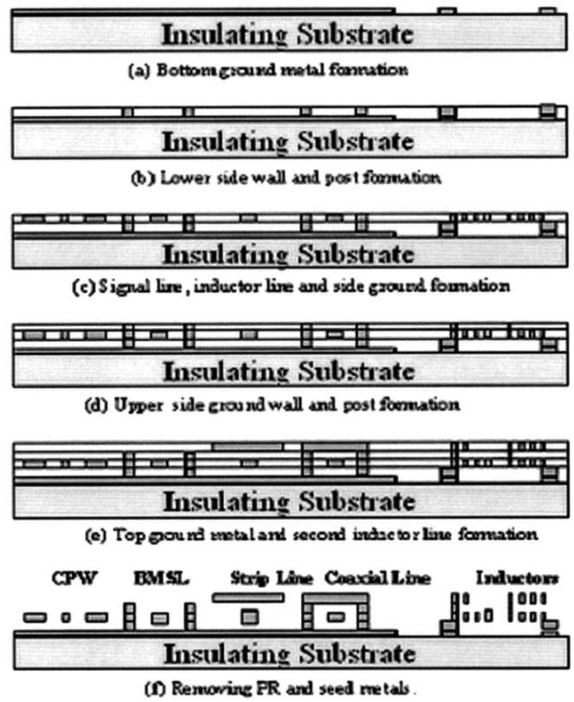

Fig. 1. Process steps for integration of the proposed transmission lines and inductors.

I. Introduction

RECENT developments of monolithic microwave integrated circuits (MMICs) are placing increasing demand on circuit interconnection technique that high frequency signal can be propagated through interconnection line without sacrificing circuit performance. At present, the most common interconnection line structures in monolithic integrated circuit technology are the microstrip line and coplanar waveguide (CPW) configurations. The geometric structure of these interconnections can change the propagating field distribution that has a large impact on the performance of the circuits and this field distribution change affects the loss and dispersion characteristics of the transmission lines over semiconductor to degrade the high frequency signal performance.

For microwave and millimeter-wave transmission lines, the air dielectric material was a good candidate to achieve low loss and high-frequency operation devices [1]–[3], [8] In spite of these advantages, the air dielectric material was not used for transmission lines and other microwave devices because of process complexity, reliability problem, and package issue. Implementation of multilayer air dielectric is very hard becauseit is difficult to remove the sacrificial layer and seed metal for electroplating process. Besides, due to poor surface roughness, it is very hard to achieve precision line width and spacing and to prevent electrical short.

In this paper, we use new process techniques to solve the above-mentioned problems and fabricate several types of the transmission lines, that is, air-gap coaxial line, air-gap strip line, air-gap CPW, and air-gap buried microstrip line (BMSL) on thick oxide silicon substrate [10], [11]. We also fabricate two types of inductor, based on same process technique. Therefore, all the transmission lines and inductors can be simultaneously made on same substrate with the developed multilayer process.

II. Air-Gap Coaxial Line

The structure of air-gap coaxial line is so simple that it can be fabricated just by lithography and Cu plating process. Fig. 1 shows the process steps to make various transmission lines and inductors. But there is just one different point, compared to conventional process. We use titanium/copper(Ti/Cu) as seed metal

Manuscript received April 2, 2002; revised August 5, 2002.

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Digital Object Identifier 10.1109/TMTT.2002.805138

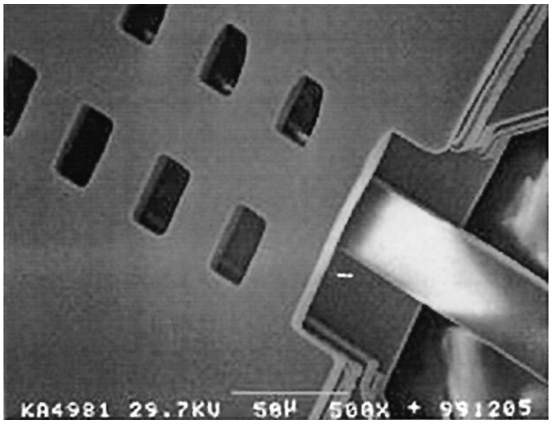

Fig. 2. SEM photograph of the fabricated air-gap rectangular coaxial line on thick oxide Si substrate.

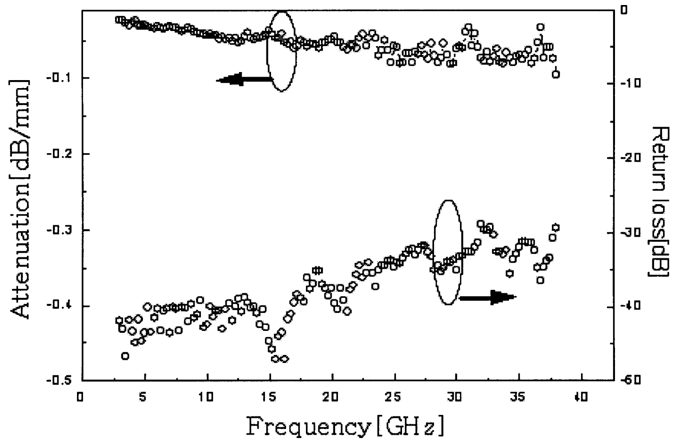

Fig. 3. Result of attenuation and return loss of air-gap rectangular coaxial lines ($w = 30$ μm, $g = 35$ μm).

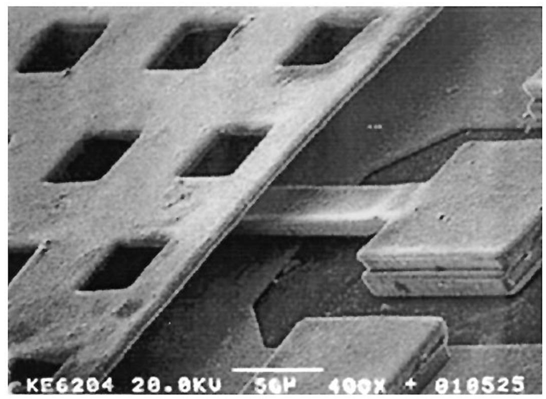

Fig. 4. SEM photograph of the fabricated air-gap strip line on thick oxide Si substrate.

for electro copper plating. But the copper seed metal is patterned before the plating process. This process method can provide fine pitch line and spacing even if the surface roughness is very poor. And it also prevents chemical attack on plated Cu metal during the process of seed metal removal.

The analysis of coaxial lines has been the subject of substantial research, where they attempt to find a simple and precise expression for characteristic impedance in the rectangular coaxial configuration. In [14], Cruzan describes that the characteristic impedance of rectangular coaxial transmission line can be readily and accurately computed by a simple equation when the capacitance per unit length is known.

In this study, the air-gap coaxial line is monolithically implemented using an air as a dielectric material. The coaxial line is designed for 50-Ω characteristic impedance.

Due to its closed structure and air characteristic, the coaxial line provides low attenuation and high isolation compared to the conventional CPWs (0.3-dB/mm attenuation at 10 GHz [10]) and the elevated CPWs (0.1-dB/mm attenuation at 20 GHz [2]).

Fig. 2 shows the scanning electron microscope (SEM) photograph of the coaxial line fabricated by our advanced process. The width (w) of the signal line is 30 μm and the gap (g) between the signal line and the sidewall ground is 35 μm. The thickness of signal line and the gap signal line to top and bottom ground are 12 μm, respectively. The characteristics of coaxial line are shown in Fig. 3.

The attenuation level of the coaxial line is lower than 0.08 dB/mm at 40 GHz. The return loss is less than -32 dB ($g = 35$ μm). To investigate the crosstalk characteristic, which is important for high-density integration, we measure the coupling between the two 50-Ω coaxial lines. The coupling length is 2 mm and the line spacing, the distance between two signal lines, is 60 μm. Fig. 8 shows the coupling of the coaxial lines with frequency. The coupling is less than -52 dB over the whole measured frequency range.

III. Air-Gap Strip Line

The proposed air-gap strip line provides very low signal attenuation and good performance in high-frequency region. Fig. 4 shows the SEM photograph of the fabricated air-gap strip line on thick oxide Si substrate using the same process as the air-gap coaxial line process. The width of the signal line is 25 μm and the thickness of the signal line is 12 μm. The gap of signal line and ground is fixed to be 12 μm. The center conductor is an air-bridged metal supported by several posts on thick oxide Si substrate. The pitch of posts is 700 μm and their cross section area is 35×25 μm. Every post is surrounded by ground plane with 20-μm separation.

The signal line width (w) for 50-Ω impedance can be easily calculated with Agilent Advanced Design System (ADS) software. The length of the fabricated air-gap strip line is 2 mm. According to the calculation result, 50-Ω line width is 26 μm. Fig. 5 shows the attenuation and the return loss of the strip line in decibels per millimeter (dB/mm) versus frequency.

As shown in Fig. 5, the attenuation of the strip line is lower than 0.1 dB/mm ($w = 26$ μm) in the frequency range of 1–25 GHz. The return loss of the 2-mm-long strip line is less than -32 dB ($w = 26$ μm). It is shown that the characteristic impedance of the strip line is very close to 50 Ω. It is very good agreement with the simulation result.

IV. BMSL

Ishikawa *et al.* proposed BMSL in 1996 [4], [5]. In this section, we investigate the BMSL structure that possibly meets low loss and high isolation requirements.

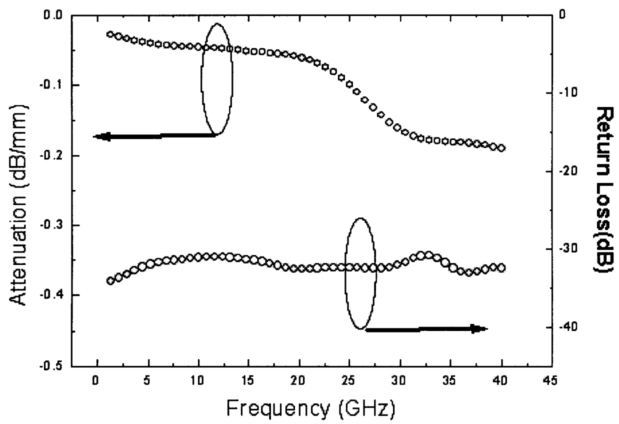

Fig. 5. Measured results of the attenuation and return loss of air-gap strip line.

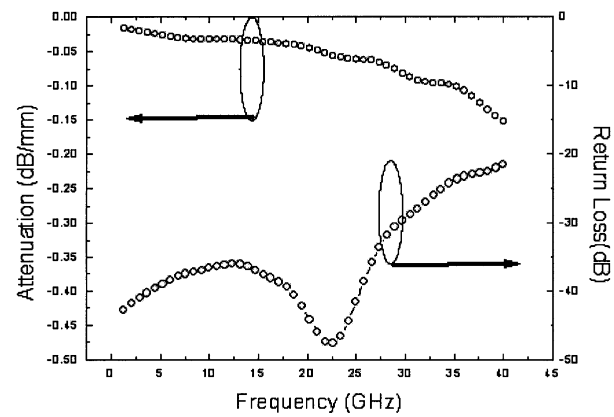

Fig. 7. Results of the attenuation and return loss of air-gap BMSL ($w = 30\ \mu$m, $g = 25\ \mu$m).

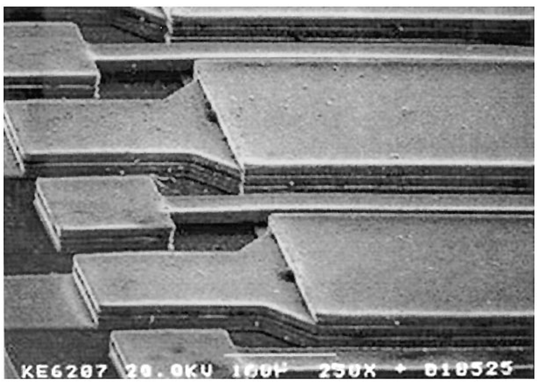

Fig. 6. SEM photograph of the fabricated air-gap BMSL on thick oxide Si substrate.

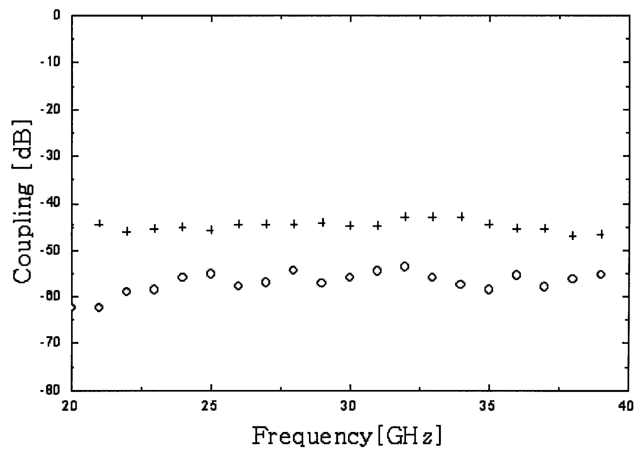

Fig. 8. Measured isolation performance of the air-gap coaxial and the air-gap BMSL. $+$: air-gap BMSL o: air-gap coaxial line.

The air-gap BMSL has low coupling property because of its structure. It also has low-loss property because of the air dielectric material. Fig. 6 shows the SEM photograph of air-gap BMSL using the air multilayer process and the copper electroplating process.

The width and the thickness of center conductor are 30 μm and 12 μm, respectively. The gap from side ground to the center conductor is 25 μm. The height from bottom ground to the center conductor is fixed to be 12 μm. The center conductor is an air-bridged metal supported by several posts and the pitch of posts is 700 μm. The thickness of side ground wall is 36 μm, it is 12 μm higher than the signal line. The process of the air-gap BMSL is also very compatible with that of the air coaxial line.

Fig. 7 shows the attenuation and the return loss of the BMSL in dB/mm versus frequency. The effects of the dielectric and conductor losses are included. The attenuation of the BMSL is lower than 0.13 dB/mm in the frequency range of 1–40 GHz. The return loss of the 2-mm long BMSL is less than -20 dB. As the air-gap coaxial line, BMSL also shows low signal propagation loss and low crosstalk even in tens of gigahertz.

To measure the coupling characteristic, two BMSLs are fabricated. The coupling length is 2 mm and the line spacing, ground width between the lines is 60 μm. Fig. 8 shows the measured coupling characteristics between the two BMSLs versus frequency. The coupling is lower than -43 dB in the measured frequency range. But the coupling of the BMSL is worse than that of the coaxial line, because its topside is opened, compared to the closed structure of coaxial line.

V. AIR-GAP CPW

A CPW is one of the most suitable structures for minimizing signal loss in high-frequency range. Thus, it is very popular interconnection structure in millimeter-wave circuit design.

In this section, we introduce air-gap CPW, which is realized with the same process used in the fabrication of the transmission lines in the previous sections. The CPW is designed for 50-Ω characteristic impedance. The characteristic impedance highly depends on the height of air dielectric, the signal line width and thickness and the gap to ground plane. The metal thickness and the height from bottom ground are same as those of previous transmission lines. Several posts support the signal line and side ground plane and they have the same physical dimensions as those of the strip line. Fig. 9 shows the SEM photograph of the air-gap CPW using the air multilayer process and the copper electroplating process.

The signal line width (w) for 50-Ω line impedance is calculated with Agilent ADS software. The width of signal line (w) is 35 μm and the gap (g) is 13 μm. The fabricated CPW has bottom ground plane.

The insertion loss of the air-gap CPW is below 0.07 dB/mm up to 40 GHz. It shows very low signal attenuation among the air-gap transmission line structure. Fig. 10 shows the signal attenuation and the return loss of the air-gap CPW with fre-

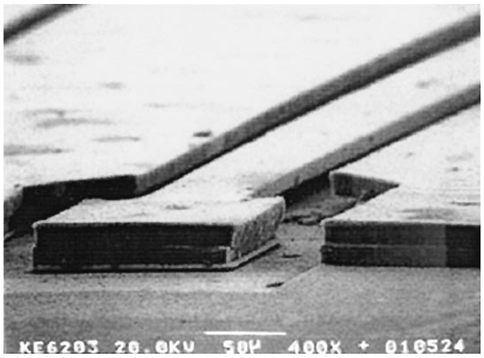

Fig. 9. SEM photograph of the fabricated air-gap CPW on thick-oxide Si substrate.

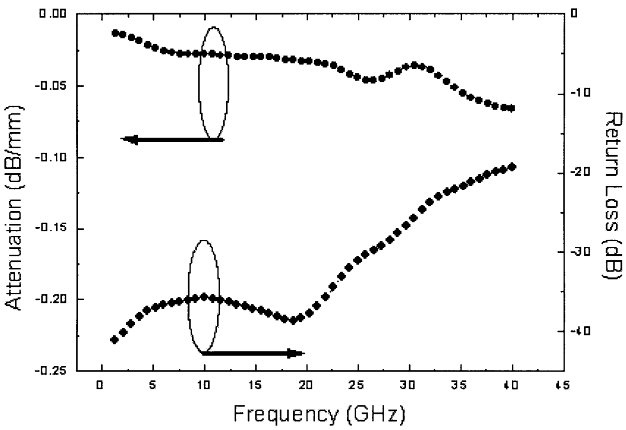

Fig. 10. Results of the attenuation and return loss of air-gap CPW ($w = 35\ \mu$m, $g = 13\ \mu$m).

quency. The measured return loss of the 2-mm-long CPW is below −20 dB.

VI. Air-Gap Spiral Inductors

Monolithic inductor on a semiconductor is key component to realize high performance radio frequency circuits. To realize an inductor with large inductance, high resonant frequency and high-Q factor, many approaches such as high resistivity semiconductor, thick dielectric material layer, stacking metal layers and micromachining technique have been reported.

In this section, air-gap inductor is fabricated using the same process used in fabricating previous transmission lines. It has a novel high-Q and high resonance frequency. There are two types of air-gap inductors. One is one-layered inductor. It has only one air dielectric layer and two metal layers. The other is two-layered inductor. it has two air dielectric layers and three metal layers.

Fig. 11 shows the SEM photographs of the fabricated one-layered air-gap inductor. The line width and spacing of the inductor is 20 μm, respectively. The thickness of the air layer and the cu plated metal is 12 μm, respectively. The inner diameter of the inductors is 150 μm. The inductor line is supported by the several metal post at corner sections.

The S-parameter is measured between 0.5 to 15 GHz using on-wafer probe and open pad reference circuit. The inductor has the inductance of 2.74 nH and series resistance less than

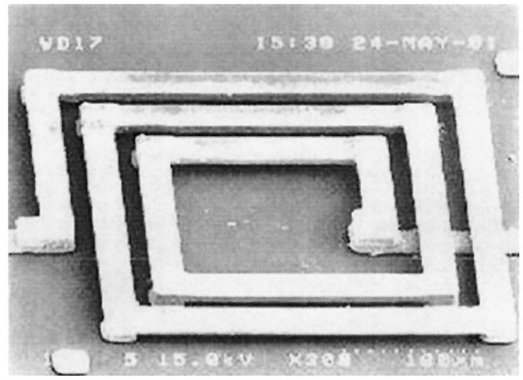

Fig. 11. The SEM photograph of the fabricated one layered air-gap inductors on thick oxide Si substrate.

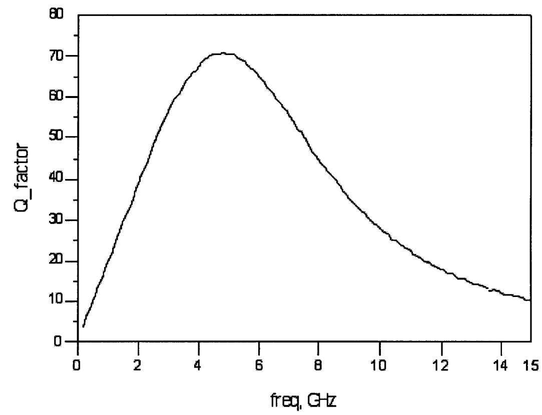

Fig. 12. Q-factors of the one-layered air-gap inductors according to frequency.

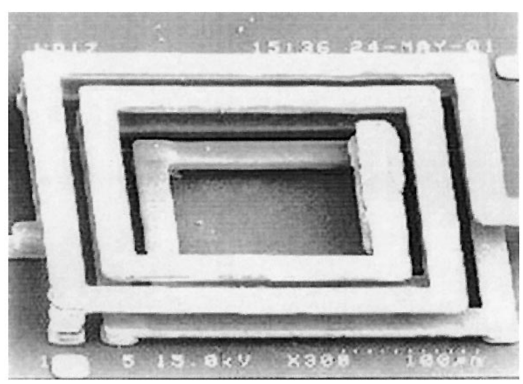

Fig. 13. SEM photograph of the fabricated two layered air-gap inductors on thick oxide Si substrate.

0.8 Ω. The shunt capacitance to the ground is less than 14 fF. It means that the parasitic effect due to the substrate can be ignored because of the 12 μm air dielectric isolation layer.

The Q-factor curve of the fabricated inductor is shown in Fig. 12, where the Q-factor is determined as the ratio of the imaginary part and the real part of the one port input impedance transformed from two-port S-parameter. The maximum Q-factor of the inductor is about 70. The resonance frequency is higher than 15 GHz.

Fig. 13 shows a photograph of the two-layered spiral inductor fabricated using the air multilayer process, which has 2.5 turns and 20-μm line width. The line-to-line spacing is 20 μm and

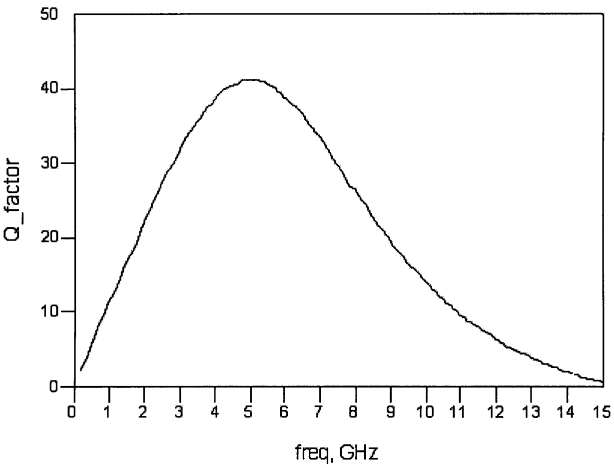

Fig. 14. Q-factor of the two-layered air-gap inductors according to frequency.

the height from the substrate is 12 μm. The inner diameter is 150 μm.

The inductor has the inductance of 5.65 nH and series resistance of 3.1 Ω. The shunt ground capacitance is about 55 fF. The extracted Q-factor curve is shown in Fig. 14, which shows maximum Q-factor of about 42 at 5 GHz and resonance frequency of about 13.4 GHz. Compared with some other works, the resonance frequency of the air-gap inductor is very high [11], [15].

VII. Conclusion

There have been many approaches to make high performance transmission lines for millimeter-wave applications. The low loss and high isolation performance is required for higher frequency applications or high-density applications. Using the proposed structures and the developed process, we can fabricate the advanced transmission lines with high isolation and low loss performance up to millimeter-wave frequency range. Only the lithography and the copper plating process are applied to fabricate air-gap transmission lines and the size of air-gap transmission lines is small, compared to other approaches.

The air-gap coaxial line shows low insertion loss of 0.08 dB/mm up to 40 GHz, including conductive metal loss. Besides, the 2-mm-long coupling is less than -52 dB at 60-μm coupling gap.

The air-gap strip line shows the loss of 0.1 dB/mm up to 25 GHz and the return loss is below -32 dB at 2 mm-long length. The attenuations of the air-gap BLSL and air-gap CPW are less than 0.13 and 0.07 dB/mm at 40 GHz, respectively. And the coupling of the BMSL is below -43 dB in case of 2-mm-long coupling length and 60-μm coupling distance.

With the developed technologies, all the air-gap transmission lines can be fabricated on same substrate at the same time. Additionally, the fabrication cost is very low and the manufacturing process is very simple. The physical size of the transmission line is very small, compared to other research results, such as microshield line, BMSL, and some other micromachined transmission lines.

Additionally, we demonstrate a new monolithic spiral inductor based on air multilayer process that offers high-Q factor and high resonance frequency. It is realized on a same substrate by the same process as those of the air-gap transmission lines.

These technologies will be very good solution in next-generation digital wireless communication system requiring high frequency operation and high isolation performance and will be widely utilized for low cost millimeter-wave modules and systems.

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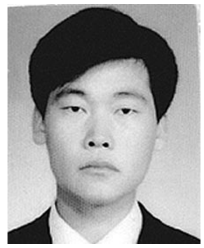

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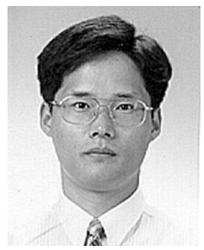

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