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A 20-GHz Miniaturized Ring Hybrid Circuit Using TFMS on Low-Resistivity Silicon

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Abstract: In this paper, a miniaturized ring hybrid circuit is characterized based on a thin film microstrip (TFMS) on low-resistivity silicon. In order to obtain low-loss characteristics, a polyimide layer with 50 μm thickness is spin-coated onto the silicon to be used for the substrate. First, propagation characteristics of TFMS lines consisting of the ring hybrid circuit are presented. Then, a ring hybrid circuit based on TFMS is featured by employing the triple concentric circle approach for miniaturization. Triple concentric circle lines with $\lambda_g/4$ or $3\lambda_g/4$ line lengths are implemented on the surface of the polyimide by circularly meandering to reduce the circuit size of the designed ring hybrid. Good agreement between measured and simulated results is obtained.

Keywords: Low-resistivity silicon, Miniaturization, Polyimide layer, Ring hybrid, Thin film microstrip (TFMS).

1. Introduction

The thin film microstrip (TFMS) line technology based on a low resistivity silicon has recently attained excellent performance in the area of low-cost highly integrated circuits. Since the ground plane is placed on the surface of the silicon to block interaction of the electromagnetic field with the silicon, the substrate loss in low resistivity silicon (1 - 30 Ω·cm) is dramatically reduced [1]. To be used as the substrate of TFMS, a thin film insulating layer such as polyimide, SiO_2, or BCB is coated on top of the ground plane. Thus, TFMS geometry exhibits several beneficial aspects such as the possibility of using small via holes and minimized transmission lines resulting in circuits of higher density, as well as a wide range of impedance values by controlling the strip width and the thickness of the insulation layer [2].

Based on TFMS technology, branch line couplers [3] or ring hybrids [4] for power combining or dividing components, which are extensively used in balanced amplifiers, mixers, and phase shifters, have been successfully implemented to realize miniaturized radio frequency integrated circuits (RFICs). However, the conventional $\lambda_g/4$ transmission line sections consisting of hybrid circuits, which are highly meandered to reduce the effective size of the hybrids, have a particularly undesirable effect on the phase difference of a ring hybrid and a somewhat empirical approach results in difficult design for high frequency range application.

To minimize the occupying area of original ring hybrids, the lumped-distributed technique as an alternative approach is employed [5], but its effectiveness for size reduction is limited below the 10 GHz range and is contrary to the full integration concept.

In this paper, TFMS with 50 μm-thick polyimide film is designed to reveal extremely low-loss characteristics in addition to a wide range of available characteristic impedances. Moreover, using design rule [6-8], a 180° ring hybrid having a 20 GHz center frequency is fabricated to verify the performance of the proposed TFMS, where the high impedance lines of $Z_0 = 70.7\ \Omega$ and the feed lines for $Z_0 = 50\ \Omega$ characteristic impedances are located on the polyimide layer and the CPW on-wafer probing structure. Furthermore, the high impedance lines are modified in accordance with the triple concentric circle approach for overall size reduction, permitting convenience in calculating the geometry of the desired ring hybrid.

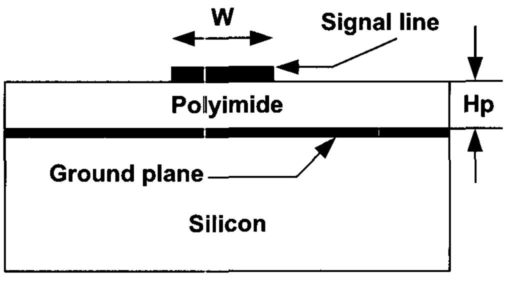

Fig. 1 Schematic of the proposed CBCPW with thin film polyimide on CMOS-grade silicon.

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2. Miniaturized Ring Hybrid Design

Fig. 1 presents the TFMS line fabricated on a polyimide layer with 50 μm-thickness on top of the ground plane placed on the surface of the low resistivity silicon. The lower metal conductor on the silicon wafer surface functions as a ground plane, while the upper metal operates as a signal line. Polyimide film with 50 μm thickness coated on a silicon wafer is used for the substrate of the TFMS line. From Fig. 1, the TFMS geometry is chosen to obtain 70.7 Ω line characteristic impedance with W = 70 μm and H_p = 50 μm for miniaturized concentric ring hybrid circuits while the 50 Ω line geometry is embodied with W = 120 μm on the top surface of the polyimide.

In TFMS, overall losses are generally determined by conductive loss instead of substrate loss due to its narrow line features. However, by increasing the substrate thickness up to 50 μm while allowing wider signal line width, the overall loss can be further reduced as shown in Fig. 2.

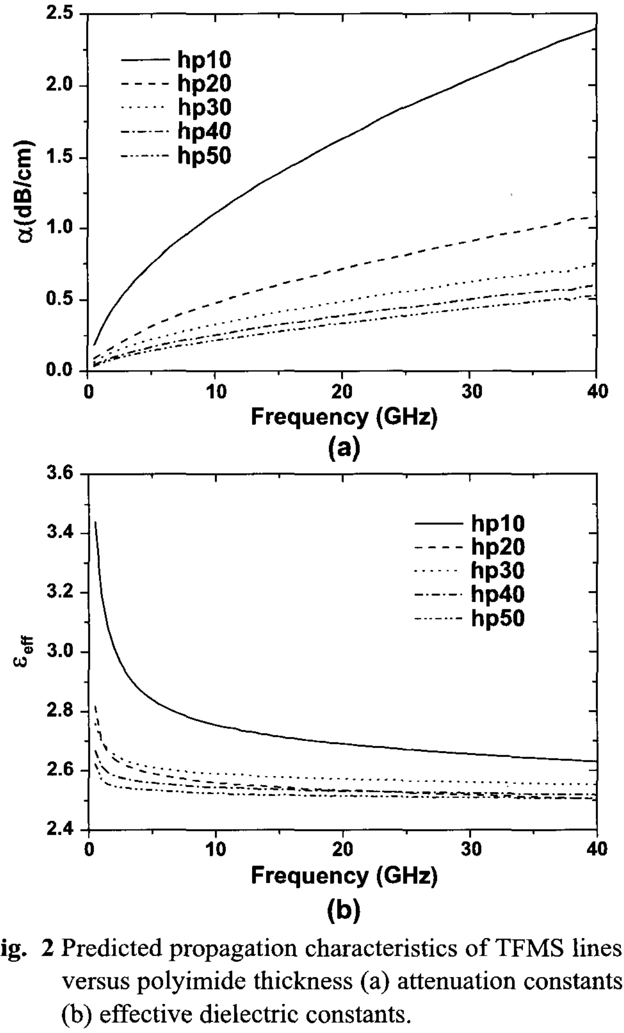


Fig. 2 Predicted propagation characteristics of TFMS lines versus polyimide thickness (a) attenuation constants, (b) effective dielectric constants.

As the polyimide thickness, H_p, increases from 10 μm to 50 μm, predicted attenuation constants are reduced from 2.3 dB/cm to 0.5 dB/cm at 40 GHz. Also, as the polyimide thickness increases, a much lower effective dielectric constant near to 2.5 is obtained. This verifies the fact that a greater amount of electromagnetic fields are confined in the air that consists of a perfect dielectric material. As such, non-dispersive characteristics suitable for high-speed digital interconnect applications are well guaranteed for the TFMS with a thicker polyimide.

Fig. 3 shows the predicted attenuation constants and effective dielectric constants for the 70.7 Ω TFMS line and 50 Ω TFMS line coated on the 50 μm-thick polyimide interface layer. Using the predicted effective dielectric constants, the miniaturized concentric ring hybrid is designed around the center frequency of 20 GHz. As well, the minimized attenuation constants do not allow the 50 Ω TFMS feed line geometry to influence the performances of the designed ring hybrid.

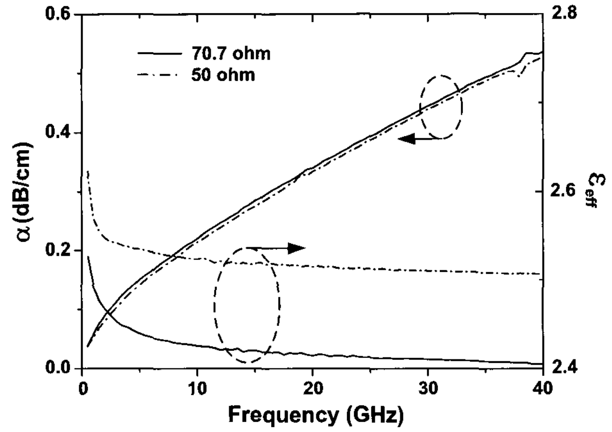
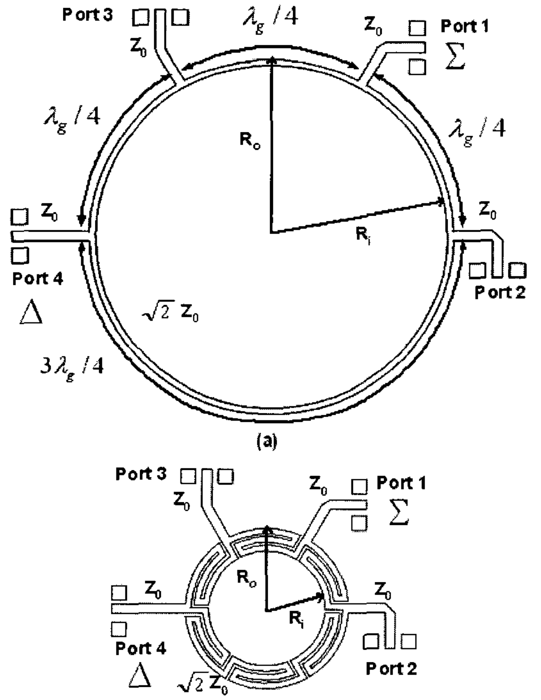


Fig. 3 Predicted attenuation constants and effective diezlectric constants of the designed TFMS lines that are used as 50Ω and 70.7Ω structures for implementing ring hybrids.

The miniaturized ring hybrid circuit is designed by using a commercially used method-of-moments (MOM) based simulator. For the design of a ring hybrid at 20 GHz, the use of 50 Ω and 70.7 Ω TFMS lines is required. For obtaining the 70.7 Ω lines, the TFMS techniques ensure the line widths of 70 μm while 50 Ω lines require 120 μm of line widths. For smaller ring hybrid circuit size and lower manufacturing cost, TFMS lines are concentrically meandered with the line space of only 50 μm. Therefore, the triple concentric circle-shaped TFMS line approach, as well as the thick polyimide configuration, provides more effective size reduction and lower loss.

Fig. 4 indicates the layouts for implementing the conventional and minimized ring hybrid circuits along with their port definitions. The signal line is laid on top of a spin-coated 50 μm thick polyimide layer that is placed on a silicon substrate sandwiched with a ground plane. The sizes of $\lambda_g/4$ and $3\lambda_g/4$ used in a conventional TFMS hybrid are too large for low-cost applications while proposed concentric circle TFMS effectively reduces the circuit area due to the narrow line width and spacing as well as the concentric circular approach. As shown in Fig. 4, the conventional ring hybrid circuit on TFMS has a radius of 2310 μm (R_o = 2345 μm and R_i = 2275 μm), while the miniaturized concentric ring hybrid exhibits a radius of 1083 μm (R_o = 1118 μm, R_i = 808 μm) allowing 77% of circuit minimization. For this design a spacing of 50 μm is used for minimal parasitic coupling between lines and for considering fabrication tolerances. By using triple concentric circle approach for the $\lambda_g/4$ and $3\lambda_g/4$ TFMS lines, the intrinsic area excluding the feed lines and pad structure for on-wafer probing of the miniaturized ring hybrid circuit is only 3.93 mm^2, compared to 17.28 mm^2 when implemented on a conventional TFMS ring hybrid on a thin film polyimide.

Fig. 5 shows a photograph of the fabricated TFMS ring hybrid with its port definition and dimension information. As indicated in Fig. 5, TFMS with 120 μm of signal line width is utilized for 50 Ω geometry while the overall dimension including line width and spacing is 210 μm for evaluating the concentric circular ring hybrid, respectively.



(a)

(b)

Fig. 4 Schematic of the designed ring hybrid circuit on TFMS (a) conventional ring hybrid, (b) miniaturized concentric circular ring hybrid.

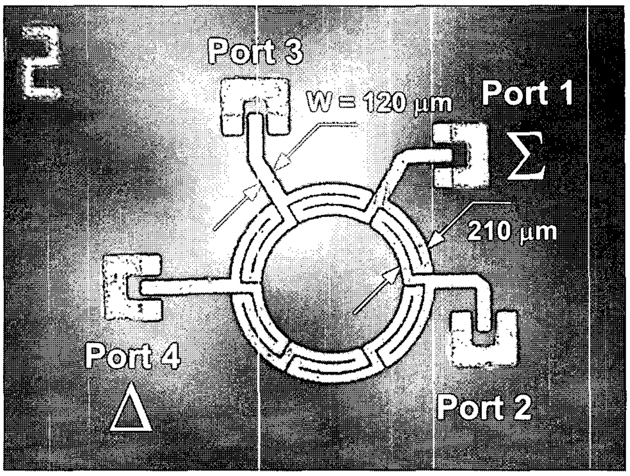


Fig. 5 Photograph of the fabricated miniaturized ring hybrid based on TFMS on low resistivity silicon.

3. Experiment Results

For the implementation of miniaturized ring hybrid circuits based on a TFMS line, 5000 Å SiO_2 is deposited on top of the silicon substrate first, then 200 Å Cr and 1 μm Cu layers are thermally evaporated as a ground plane. For improved adhesion of the polyimide material, promoter (VM652) is applied on the metal layer and a 50 μm thick polyimide layer (Dupont PI-2611) consisting of ε_r = 3.1 and tan δ = 0.003 is spin-coated and cured at 350°C for one hour. To form the via holes connecting the top conductor to the ground layer, a 3000 Å Al layer is evaporated and 100% O_2 RIE process is used to selectively etch the polyimide layer. To form concentric circular ring hybrid circuits on top of the polyimide surface, positive PR (AZ 4620) is used as the electroplating mold and sacrificial layer. Finally, the sacrificial layer is removed by the wet etching technique and dried at 80°C in a convection oven.

For on wafer measurement, the Open-Short-Load-Thru de-embedding procedure is performed by using a vector network analyzer with G-S-G high frequency coplanar probes having 200 μm pitch. Two pairs of via holes are fabricated on both sides of the ground pads of the CPW probe area and probe tips are utilized to make electrical contacts to the TFMS ground plane on silicon. During characterization, two of the four ports are terminated with RF probes and broadband 50 Ω terminations.

The measured and simulated magnitude responses of the miniature ring hybrid circuit, including a 500 μm length of TFMS line at each port, are illustrated in Fig. 6. First, it is observed that the measured responses agree well compared to the simulated data except for the slight frequency shift and loss reduction. The slight frequency shift is thought to be a result of the fabricated tolerances since the designed line widths of the concentric hybrid with 70.7 Ω is 70 μm.

However, measured line widths are approximately 90 μm resulting in the variation of $\lambda_g/4$ concentric transmission characteristic impedances into 62 Ω structures.

The simulated ring hybrid performances exhibit coupling losses S_{21} and $S_{31}$of 3.4 ± 0.3 dB over 17.5 and 22.5 GHz. The return loss S_{11} and isolation S_{41} is 13.5 dB and 45 dB at 20 GHz, respectively. For measured performances, the return loss is 12.5 dB or higher, but there is a slight upward shift in frequency to 21.5 GHz compared to the simulated results.

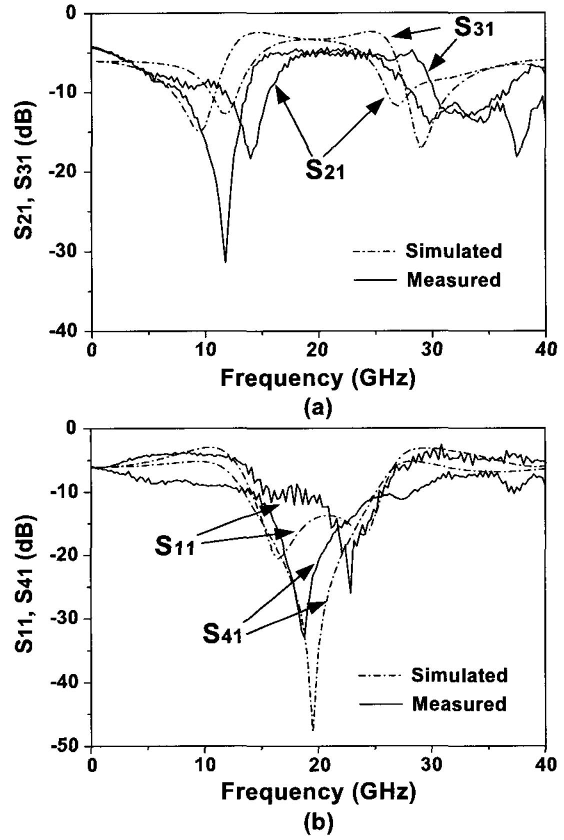


Fig. 6 Measured and simulated magnitude responses of the fabricated miniature ring hybrid (a) coupling loss (S_{21} and S_{31}), (b) return loss (S_{11}) and isolation (S_{41}).

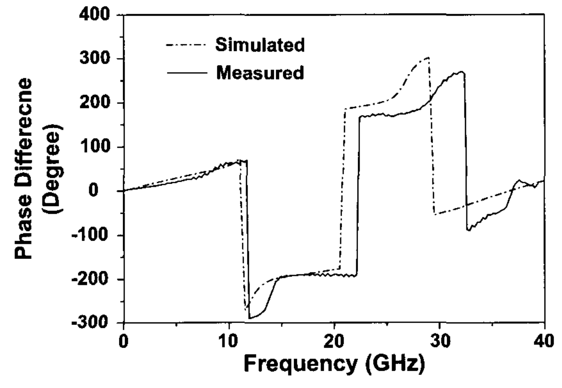


Fig. 7 Measured and simulated phase differences.

The isolation at port 4 when fed at port 1 is greater than 33 dB at 18.5 GHz and greater than 12.5 dB over an 8.5 GHz bandwidth. Also, it shows a coupling loss of 5.2 ± 0.3 dB between 15 and 25 GHz.

The simulated miniaturized ring hybrid circuits also offers a phase difference of 180° (-180°) ± 10° for a 15.5 to 23.5 GHz bandwidth while the measured phase difference is 180° (-180°) ± 10° over 15.5 to 28.5 GHz, as shown in Fig. 7. The measured performances exhibit good agreement with the simulated results maintaining a slight frequency shift.

4. Conclusion

In this paper, a 20 GHz miniaturized ring hybrid circuit obtained by using the triple concentric circle approach is designed and characterized based on thin film microstrip (TFMS) on low resistivity silicon. For low-loss property, 50 μm-thick polyimide is placed on the ground plane as a substrate of the designed TFMS lines. Attenuation constants and effective dielectric constants are presented versus geometry parameters. And then, based on a simplified design approach that utilizes the triple concentric circles to efficiently calculate the dimension, the miniature ring hybrid is implemented. The measured and simulated responses of the miniature ring hybrid have good agreement, which are not affected by the low resistivity silicon wafer. Therefore, the miniature ring hybrid with multiple concentric circle approach can be applied as a more flexible alternative for circuit size reduction scheme irrelevant to any kind of processing technique.

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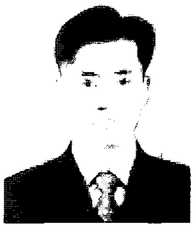

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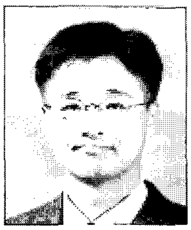

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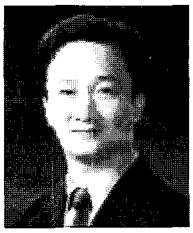

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