Integrating Passive Components With Active Circuits Using Standard Silicon Process for Millimeter-Wave Applications (Invited Paper)

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***Abstract*-Several passive components based on the quarter-wavelength transmission line can be integrated with active circuits for millimeter-wave applications. Passive components such as Marchand baluns, quadrature couplers, and rat-race hybrids are directly implemented on the standard low-resisitivity (~10 Ω· cm) silicon substrate. New circuit design concepts such as balanced loss and distortionless transmission line are applied to tolerate the unavoidable loss and thus the size reduction is achieved because of the high effective dielectric constant.**

I. Introduction

High data rate and wide bandwidth wireless communication systems are easily feasible in millimeter-wave frequencies because the usable bandwidth increases as the carrier frequency becomes higher. The advanced deep sub-micron silicon-based technologies have made the silicon devices with cut-off frequency more than 100 GHz possible [1-2] and thus the era of silicon millimeter wave is impending. Together with the properties of high integration and low-cost production in silicon fabrication process, the millimeter-wave SOC (System on Chip) can become a reality. The silicon radio-frequency/microwave integrated circuit revolution has brought the inductors and transformers into the integrated circuit. As the silicon circuit reaches the millimeter-wave regime, new circuit design concepts arise. It is now feasible to integrate passive components based on quarter-wavelength transmission line in the integrated circuit. In this invited paper, it demonstrates that passive components such as couplers, hybrids and baluns have been already integrated into standard silicon-based ICs. However, signal attenuation and crosstalk between two adjacent passive components resulting from the low-resisitivity (~10 Ω· cm) silicon substrate have strong influences on the microwave passive components. In the past, extra post-fabrication processes, high resistivity substrate and silicon-on-insulator (SOI) process are proposed to lessen the substrate effect [3-5]. Nevertheless, the extra process increases the cost and the high-resistivity substrate is prone to the undesired latch-up effect. The passive component size and the loss resulting from the substrate are big challenges. In this paper, our passive components operate well using standard silicon-based process because of the new design concepts such as balanced loss. The implementation directly on the silicon substrate is good for size compactness. Meander lines and a lumped-element technique also shrink the size further. The demonstrated circuits include wideband micromixers with an LO Marchand balun, an IQ downconverter using a quadrature coupler, a Gilbert micromixer with an integrated rat-race coupler and a resistive sub-harmonic mixer with an integrated Marchand balun LO.

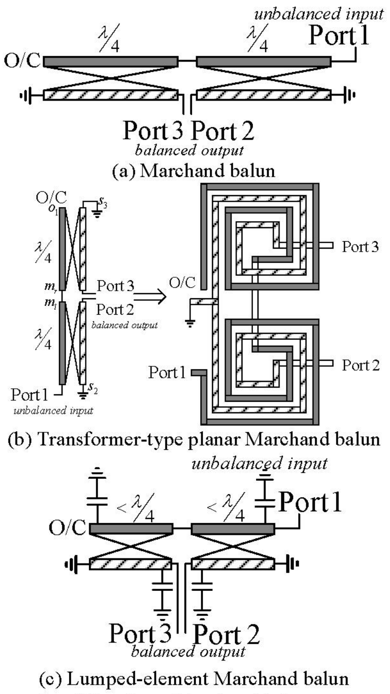
II. Millimeter-Wave Passive Components

A. Transmission Lines

In the low frequency circuit design, the parasitics of interconnections such as capacitance and metal resistance are taken into consideration in post-layout simulations. However, the substrate effects like skin and proximity effects influence circuit performance at high frequencies and needs to be considered in the simulations. If a signal path directly on the substrate does not have well-defined ground plane, it is not easy to perform simulation precisely. Because the operation frequency is up to millimeter-wave regime, multi-layer interconnect metals can be designed as a transmission line for better signal integrity. The MS and CPWG types using interconnect metals have shielding against the substrate loss, but effective dielectric constant is about 4 because of the silicon dioxide dielectric constant and it is not good for size reduction. On the other hand, CPW and CPS transmission lines are implemented directly on silicon substrate to reduce the size at the cost of loss. Nevertheless, by extraction from the measurement results of CPS transmission lines, the attenuation constant is 1.8 dB/mm and can be tolerable for some applications. In addition, non-dispersive distortionless transmission lines with real characteristic impedance can be utilized in the passive component design [6].

B. 3-Port 180°Balun

The Marchand balun, which is proposed in 1944, is a very broadband 3-port passive balun and has one unbalanced input and two balanced outputs [7]. Figure 2(a) illustrates the planar Marchand balun composed of two back-to-back quarter-wavelength coupled lines [8]. Monolithic Marchand baluns had been realized in ICs and most of them are fabricated on the semi-insulating GaAs substrate or the high-resistivity (>4000 Ωcm) silicon substrate [9-10]. Recently, the Marchand baluns are implemented using interconnect metals with shielding ground plane on a standard silicon substrate. However, the size is large because of the low dielectric constant and the balun bandwidth is reduced because of the low ratio of the even-mode to odd-mode characteristic



(a) Marchand balun

(b) Transformer-type planar Marchand balun

(c) Lumped-element Marchand balun

Fig. 2. Schematic of the planar Marchand balun

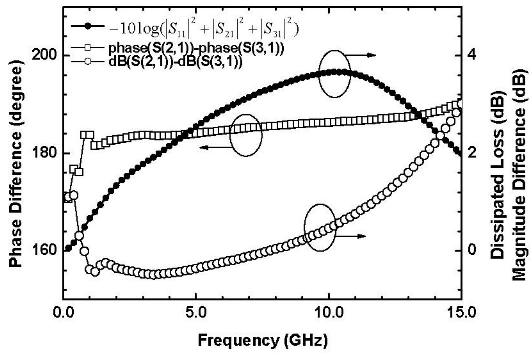
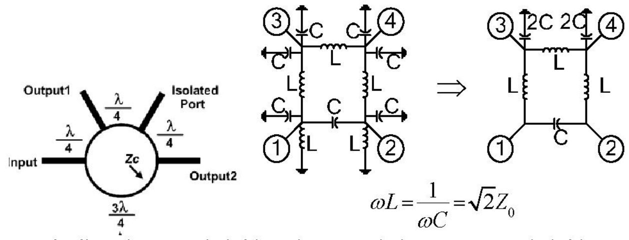


Fig. 3. Output difference and dissipated loss of the lumped-element Marchand balun.



(a) Distributed rat-race hybrid (b)Lumped-element rat-race hybrid

Fig. 4. Schematic of the rat-race hybrid

impedance of the coupled line [11-12]. Because the balun directly on the substrate without the shielding ground plane has higher effective dielectric constant, wide bandwidth and size reduction can be achieve on our proposed Marhcnad balun at the cost of the loss. The coupled lines in the planar Marchand balun can be formed by Lange couplers [13], broadside coupled lines [9], and spiral transmission coupled lines [9-11]. An interleave transformer as a quarter wavelength coupled line is employed in our work to shrink the balun size, as shown in Fig. 2(b) and can achieve the desired coupling coefficient. This Marchand balun designed at the center frequency of 12 GHz has the size of about 660 μm x 250 μm with more than 10-GHz bandwidth. The balun loss is acceptable and the dissipated loss is about 6 dB [14].

For size reduction and loss improvement, the lumped-element technique (adding capacitors at three ports and one open end) is utilized, as shown in Fig. 2(c) [15-16]. The length of coupled lines is hence shortened more than 60% and the dissipated loss is hence alleviated and less than 4 dB. This miniaturized Marchand balun with the size of 0.25 × 0.5 mm^2 operates from 2.5 GHz to 12 GHz. At the center frequency of 7.2 GHz, input return loss and insertion loss are about -11.6 dB and -6.8 dB, respectively. As shown in Fig.3, the output magnitude imbalance is below 1 dB up to 12 GHz when the phase error is about 4°. Thanks to the balanced structure of the Marchand balun, the outputs keep balanced and the dissipated loss is small enough [17].

C. 4-Port 180°Hybrids

Four-port passive components have better port matching than three-port elements. The most commonly used four-port element is a rat-race coupler, which consists of three one-quarter-wavelength and one three-quarter-wavelength transmission lines [18], as shown in Fig. 4(a). For size reduction, the transmission line can be replaced by high-pass and low-pass ‘pi’ or ‘T’ networks, as shown in Fig. 4(b). A lumped-element rat-race hybrid is simplified when the adjacent shunt capacitor and inductor cancel each other and two neighboring shunt capacitors are combined to reduce the number of lumped elements. The lumped-element technique shrinks the size but reduces the bandwidth [19-20].

The extra half-wavelength transmission line offers 180° phase delay only at the specific frequency and the useful bandwidth is limited. The output magnitude imbalance occurs due to unequal path loss as well. Therefore, a wideband phase inverter is employed in the middle of the quarter-wavelength transmission line to take place of the three-quarter-wavelength transmission line for bandwidth extension. It is an effective way to minimize the size and to extend the bandwidth simultaneously for the rat-race coupler [21]. On account of the low loss property of the phase inverter and equal path loss, this rat-race coupler maintains output signals balanced regardless of the substrate loss.

Most couplers are created on the silicon substrate with substrate shielding [22-23]. Due to a low effective dielectric constant, the coupler size is large. The 60 and 77 GHz finite-ground CPW phase-inverter rat-race couplers are realized directly on the silicon substrate [24] and size reduction techniques was applied at the cost of bandwidth even at such high frequencies. In our work, a symmetrical spiral-shaped

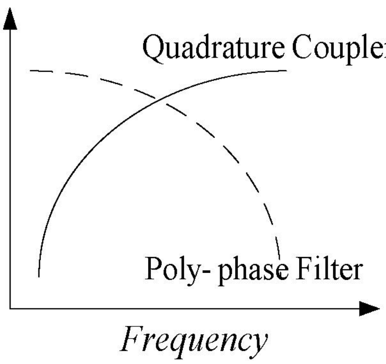


Fig. 5. Schematic of the lumped-element rat-race hybrid

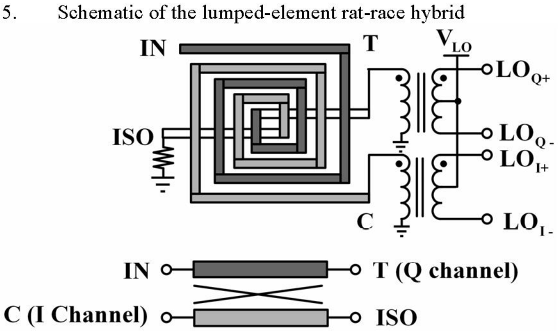


Fig. 6. Schematic of the lumped-element rat-race hybrid

rat-race coupler with a phase inverter on a low-resistivity silicon substrate works from 5 GHz to 23 GHz with 4.6 to 1 bandwidth ratio. The length of the quarter-wavelength coplanar stripline is approximately 1800 μm. The magnitude imbalanced between S_{21} and S_{41} is small and approximately 1 dB while the phase difference is always close to 180 degrees. The insertion loss is about 7 dB and its dissipated loss is about 5.5 dB.

D. 90°Couplers

Quadrature generators are often employed in complex mixers, balanced amplifiers, and image-rejection receivers. At low frequencies, the commonly used quadrature generator is a polyphase filter consisting of R-C and C-R sections. For high frequency applications, the parasitics and the resistor self-cutoff frequency deteriorate phase and magnitude accuracy so that the polyphase filter is not appropriate [25]. As shown in Fig. 5, the polyphase filter is suitable at low frequencies while a quadrature coupler is proper for millimeter-wave applications. In consideration of size, an interleave transformer is utilized as a quarter-wavelength coupled line in our Gilbert I/Q downconverter, as shown in Fig. 6 [26]. The outer diameter is designed as 266 μm and the average phase error is below 2° .

III. Millimeter-Wave Active Circuits

Thanks to the advancement in silicon technology, transistors can work at high frequencies and the analog design concept can be applied for millimeter-wave applications. The common implemented active mixer is a Gilbert mixer performing current commutation [27]. Differential LO signals are

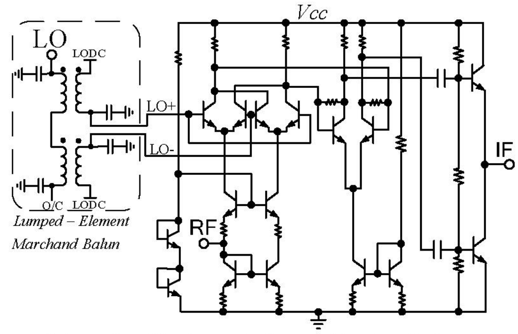


Fig. 7. Schematic of the lumped-element Marchand balun mixer.

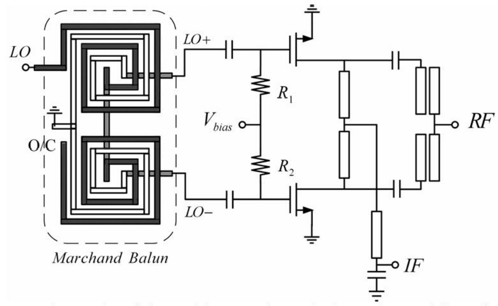


Fig. 8. Schematic of the subharmonic resistive mixer with an integrated LO Marchand balun.

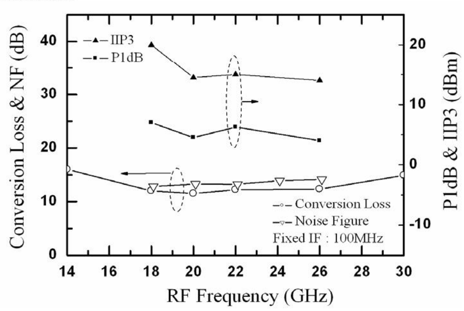


Fig. 9. Measured conversion loss, noise figure, IP_{1dB} and IIP_3 as a function of the RF frequency at the LO power of 7 dBm.

demanded in the Gilbert switch quad of the balanced mixers. The differential signals experience the different delay paths on the circuit board especially at high frequencies for an off-chip balun. Because it is difficult to achieve truly differential signals by an on-chip active balun in addition to more power consumption at high frequencies, the 180° passive components are employed at the LO stage in our works [14][17]. The 0.35-um SiGe HBT lumped-element Marchand balun mixer shown in Fig. 7 works from 3.1 GHz to 10.6 GHz with the conversion gain of around 15.5 dB and within the gain flatness of 1 dB. Figure 8 depicts the schematic of the sub-harmonically pumped resistive mixer using the standard 1P8M 0.13 um CMOS technology. The passive down-converter basically consists of two identical NMOS devices, a miniature marchand balun and RF/IF filters [28]. The measurement results are displayed in Fig. 9. The conversion loss is less than 12.5 dB within 0.5 dB variation at the LO power of 7 dBm. The IP_{1dB} and IIP_3 are better than 4 dBm and 14 dBm, respectively.

It is interesting that Schottky barrier diodes are successfully realized using CMOS process [29]. Based on this, diode mixers can be implemented on silicon technologies for millimeter-wave applications.

IV. Conclusions

Passive components like hybrids, baluns and couplers are implemented directly on a low-resistivity (~10 Ω cm) silicon substrate and merged into ICs for radio-frequency, microwave, and millimeter-wave applications. Because of the advanced transistors and successful passive component implementations, silicon technologies provide a new choice for millimeter-wave applications. The demonstrated passive components will be more useful at the millimeter-wave regime because of the size and loss reduction.

Acknowledgment

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References

[1] C. H. Doan, S. Emami, A. M. Niknejad, and R. W. Brodersen, "Millimeter-wave CMOS design," *IEEE J. Solid-State Circuits*, vol. 40, no. 1, pp. 144-155, Jan. 2005.

[2] K. Masu, K. Okada, and H. Ito, "RF passive components using metal line on Si CMOS," *IEICE Trans. Electron.*, vol. E89-C, no. 6, pp. 681-691, June 2006.

[3] K. T. Chan, A. Chin, S. P. McAlister, C. Y. Chang, J. Liu, S. C. Chien, D. S. Duh, and W. J. Lin, "Low RF noise and power loss for ion-implanted Si having an improved implantation process," *IEEE Electron Device Lett.*, vol. 24, no. 1, pp. 28-30, Jan. 2003.

[4] T. Wang, H.-C. Chen, H.-W. Chiu, Y.-S. Lin, G. W. Huang, and S.-S. Lu, "Micromachined CMOS LNA and VCO by CMOS-compatible ICP deep trench technology," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 580-588, Feb 2006.

[5] Y. J. Yoon, Y. Lu, R. C. Frye, and P. R. Smith, "A silicon monolithic spiral transmission line balun with symmetrical design," *IEEE Electron Device Lett.*, vol. 20, no. 4, pp. 182-184, April 1999.

[6] D. K. Cheng, *Field and Wave Electromagnetics*, 2nd Ed., USA: Addison-Wesley Publishing Company Inc., 1989, pp. 437-444.

[7] N. Marchand, "Transmission-line conversion transformers," *Electronics*, vol. 17, no. 12, pp. 142–145, 1944.

[8] K. S. Ang and I. D. Robertson, "Analysis and design of impedance-transforming planar Marchand baluns," *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 2, pp. 402-406, Feb. 2001.

[9] T. Gokdemir, S. B. Economides, A. Khalid, A. A. Rezazadeh, and I.D. Robertson, "Design and performance of GaAs MMIC CPW baluns using overlaid and spiral couplers," *in IEEE MTT-S Int. Microwave Symp. Dig.*, Denver, CO, June 1997, pp. 401-404.

[10] Y. J. Yoon, Y. Lu, R. C. Frye, M. Y. Lau, P. R. Smith, L. Ahlquist, and D. P. Kossives, "Design and characterization of multilayer spiral transmission-line baluns," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 9, pp. 1841-1847, Sept. 1999.

[11] M. Shimozawa, K. Itoh, Y. Sasaki, H. Kawano, Y. Isota, and O. Ishida, "A parallel connected Marchand balun using spiral shaped equal length coupled lines," *in IEEE MTT-S Int. Microwave Symp. Dig.*, Anaheim, CA, June 1999, pp. 1737-1740.

[12] H.-Y. Chang, P.-S. Wu, T.-W. Huang, H. Wang, C.-L. Chang, and J. G. J. Chern, "Design and Analysis of CMOS Broad-Band Compact High-Linearity Modulators for Gigabit Microwave/Millimeter-Wave Applications," *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 1, pp. 20-30, Jan. 2006.

[13] C. Nguyen and D. Smith, "Novel miniaturised wideband baluns for MIC and MMIC applications," *Electronics Letters*, vol. 29, no. 12, pp. 1060-1061, June 1993.

[14] S. C. Tsneg, C. C. Meng, C. H. Chang, C. K. Wu, and G. W. Huang, "Monolithic broadband Gilbert micromixer with an integrated Marchand balun using standard silicon IC process," *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 12, pp. 4362-4371, Dec. 2006.

[15] K. S. Ang, Y. C. Leong, and C. H. Lee, "Analysis and design of miniaturized lumped-distributed impedance-transforming baluns," *IEEE Trans. Microwave Theory Tech.*, vol. 51, no. 3, pp. 1009-1017, Mar. 2003.

[16] C. W. Tang and C. Y. Chang, "A semi-lumped balun fabricated by low temperature co-fired ceramic," *in IEEE MTT-S Int. Microw. Symp. Dig.*, Seattle, WA, June 2002, pp. 2201–2204.

[17] S.-C. Tseng, C. C. Meng, C.-H. Chang, and G.-W. Hung, "SiGe HBT Gilbert downconverter with an integrated miniaturized Marchand balun for UWB applications," *in IEEE MTT-S Int. Microwave Symp. Dig.*, Honolulu, HI, June 2007, pp. 2141-2144.

[18] D. M. Pozar, *Microwave Engineering*, 2nd Ed., New York, NY: John Wiley & Sons, Inc., 1998, pp. 401-407.

[19] S. C. Tseng, C. C. Meng, and G. W. Huang, "SiGe BiCMOS sub-harmonic Gilbert mixer using lumped-element rat-race couplers," *Microwave and Optical Technology Letters*, vol. 49, no.8, pp. 2018-2020, Aug. 2007.

[20] T. H. Wu, C. C. Meng, T. H. Wu, and G. W. Huang, "A monolithic SiGe heterojunction bipolar transistor Gilbert upconverter with inductor-capacitor current mirror load and lumped-element rat-race balun", *Japanese J. of Applied Physics*, vol. 45, no. 8A, pp. 6236-6244, August 2006.

[21] T. Wang and K. Wu, "Size-reduction and band-broadening design technique of uniplanar hybrid ring coupler using phase inverter for M(H)MIC's," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 2, pp. 198-206, Feb. 1999.

[22] M. K. Chirala, and C. Nguyen, "Multilayer design techniques for extremely miniaturized CMOS microwave and millimeter-wave distributed passive circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 12, pp. 4218-4224, Dec. 2006.

[23] M.-J. Chiang, H.-S. Wu, and C.-K. C. Tzuang, "Design of synthetic quasi-TEM transmission Line for CMOS compact integrated circuit," *IEEE Trans. Microwave Theory Tech.*, vol. 55, no. 12, pp. 2512-2520, Dec. 2006.

[24] M. K. Chirala and B. A. Floyd, "Millimeter-wave Lange and ring hybrid couplers in a silicon technology for E-band applications," in *IEEE MTT-S Int. Microw. Symp. Dig.*, San Francisco, CA, Jun. 11–16, 2006, pp. 1547–1550.

[25] F. Behbahani, Y. Kishigami, J. Leete, and A. A. Abidi, "CMOS mixers and polyphase filters for large image rejection," *IEEE J. Solid-State Circuits*, vol. 36, no. 6, pp. 873-887, Jun. 2001.

[26] Jin-Siang Syu, Chinchun Meng, and Ying-Chieh Yen, "5.7 GHz Gilbert I/Q Downconverter Integrated With a Passive LO Quadrature Generator and an RF Marchand Balun," *IEEE Microwave and Wireless Components Letters*, accepted for publication, Feb. 2008.

[27] B. Gilbert,, "The MICROMIXER: a highly linear variant of the Gilbert mixer using a bisymmetric Class-AB input stage," *IEEE J. Solid-State Circuits*, vol. 32, no. 9, pp. 1412-1423, Sept. 1997.

[28] Hung-Ju Wei, Chinchun Meng, Po-Yi Wu, and Kuan-Chang Tsung, "K-Band CMOS Sub-Harmonic Resistive Mixer With a Miniature Marchand Balun on Lossy Silicon Substrate," *IEEE Microwave and Wireless Components Letters*, vol. 18, no. 1, pp. 40-42, January 2008.

[29] S. Sankaran and K.O. Kenneth, "Schottky barrier diodes for millimeter wave detection in a foundry CMOS process," *IEEE Electron Device Lett.*, vol. 26, no. 7, pp. 492-494, July. 2005.