Progress In Electromagnetics Research Letters, Vol. 51, 109–115, 2015

An Improved Wideband 180-Degree Hybrid Applied to Balanced Mixer

Wei Zhao, Yong Zhang*, Shuang Liu, Li Li, and Ruimin Xu

Abstract—In this paper, an improved wideband millimeter-wave 180° hybrid is proposed to apply to balanced mixers and multipliers. The proposed hybrid consists of a transition of standard waveguide to suspended coplanar waveguide (SCPW) and a transition of SCPW to suspended stripline. According to the inherent electromagnetic field characteristics of the two transitions, the proposed hybrid has merits of broadband power distribution and high isolation, which does not rely on resonant circuits. The measured insertion losses and isolation of two transitions at Ka-band are typically 1.4 dB and 25 dB, respectively. To verify the application of the proposed hybrid, A W-band single balanced mixer based on the hybrid has been designed and fabricated. The measured single-sideband (SSB) conversion losses of the fabricated mixer are less than 9.5 dB for the radio frequency (RF) range from 80 to 108 GHz. The presented hybrid has been proven to be efficient for the design of millimeter-wave balanced mixers and could be well applied in multipliers and other integrated circuits.

1. INTRODUCTION

Rapidly expanding activities in millimeter-wave system developments have created an urgent need for broadband mixers and multipliers used in electronics warfare, meteorology, radio meter and communication systems. The cross-bar balanced mixers and multipliers are preferred in millimeter-wave bands for merits of low loss, high isolation and broad band, owing to the inherent mode isolation between the radio frequency (RF) and local oscillator (LO) signals or between the input and output signals [1–8]. In cross-bar mixers, the cross-bar balanced architecture with a pair of balanced diodes physically locates inside either the LO waveguide [1] or the RF waveguide [2–4]. In cross-bar multipliers, the cross-bar balanced architecture with a pair of balanced diodes physically locates inside either the input waveguide [5–7] or the output waveguide [8]. However, the design of the cross-bar hybrid relies on the cross-bar structure with a pair of balanced diodes, which cannot be pre-designed as a simplex hybrid like the rat-race hybrid or the others [9, 10].

In this paper, an improved wideband millimeter-wave 180° hybrid based on the cross-bar structure is proposed. The proposed hybrid consists of a transition of standard waveguide to suspended coplanar waveguide (SCPW) and a transition of SCPW to suspended stripline. The phase, power distribution and isolation characteristics of the 180° hybrid are inherently achieved by field transformations of the two transitions. The tapered structure is employed for reducing the insertion loss and impedance matching. And the improved hybrid could be pre-designed as a simplex circuit. The proposed hybrid has merits of low loss, high isolation, and broad band and could be well applied in mixers, multipliers and other integrated circuits. A W-band single balanced mixer based on the proposed hybrid has been designed and fabricated to demonstrate the function of the hybrid.

Received 17 December 2014, Accepted 1 February 2015, Scheduled 14 February 2015

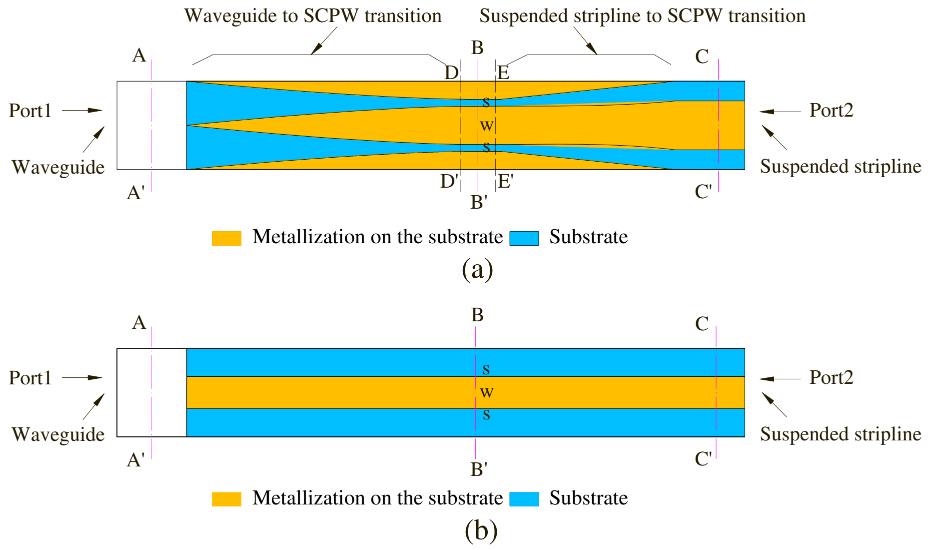
* Corresponding author: Yong Zhang (yongzhang@uestc.edu.cn).

The authors are with the Fundamental Science on EHF Laboratory, University of Electronic Science and Technology of China, Chengdu 611731, China.

2. HYBRID DESIGN

The configuration of the improved hybrid is shown in Fig. 1(a). It consists of a transition of standard waveguide to SCPW and a transition of SCPW to suspended stripline. The SCPW structure can support both the odd mode and even mode of propagation [11]. However, only one mode could be excited in the SCPW structure when signals are fed into the hybrid from the Port 1 and Port 2, respectively. Only odd mode is excited in the SCPW when signal is incident at Port 1 through the transition of standard waveguide to SCPW and the even mode of the SCPW is prevented from propagating into the waveguide. Only even mode is excited in the SCPW when the signal is incident at Port 2 through the transition of suspended stripline to SCPW and the odd mode of the SCPW is prevented from propagating into the suspended stripline structure. Consequently, the phase and isolation have wideband performances, which are inherently achieved by field transformations through physical transitions and do not rely on resonant circuits.

Compared with the traditional cross-bar structure as shown in Fig. 1(b), the conductor width (w) and the slit width (s) can be easily adjusted to meet the size of the diodes placed on the substrate, when the width of the waveguide metal cavity is fixed. This eliminates the need for the special beam leads connecting the diodes with the metal cavity in the cross-bar structure, which will lead to discontinuities of the electric field. Meanwhile, a stronger electric field at diodes is obtained because the signals are constrained in the interior of the SCPW structure. The insertion loss is reduced because of the introduced taper. And the improved hybrid can be predesigned as a simplex circuit.



(a)

(b)

Figure 1. (a) Configuration of the improved hybrid. (b) Configuration of the traditional hybrid.

In order to verify the insertion loss and isolation performance of the hybrid, three kinds of test structures at Ka-band have been designed and fabricated, including a back-to-back structure of standard waveguide to SCPW for testing insertion loss from Port 1 to Port $1'$, a transition structure of standard waveguide to SCPW to suspended stripline to standard waveguide for testing isolation from Port 1 to Port 2 and a back-to-back structure of standard waveguide to suspended stripline to SCPW for testing insertion loss from Port 2 to Port $2'$, as shown in Fig. 2. The Port 1 and Port 2 shown in Fig. 2 correspond to the ports shown in Fig. 1.

The test structures are measured by Agilent E8363B vector network analyzer (VNA) from 26.5 GHz to 40 GHz. As shown in Fig. 3, the measured insertion losses of the two transitions and the isolation are typically 1.4 dB and 25 dB, respectively. The results show that the proposed hybrid has merits of low loss, high isolation, and broad band.

Two Schottky diodes could be placed in the D-D'-E-E' zone along the B-B' plane which referred to the lines in Fig. 1(a) with two topology types as shown in Fig. 4(a) and Fig. 4(b). When diodes are

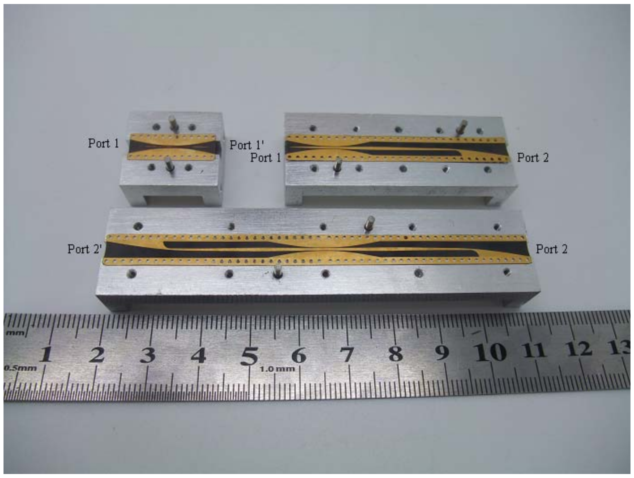


Figure 2. Test structures of the hybrid.

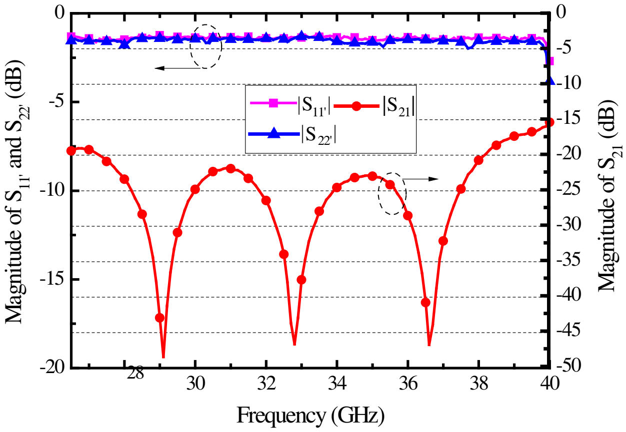
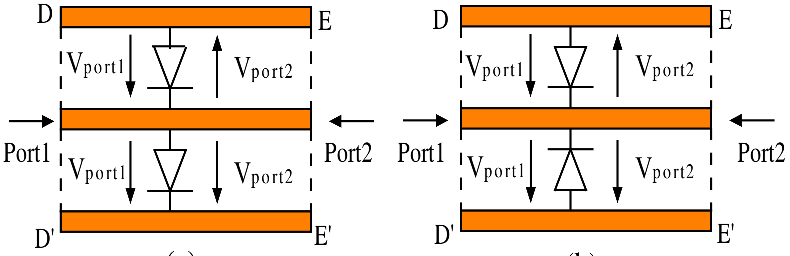


Figure 3. Measured results of the test structures.



(a) (b)

Figure 4. Circuit Topology: (a) type I and (b) type II.

placed in series as shown in Fig. 4(a), the signal voltages fed from Port 1 are applied to the diodes with the same phase, and the signal voltages fed from Port 2 are applied to the diodes with the opposite phase. When the diodes are placed in anti-series as shown in Fig. 4(b), the signal voltages fed from Port 1 are applied to the diodes with the opposite phase, and the signal voltage fed from Port 2 are applied to the diodes with the same phase. Because the structure is symmetric relative to the median of the upper and lower of the view as shown in Fig. 1(a), the transition of waveguide to SCPW and the transition of suspended stripline to SCPW act as 3-dB power dividers, which divide equal power to two diodes. Therefore, both types of hybrids are 180° hybrids which constitute the basic structure of single balanced mixers and multipliers. The new hybrid could be well applied in mixers, multipliers and other integrated circuits.

3. DESIGN OF THE BALANCED MIXER

For the millimeter-wave mixers and multipliers, the general design method is extracting the parasitic parameter of diodes to obtain the equivalent circuit model, simulating the different parts of the circuits separately by using three-dimensional field simulation software, such as High Frequency Structure Simulator (HFSS), and then exporting the simulated results as S-parameter Touchstone files into Advanced Design System (ADS) to further obtain and optimize the conversion loss and other characteristics. However, because the characteristics of the orthogonal field structures with two propagating modes at one port cannot be represented in ADS using one port, the cross-bar balanced mixers, which use RF and LO orthogonal field to form a broadband 180° hybrid, cannot be well designed by the above method. Currently, the 3D electromagnetic model of the Schottky diode is built to eliminate the limitation of the design. The 3D electromagnetic model of the Schottky diode has been built for accurately extracting parasitic parameters of the diodes and the design of subharmonic mixer, starting with the work of Hesler [12].

As shown in Fig. 5, the epitaxial GaAs structure upon the semi-insulating (S.I.) GaAs substrate consists of a thick, heavily doped (n++ GaAs) layer and a thin, lightly doped (n− GaAs) layer. The anode and pads are formed on n− GaAs layer, and n− GaAs layer is formed on n++ GaAs layer. The n− GaAs layer with finger and n++ GaAs layer with cathode pad are leading to Schottky contact and ohmic contact, respectively. By setting the port in the 3D electromagnetic model of the diode, the transmission line port with two propagating modes is replaced by the diode port with one mode. So the S-parameter Touchstone files of the HFSS simulated results could be exported into ADS to further obtain and optimize the conversion loss and other characteristics. However, the structure and dimensions of the diode 3D electromagnetic model are set according to the Schottky diode's basic physical structure. The structural dimensions need to know in advance, which is difficult to obtain from manufacturers when commercial diodes used. In this paper, the 3D electromagnetic model of the Schottky diode is built by calculation of diode electrical parameters.

Reverse breakdown voltage is mainly determined by epitaxial layer doping levels N_d [13],

$$V_{br} = 2.9 + 1.4 \times 10^{14} \times N_d^{-0.77} \tag{1}$$

So we can approximate calculate the N_d through V_{br}.

The non-linear junction capacitance, $C_j(V_j)$ is mainly determined by anode area A_a [14]. The A_a can be inferred through

$$C_{j0} = A_a \times \sqrt{\frac{q \cdot N_d \cdot \varepsilon_s}{2 \cdot V_{bi}}} \tag{2}$$

In order to decrease the series resistance, the epitaxial layer thickness was required to be as small as possible but larger than the maximum width of the depletion layer in order to avoid punch-through, so the epitaxial layer thickness t_{epi} is much larger than $w(V_{br})$ [14].

$$w(V_{br}) = \left[\frac{2\varepsilon_s(V_{bi} - V_{br})}{qN_d}\right]^{\frac{1}{2}} \tag{3}$$

For the commercial diode M/A-COM MA4E2038 used in this paper, the main electrical parameters and calculated structural dimensions are shown in Table 1.

Based on the proposed hybrid and the 3D electromagnetic model of the Schottky diode, a W-band single balanced mixer has been designed. The configuration of the W-band balanced mixer is shown in Fig. 6. The polarities of the LO and RF voltages at the diode are selected as shown in Fig. 4(a). RF inputs from Port 1 and LO inputs from Port 2. The architecture of the balanced mixer implies that the pair of Schottky diodes is seen in series by the RF signal and in anti-parallel configuration by the LO and intermediate frequency (IF) signals. The RF voltage applied to the diodes has the same

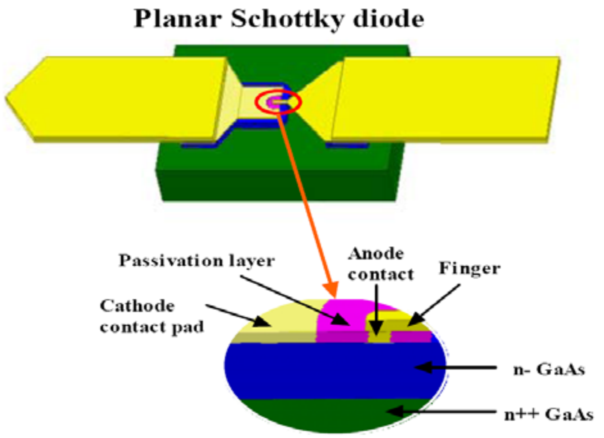


Figure 5. 3D electromagnetic model of the Schottky diode.

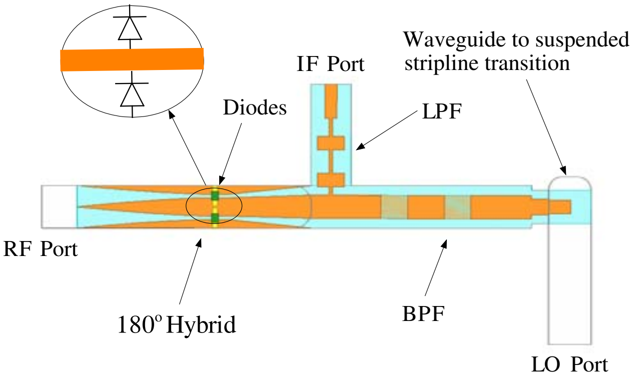


Figure 6. Configuration of the balanced mixer.

Table 1. Main electrical parameters and structural dimensions of MA4E2038.

Vbr(@-10uA)	C_{j0}	R_s	A_a	N_d	T_{epi}
7 V	15 fF	6.5	7 µm^2	3.7e17/cm^3	0.2 µm

phase, and the LO voltage pumps the diodes out of phase. The RF signal is coupled into the diodes through a transition of WR-10 standard waveguide to SCPW. And the LO signal is coupled into the diodes through the transition of WR-10 standard waveguide to suspended stripline, suspended stripline bandpass filter and the transition of suspended stripline to SCPW. The transition of waveguide to suspended stripline is easy to be fabricated and has the advantage of wide bandwidth. The bandpass filter is required to pass the LO signal and reject the IF signal. Here, the resonators are coupled on both sides of the suspended stripline. This kind of filter has smaller volume and wider pass-band, compared with the traditional suspended stripline filter with terminal coupling. The IF output is taken by a microstrip five-stage low-pass Chebyshev filter and a SMA connector.

The balanced mixer has been designed on the RT/Duriod5880 substrate with dielectric constant of 2.2, thickness of 0.127 mm. Since the 3D electromagnetic model of Schottky diode is used, the S-parameter Touchstone files obtained by using HFSS could be exported into ADS to further obtain and optimize the conversion loss. By proper design and optimization, the simulated conversion losses of the mixer are shown in Fig. 7. The simulated single-sideband (SSB) conversion losses of the fabricated mixer are less than 9 dB for the RF range from 80 to 108 GHz with LO frequency fixed at 94 GHz.

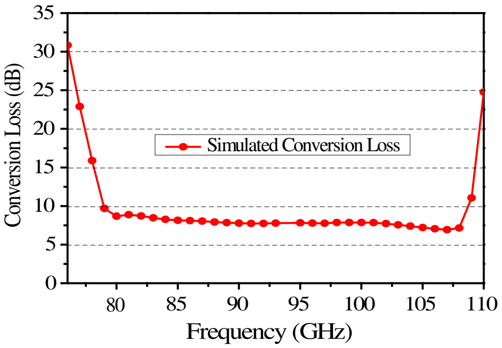


Figure 7. Simulated conversion losses of the mixer.

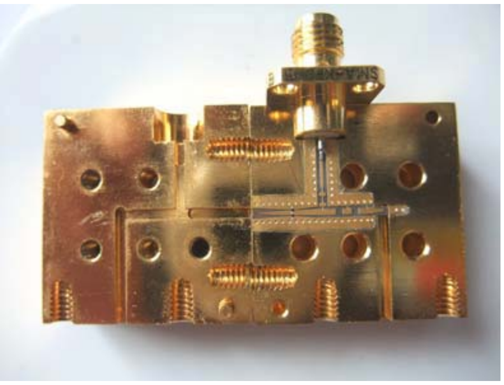


Figure 8. Photograph of the fabricated mixer.

4. PERFORMANCE OF THE BALANCED MIXER

We fabricated and evaluated the balanced mixer which was designed using the proposed hybrid. The photograph of the fabricated mixer is shown in Fig. 8. For the mixer measurement, the LO signal was obtained in the way that the initial signal was generated by a PSG analog signal generator Agilent E8257D and then it was multiplied and amplified by microwave amplifier HP 8549B with an mm-wave source module Agilent 83558A and a home-made W-band amplifier. The RF signal was obtained by a swept signal generator Agilent 83623B with an mm-wave source module Agilent 83558A. The LO power used in the measurement was 13 dBm with frequency fixed at 94 GHz, and the RF power was 0 dBm. A spectrum analyzer HP 8563E was used to measure the output power of the IF signal.

The measured and simulated conversion losses of the fabricated W-band balanced mixer versus RF frequency are shown in Fig. 9. The measured SSB conversion loss is less than 9.5 dB for the frequency range from 80 to 108 GHz. And the best SSB conversion loss of 5.8 dB is achieved with RF of 104 GHz. The measured results agree well with the simulated results.

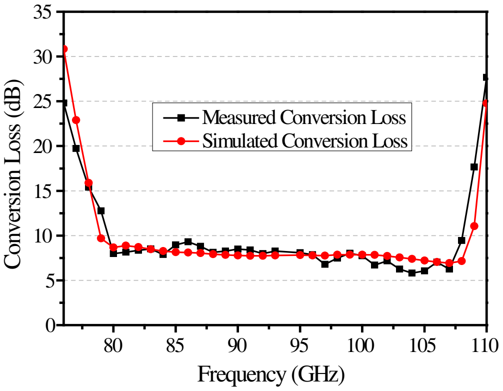


Figure 9. Measured and simulated conversion losses of the mixer.

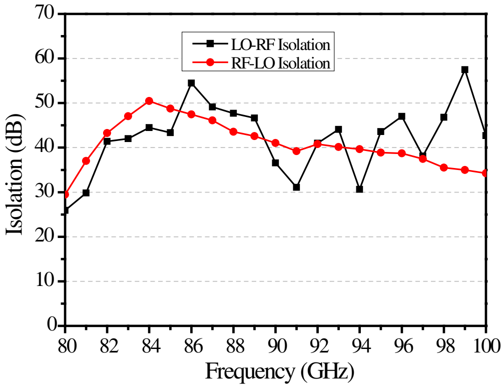


Figure 10. Measured LO-RF and RF-LO isolations of the mixer.

The important port-to-port isolation in mixer is the isolations of LO-RF, RF-LO and LO-IF. The LO-RF isolation is measured under large-signal condition. The LO port is terminated by the LO power chain, the RF port is terminated by the spectrum analyzer with 75 ∼ 110 GHz extended mixer and the IF port is terminated by a 50 Ω load. The RF-LO isolation is measured under small-signal condition. The RF and LO ports are terminated by the Rohde & Schwarz ZVA67 VNA with ZVA-Z110 75 ∼ 110 GHz frequency extenders and the IF port is terminated by the 50 Ω load. The frequency is measured from 80 GHz to 100 GHz for the limitation of the operating frequency of the LO chain. The measured LO-RF and RF-LO isolations of the mixer are shown in Fig. 10. Both LO-RF and RF-LO isolations have good performance mostly more than 30 dB isolation. The LO-IF isolation is considered good for the use of IF low-pass filter and the SMA connector. The SMA connector is recommended to work below 18 GHz which cannot work at W-band. The measured results show that the proposed hybrid can be sufficiently used for the design of millimeter-wave balanced mixers.

5. CONCLUSION

An improved wideband millimeter-wave 180° hybrid is proposed and a 3D electromagnetic model of the commercial diodes is presented in this paper. Based on the proposed hybrid and the 3D electromagnetic model of the Schottky diode, a W-band single balanced mixer has been designed, fabricated and measured. The results demonstrate that the proposed hybrid has merits of low loss, high isolation, and broad band, which could be well applied in mixers, multipliers and other integrated circuits.

ACKNOWLEDGMENT

This work was supported by the National High-tech R&D Program of China (863 Program) under Grant 2011AA010203.

REFERENCES

1. Schlecht, E. T., J. J. Gill, R. H. Lin, R. J. Dengler, and I. Mehdi, "A 520–590 GHz crossbar balanced fundamental Schottky mixer," *IEEE Microw. Wireless Compon. Lett.*, Vol. 20, No. 7, 387–389, 2010.
2. Wells, J. A., N. J. Cronin, and P. H. Reece, "Rugged 94 GHz crossbar balanced mixer," *IEE Proc. H — Microwaves, Antennas Propag.* Vol. 137, No. 4, 235–237, 1990.
3. Erickson, N. R. and T. M. Goyette, "Terahertz Schottky-diode balanced mixers," *21st International Symposium on Space Terahertz Technology*, 150–153, Oxford, March 2010.

4. Thomas, B., A. Maestrini, J. Gill, C. Lee, R. Lin, I. Mehdi, and P. de Maagt, "A broadband 835-900-GHz fundamental balanced mixer based on monolithic GaAs membrane Schottky diodes," *IEEE Trans. Microw. Theory and Tech.*, Vol. 58, No. 7, 1917–1924, 2010.
5. Erickson, N., "High efficiency submillimeter frequency multipliers," *IEEE MTT-S International Microwave Symposium Digest, 1990*, 1301–1304, Dallas, May 1990.
6. Porterfield, D. W., T. W. Crowe, R. F. Bradley, and N. R. Erickson, "A high-power, fixed-tuned, millimeter-wave balanced frequency doubler," *IEEE Trans. Microw. Theory and Tech.*, Vol. 47, No. 4, 419–425, 1999.
7. Chattopadhyay, G., E. Schlecht, J. S. Ward, J. Gill, H. H. S. Javadi, F. Maiwald, and I. Mehdi, "An all solid-state broadband frequency multiplier chain at 1500 GHz," *IEEE Trans. Microw. Theory and Tech.*, Vol. 52, No. 5, 1538–1547, 2004.
8. Siles, J. V., A. Maestrini, B. Alderman, S. Davies, H. Wang, J. Treuttel, E. Leclerc, T. Narhi, and C. Goldstein, "A single-waveguide in-phase power-combined frequency doubler at 190 GHz," *IEEE Microw. Wireless Compon. Lett.*, Vol. 21, No. 6, 332–334, 2011.
9. Guo, J., Z. Xu, C. Qian, and W.-B. Dou, "Design of a microstrip balanced mixer for satellite communication," *Progress In Electromagnetics Research*, Vol. 115, 289–301, 2011.
10. Zhan, M. Z., Q. Xu, W. Zhao, Y. Zhang, R.-M. Xu, and W. Lin, "Planar W-band mixer with a novel IF-block," *Progress In Electromagnetics Research C*, Vol. 21, 205–215, 2011.
11. Simons, R. N., *Coplanar Waveguide Circuits, Components, and Systems*, John Wiley & Sons., New York, 2001.
12. Hesler, J. L., "Planar Schottky diodes in submillimeter-wavelength waveguide receivers," Ph.D. Dissertation, University of Virginia, 1996.
13. Porterfield, D. W., "Millimeter-wave planar varactor frequency doublers," Ph.D. Dissertation, University of Virginia, 1998.
14. Neamen, D. A. and B. Pevzner, *Semiconductor Physics and Devices: Basic Principles*, McGraw-Hill, New York, 2003.