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Research Article

Design of Low-Cost Full W-Band 8th Harmonic Mixers for Frequency Extension of Spectrum Analyzer

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High-order harmonic mixer is popular for frequency extension of spectrum analyzer (SA) from microwave to millimeter-wave or even terahertz band. The manufactures of SA usually offer expensive harmonic mixers where frequency extension is needed. In this work, low-cost designs of 2-port and 3-port W-band 8th harmonic mixers covering 75–110 GHz are proposed, and design method of two port mixer without frequency diplexer to separate local oscillator (LO) and intermediate frequency (IF) signals are first presented. These two kinds of mixers are compatible with almost all the current SAs with frequency extension options, which provides LO for the external harmonic mixer. The mixers are designed with planar microstrip lines and antiparallel Schottky diodes. The circuit of 2-port mixer includes the input broadband bandpass filter, diodes, output lowpass filter, and matching circuits. As for 3-port mixer, only an extra diplexer is needed to separate the IF signal and LO signal. The diplexer is composed of a planar semi-lumped lowpass and a highpass filter. The planar circuits are easily fabricated with low-cost print circuit board process on polytetrafluoroethylene substrate. The measured conversion loss of 2-port 8th harmonic mixer is from 20 to 26 dB, and 23 to 28 dB for 3-port mixer at full W-band. The good measured results indicate the proposed mixers are simple and effective.

1. Introduction

High-order harmonic mixer is very useful to convert millimeter-wave (MMW) and terahertz (THz) radio frequency (RF) signal to intermediate frequency (IF) within the frequency range of spectrum analyzer (SA) [1–4]. By this way, the testing frequency of SA is significantly extended. For example, SAs from Keysight can measure up to 1.1 THz signal by down-converting it to a fixer IF of 322.5 MHz with external harmonic mixers.

Most of the current high-performance SAs have the options to extend measuring frequency up to THz region, such as PSA-Series and PXA-Series from Keysight and FSW-Series from Rohde & Schwarz (RS). Keysight PSA with frequency extension option has two extra coaxial connectors on its front panel, IF connector and local oscillator (LO) connector, for external harmonic mixer. The instrument provides LO signal to the external harmonic mixer, from which it receives the IF signal for analyzing. This kind of SA is categorized into SA-I in this work. While PXA-Series SA has only one coaxial connector labeled "LO/IF" for external mixing, with a diplexer inside the instrument. The LO and IF signals come out of and into the instrument from this single connector. This kind of SA is categorized into SA-II in this work. FSW-Series SA has three connectors, which are a pair of LO and IF connectors like PSA and another LO/IF connector like PXA. This kind of SA can work as either SA-I or SA-II regarding frequency extension.

As for harmonic mixers, they are divided into two categories according to the port numbers. The traditional mixer has three ports, which are RF, LO, and IF, and it is named 3-port harmonic mixer. A 2-port mixer, especially designed for frequency extension for SA like PXA, has two ports as an RF port and a combined IF/LO port, with an internal diplexer to separate the IF and LO signals. This kind of mixer was first presented by Keysight in 2013, along with the PXA

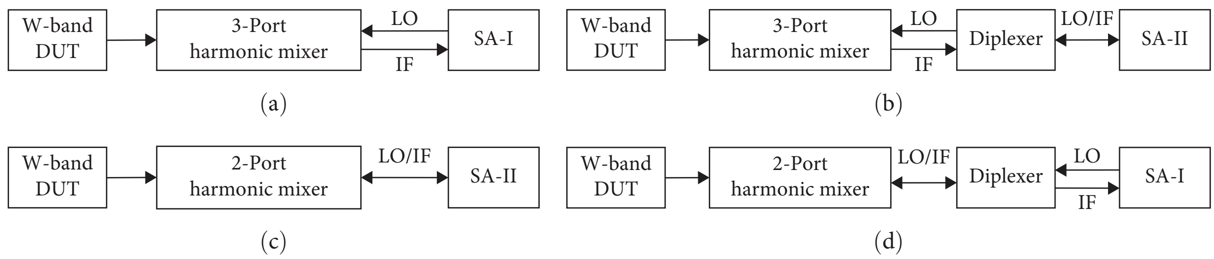


Figure 1: Combinations of harmonic mixers and SA for signal measurement: (a) SA-I extension with 3-port mixer; (b) SA-II extension with 3-port mixer and a diplexer; (c) SA-II extension with 2-port mixer; (d) SA-I extension with 2-port mixer and a diplexer.

Table 1: Commercial mixers for SA frequency extension.

Model number	Vendor	Number of ports	Harmonic number	Conversion loss (dB)	Compatible SA
11970W	Keysight	3	18	46	PSA/PXA with diplexer/FSW
M1970W	Keysight	2	8	20 (27 max)	PXA
M1971W	Keysight	3	8	20 (27 max)	PXA with diplexer
FS-Z110	R&S	3	6	23 (30 max)	PSA/PXA with diplexer/FSW
M10HWD	OML	2	18	40 (44 max)	PSA with diplexer/PAX/FSW
WR10EHM	VDI	3	12	25	PSA/PXA with diplexer/FSW

series SA. The interface of RF port is usually a rectangular waveguide, covering a standard waveguide band.

The harmonic mixer, combined with SA, can perform high-frequency measurement beyond the measuring frequency of SA itself. There are several combinations between the mixers, SAs, and the device under test, as shown in Figure 1, and sometimes an external diplexer is needed.

The harmonic mixer module adopts waveguide interface for the input RF signal. Electronic Industries Association uses a WR designator to indicate the rectangular waveguide size. WR-10 waveguide covers W-band, which is from 75 to 110 GHz. W-band is very popular for communication and radar applications these days [5, 6]. And this work focuses on the design of harmonic mixers at W-band.

Commercial harmonic mixers for SA frequency extension are available from several vendors, as in Table 1. Keysight 11,970 W waveguide mixer [7] is a 3-port 18th harmonic mixer. It covers full W-band with a maximum conversion loss of 46 dB and gain flatness of 6 dB. This high-loss 18th harmonic mixer is suited for E4440 series SA from Keysight, because the early SA only provides low LO frequency from 2.85 to 6.9214 GHz. Modern SAs have much higher LO frequency, up to 14.1 GH of Keysight PXA-Series SA, supporting 8th harmonic mixing up to W-band. Keysight launches new M1970-Series [8] and M1971-Series [9] smart harmonic mixers with much lower conversion loss these days. They are 8th harmonic mixers with maximum 27 dB conversion loss. When used together with PXA-Series SA, the mixer model and the serial number are automatically detected by the analyzer, and then the conversion loss of the mixer is compensated. M1971-Series mixer is a three ports mixer, whereas M1970-Series is a 2-port one. FS-Z110 [10] from RS is a 3-port 8th harmonic mixer with a typical conversion loss of 23 dB. M10HWD [11] from OML is 2-port 18th harmonic mixer with maximum 44 dB conversion loss. WR10EHM [12] from VDI is 3-port 12th harmonic mixer with typical 25 dB conversion loss.

Although the commercial harmonic mixers for SA frequency extension have been released for many years, little information about the design approach is revealed. Most of all, they are all very expensive.

Most of the reported MMW and THz harmonic mixers are even harmonic mixers adopting antiparallel diodes [13–17], because they are easy to design and fabricate. The even harmonic mixer usually incorporates suspended stripline and waveguide, and the waveguide transition is an essential part of the mixer topology. There are also some odd harmonic mixers [1, 18] designed with series Schottky diodes and waveguide balun to distribute the RF signal. The series diodes of the mixer are coupling the input signal directly from the waveguide. Thus, they are bulky and cannot be easily integrated with other chips, such as amplifiers and filters. Besides, although these harmonic mixers are broadband, most of them cover only part of the waveguide band [13, 14, 16, 17].

In conclusion, the commercial harmonic mixers with high-order harmonic, such as the 18th-order harmonic mixer from Keysight, have high conversion loss, while the lower order harmonic mixers with better performance are very expensive. As for the reported harmonic mixers, almost all of them adopt waveguide structure for signal coupling and cannot cover full waveguide band, making them bulky and not convenient for practical application.

Full W-band 2-port and 3-port 8th harmonic mixer designs are proposed in this work to substitute the expensive commercial ones. These mixers are designed with planar microstrip line (MSL), which are more reliable and easy for fabrication, mounting, and integration with other devices.

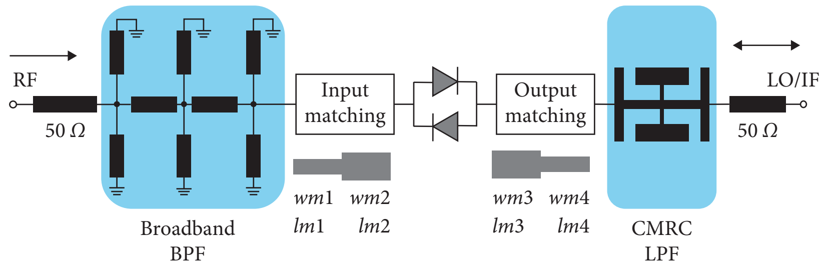


FIGURE 2: Design schematic of the 2-port harmonic mixer (*wm*1 to *wm*4 and *lm*1 to *lm*4 are widths and lengths of the matching lines, respectively).

A 2-port mixer without an internal diplexer is first presented in this work. These mixers are simply fabricated with low-cost polytetrafluoroethylene substrate (RT/D5880) from Rogers.

2. Design Methodology of the 8th Harmonic Mixers

The most important principle for a successful harmonic mixer design is providing RF, LO, and IF signal with effective return path, respectively, and harvesting as much power as possible from the idle frequencies [15, 19–21]. Besides, proper input and output impedance matching circuits are also necessary for low conversion loss designs.

Harmonic mixers for SA frequency extension usually need to cover the full waveguide band, which is 75–110 GHz of W-band. The harmonic mixer converts the full RF band to an IF band from DC to 1.5 GHz with LO from 9.1875 to 13.75 GHz. The IF frequency band is determined to cover the basic IF requirement of SAs of Keysight (322.5 MHz) and RS (1.33 GHz). In the case of a full-band high-order harmonic mixer, it is impractical to reuse all of the idle frequencies because they may lie in-band, such as 6LO and 8LO. Corresponding return paths for these idle frequencies also impact the RF signal transmission, leading to unacceptable frequency response. Thus, we mainly focus on the design and optimization of RF, LO, and IF return path and impedance-matching circuits.

The 3-port mixer is actually composed of a 2-port mixer and a frequency diplexer, separating the IF and LO signal. The design methods of the 2-port and 3-port mixers are introduced in the following sections.

2.1. Antiparallel Schottky Diodes. Antiparallel Schottky diodes are essential to build passive, even harmonic mixers. They take in the input LO signal, mixing the harmonics with the RF signal by the nonlinearity of the didoes. As described by Matthaei et al. [22], the antiparallel diodes only support even harmonics of LO frequency, whereas odd LO harmonics only exist in the circulation of the diode pair. By this way, the design of an idle frequency circuit is tremendously simplified.

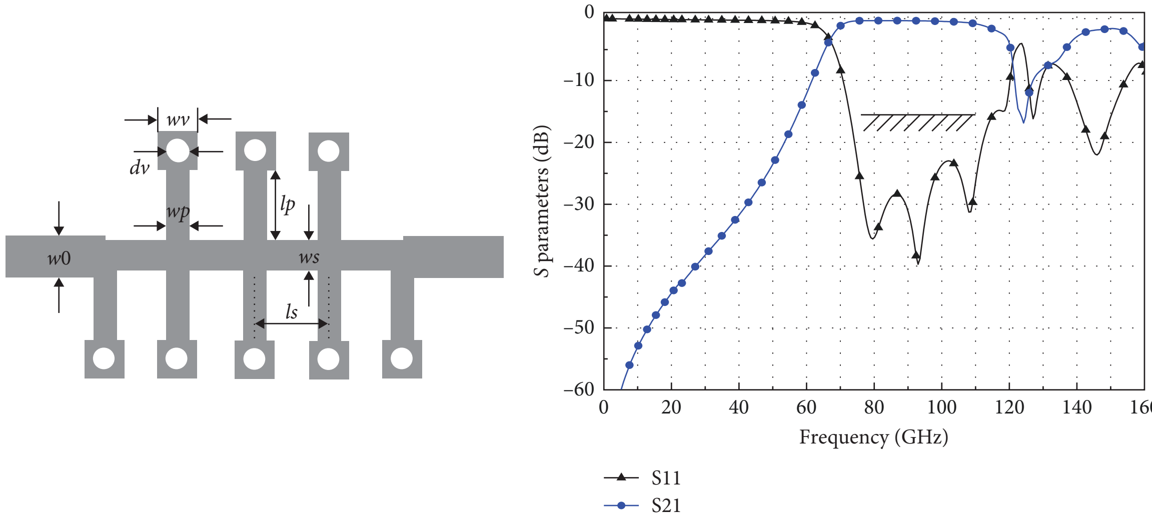
High-performance diodes and accurate models are necessary for successful mixer design. In this work, antiparallel Schottky diodes from Hebei Semiconductor Research Institute are adopted. These didoes work at frequencies up to 500 GHz. They have two configurations, flip chip and beam lead, for different applications. The beam lead configuration is used in this work for easy assembly. The modeling and parameters have been introduced by Liu et al. [3] and Waveguide Harmonic Mixers [9] in detail, and the parameters include $Rs = 12\,\Omega$, $Is = 32$ fA, $C_{j0} = 1.4$ fF, $V_j = 0.75$ V, $N = 1.22$ and anode diameter of 1 μm.

2.2. A 2-Port Harmonic Mixer. A 2-port harmonic mixer is specially designed for PXA-series and FSW-series SAs. Only a coaxial cable is needed for SA connection.

The design schematic of the 2-port mixer is shown in Figure 2. RT/D5880 substrate is adopted in this work, with a thickness of 5 mil, dielectric constant of 2.2, and dissipation factor of 0.0009. The mixer circuit is composed of input and output 50 Ω MSLs, input broadband bandpass filter (BPF), input and output matching circuits, antiparallel Schottky diodes, and a compact microstrip resonant cell (CMRC) low-pass filter (LPF). Both the input and the output matching circuits consist of two-stepped impedance MSLs, which feature broadband matching characteristics. The RF port is an input port, and the broadband BPF passes the RF signal. While the CMRC LPF provides the RF return path. The LO/IF port is a bidirectional port. The input LO signal passes through the LPF to drive the diodes, and the BPF provides the LO return path. IF signal is produced from the nonlinearity of the diodes and passes through the LPF to the LO/IF port. Here, the BPF also provides the IF and DC return path.

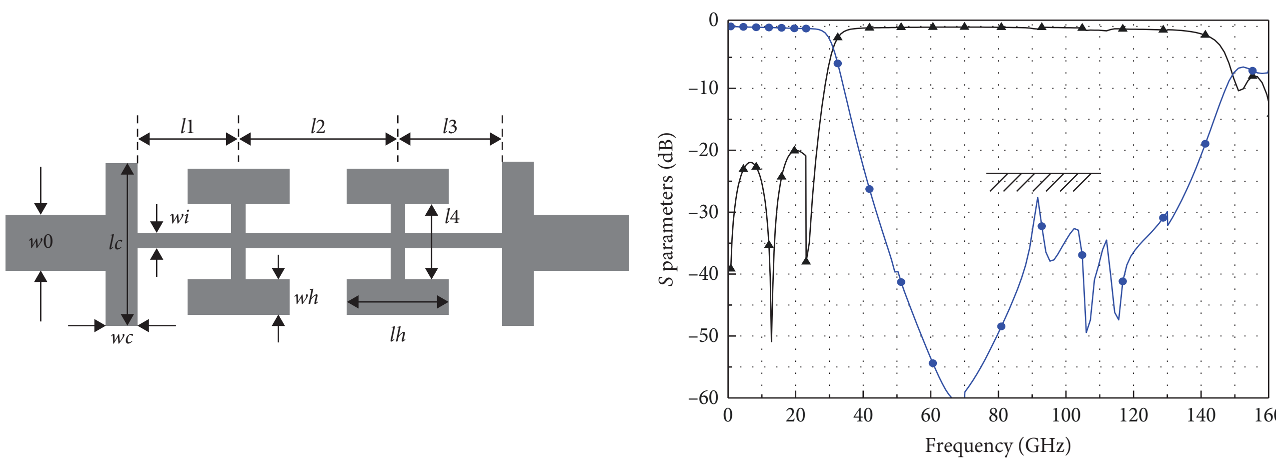
The design considerations of these circuits are further introduced as follows in this section.

BPF is needed for the RF input, not only to pass the 75–110 GHz RF signal but also to reject the LO and IF signal from leaking to the RF port. The BPF, combined with the input matching circuit, provides a return path for IF and LO. Shunt quarter wavelength short stub BPF has broad passband and low insertion loss [23] and is adopted in this work. The initial line lengths and widths of the series and shunt stubs are calculated by the equations, and then a 3D model is built in ANSYS high-frequency structure simulator (HFSS) for performance evaluation. The shunt stubs are fulfilled by grounding via holes at the ends of the stubs. All the size parameters, including the via holes, are optimized to achieve the required in-band and out-of-band performances. The simulation model and dimensions are shown in Figure 3(a), and the simulated results are shown in Figure 3(b). The insertion loss is less than 1 dB, and return loss is more than 20 dB at RF from 75 to 110 GHz. The actual insertion loss of the BPF is higher than simulation in W-band,



(a) (b)

Figure 3: (a) Simulation model and (b) simulated results of the input BPF ($w0 = 0.38$, $wv = 0.5$, $dv = 0.25$, $wp = 0.42$, $lp = 0.39$, $ws = 0.42$, $ls = 0.6$) (units in mm).



(a) (b)

Figure 4: (a) Simulation model and (b) results of the two-cell CMRC LPF ($w0 = 0.38$, $wc = 0.2$, $lc = 1.3$, $wi = 0.1$, $l1 = 1$, $l2 = 1.2$, $l3 = 1$, $lh = 0.8$, $wh = 0.35$, $ls = 0.45$) (units in mm).

because the given parameters of the substrate are at a much lower frequency, such as 10 GHz of RT/D5880, and the surface roughness of the substrate and the metal lines is not considered, either. The rejection is more than 40 dB at LO from 9.1875 to 13.75 GHz and more than 60 dB at IF from DC to 1.5 GHz. These results show that this BPF is qualified for the design purpose mentioned above.

As for the LO and IF port, a broadband LPF with wide stopband is essential. This LPF passes the IF and LO signal, whereas it rejects the RF signal at full W-band. The CMRC LPF exactly meets the requirement [24, 25]. In order to enhance the out-of-band rejection, two-cell CMRC LPF is adopted. Although CMRC LPF has a very broad stopband, it still has parasitic passband. In order to reject the RF signal effectively, the cutoff frequency of the LPF is set much higher than IF and LO frequency, which is 28 GHz in this case, to push the parasitic passband far away from W-band. The simulation model, dimensions, and simulated S parameters are shown in Figures 4(a) and 4(b). The return loss in passband is less than 20 dB from DC to 28 GHz. Broad stopband is achieved from 42 to 130 GHz with more than 25 dB out-of-band rejection.

Both the input and output matching circuits are composed of two series transmission lines with different widths and lengths. Conventional matching circuit design includes diode impedance calculation with harmonic balance algorithm under specific LO power and then determining the optimal source and load impedances. The input and output circuits are then designed based on these impedances. This design method is relatively simple for single frequency point or narrow band but very difficult and tedious for broadband design, not to mention covering the full waveguide band.

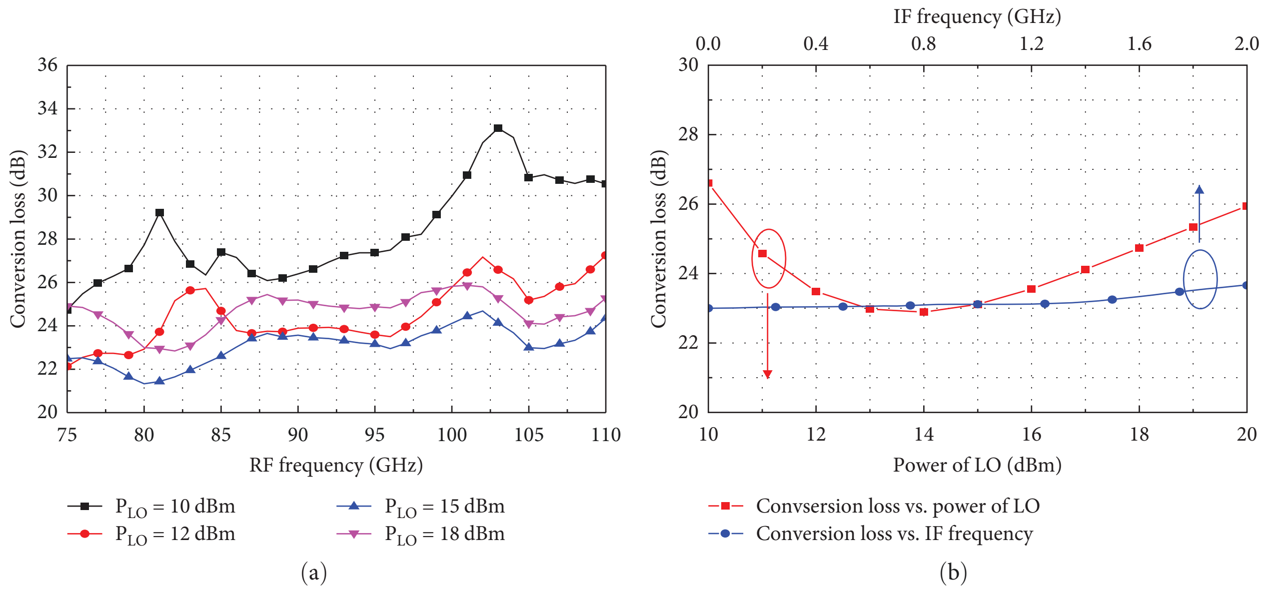


FIGURE 5: Simulated conversion loss of the 2-port harmonic mixer (a) full W-band response with IF = 1.5 GHz, (b) swept LO power response with RF = 94 GHz and IF = 1.5 GHz, and swept IF response with RF = 90 GHz and 15 dBm LO power.

Field-circuit cosimulation method is adopted to optimize the matching circuit and the mixer performance in this work. The field simulator HFSS is used for the passive circuits *S* parameters simulation, including BPF, LPF, the diodes structure, and so on. The circuit simulator advanced design system (ADS) from Keysight is used for the nonlinear device performance simulation based on the SPICE parameters of the diode.

The optimization goal in ADS is usually set to achieve a specific conversion loss at the desired frequency band, and the line lengths and widths of the matching circuits are then continuously adjusted by the controller until the goal is approached. The optimized parameters of the matching circuits, as illustrated in Figure 2, include $wm1 = 0.25$, $lm1 = 0.6$, $wm2 = 0.2$, $lm2 = 0.15$, $wm3 = 0.2$, $lm3 = 0.45$, $wm4 = 0.1$, and $lm4 = 0.57$ mm.

The 2-port mixer design steps are summarized as follows:

(1) Build 3D models of the input BPF and LPF in HFSS and then optimize the performance of them.
(2) Build 3D model of diode pair with additional input and output transmission lines, and perform simulation.
(3) Build the mixer circuit in ADS according to Figure 2. The BPF, LPF, and diode pair are modeled with their *S* parameters exported from HFSS from steps (1) and (2). The input and output matching circuits are composed of several series of microstrip stubs with different lengths and widths.
(4) Optimize the mixer performance with the goal of minimum conversion loss at full W-band by tuning the matching line lengths and widths of matching circuits in ADS.
(5) Build a complete 3D model using the line lengths and widths from step (4) in HFSS with all the components above, and perform the simulation.
(6) Simulate the mixer performance in ADS with the *S* parameters from step (5). If the simulated conversion loss deviates from the optimized one from step (4), then the sizes of the matching stubs are slightly tuned until an acceptable performance is achieved.

Using the steps above, a W-band 2-port 8th harmonic mixer is successfully designed. The simulated full band conversion losses under four different LO powers are shown in Figure 5(a). It indicates that low LO power, 10 dBm, for example, results in significant response bumps, whereas excessive LO power leads to higher conversion loss. Thus 12–18 dBm LO power is appropriate for the mixer excitation. Figure 5(b) gives the conversion loss at 94 GHz RF and 1.5 GHz IF with LO powers from 10 to 20 dBm. Minimum conversion loss is achieved with about 14 dBm LO power.

2.3. A 3-Port Harmonic Mixer. A 3-port mixer is designed for SAs as FSW-series. Furthermore, if the SA does not have mixer extension option, the 3-port mixer still can convert the RF signal down to IF with an additional signal generator providing LO.

The schematic of the 3-port mixer is shown in Figure 6. Comparing with the 2-port mixer, the only difference is that a diplexer is needed to separate the LO and IF signals.

The model and simulated results of the diplexer are shown in Figure 7. The prototype of diplexer is shown in Figure 7(a) fulfilled with lumped elements. It is obvious that the diplexer is composed of an LC highpass filter and an LC LPF. Lumped capacitors, such as surface mount 0201 and 0402 size ceramic capacitors, work well with frequencies up to 10 GHz. However, the real challenge is the high-frequency surface mount inductor. Thus, the semi-lumped filter techniques are introduced [26, 28] here, with all the inductors in Figure 7(a) fulfilled with high impedance MSL, the width of which is 0.1 mm. Together with the surface

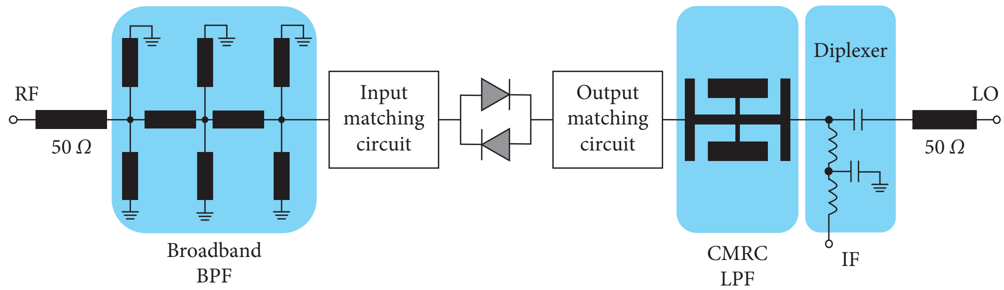


Figure 6: Design schematic of the 3-port harmonic mixer.

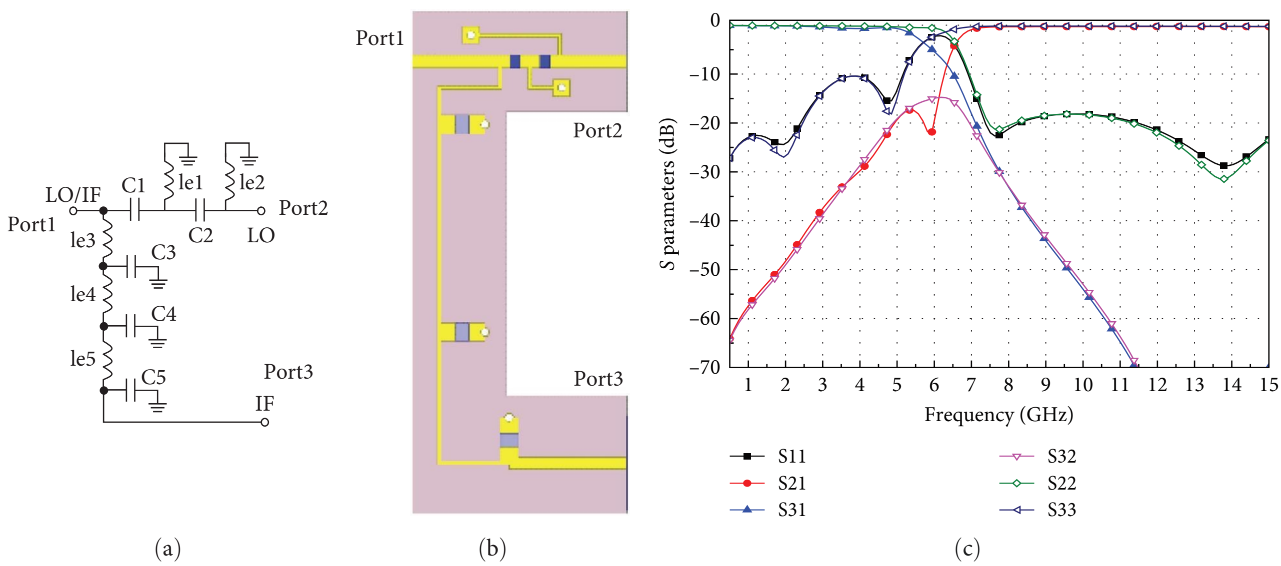


Figure 7: Diplexer designed with lumped capacitors and semi-lumped inductors (a) lumped elements representation, (b) model in HFSS with capacitance C1 = C2 = 0.3 pF, C3 = C4 = C5 = 0.75 pF, and length le1 = 1.2, le2 = 3.1, Le3 = 3.2, le4 = 5.65, le5 = 5.4 mm, and (c) simulation results of the diplexer.

mount capacitors, the diplexer is modeled in HFSS, and the sizes of the high impedance lines and the values of the capacitors are then optimized as in Figure 7(b). The simulated performance of shown in Figure 7(c). The IF to LO isolation at IF band is more than 50 dB and more than 40 dB at LO band. The results also indicate good return loss at all three ports.

The design steps of 3-port harmonic mixer are similar to the ones of 2-port harmonic mixer, except that a diplexer is added right after the CMRC LPF, as shown in Figure 6.

A W-band 3-port mixer is then designed according to the design steps, and the simulated performance is shown in Figure 8. It is concluded that LO power of 13–18 dBm is recommended for the 3-port mixer to get both low conversion loss and flat response.

3. Measurement and Discussion

According to the optimized sizes of the circuits and the modules, the 2-port and 3-port mixers are fabricated. Subminiature version A (SMA) connectors are adopted for LO and IF cables connection. The RF interface adopts WR-10 waveguide, and a waveguide to MSL transition is used to evaluate the circuit performance. The transition adopts E-plane probe, which is very common and easy to implement [29, 30]. The design of the transition is not elaborated in this work, and the simulation and test results of a back-to-back module are shown in Figure 9. The insertion loss is from 0.7 to 1.8 dB. Thus, the loss of a single transition is 0.35–0.9 dB, with higher loss at higher frequency.

During the assembly, the mixer substrate and the E-plane probe substrate are mounted on the gold-plated copper module with conductive epoxy, and then the antiparallel diodes are mounted on the mixer substrate with conductive epoxy, too. Wire bonding is used to connect the transition probe with RF port of the mixer. The photos of the mixer modules are shown in Figure 10.

The test bench of the mixers is shown in Figure 11.

W-band frequency multiplier source HP83558A, followed by a mechanical tuned attenuator, is used as the RF input signal of the mixer. A microwave signal generator, E8267D from Keysight, is used to drive the multiplier source. The mechanical attenuator is adjusted to achieve about −20 dBm power to measure frequency response of the mixers.

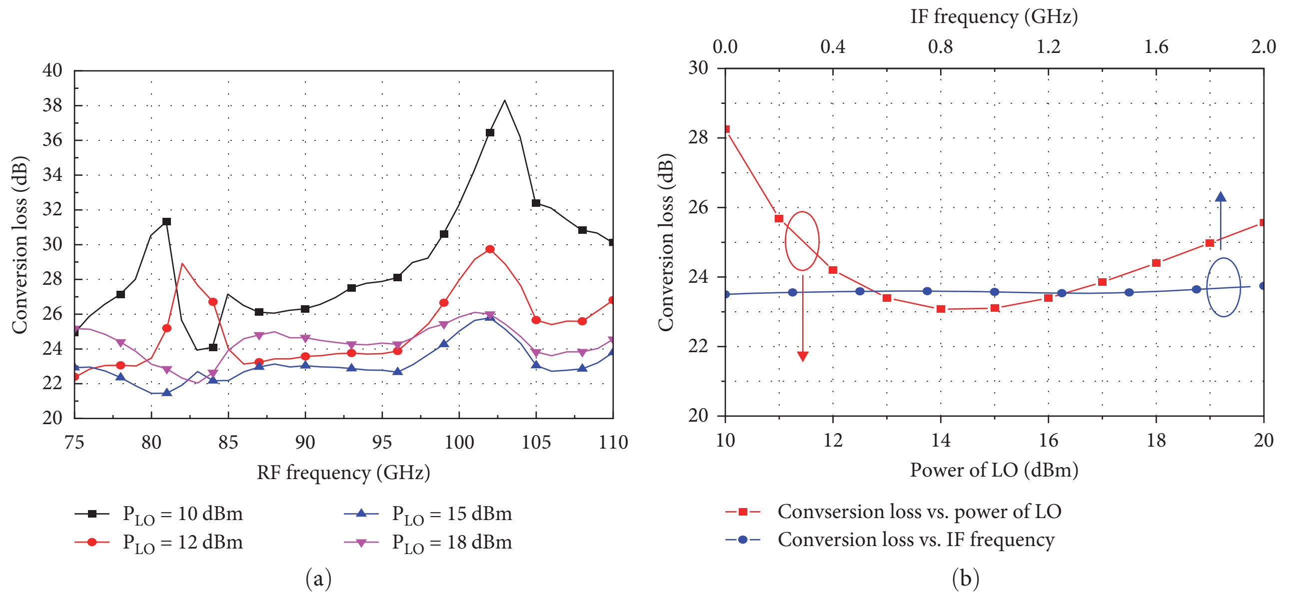


FIGURE 8: Simulated conversion loss of the 3-port harmonic mixer (a) full w-band response with IF = 1.5 GHz, (b) swept LO power response with RF = 94 and IF = 1.5 GHz, and swept IF response with RF = 90 GHz and 15 dBm LO power.

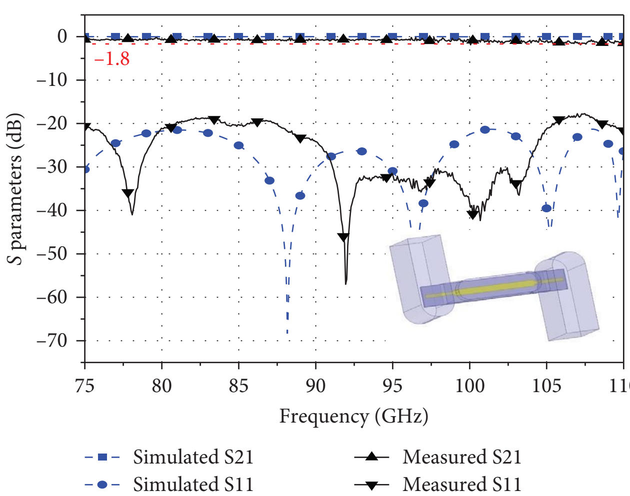


FIGURE 9: Simulated and tested the performance of waveguide to MSL transition.

The measured frequency response of the 3-port mixer is shown in Figure 12. It is indicated that the flatness of frequency response is strongly dependent on the LO power, which is consistent with the simulated results. The lower the LO power, the higher the response fluctuation. LO powers from 13 to 18 dBm are appropriate from the point of view of both conversion loss and response flatness. The flattest response is about 5 dB at frequencies from 75 to 110 GHz with LO power of 18 dBm, and the conversion loss is from 23 to 28 dB with typical value of 25 dB. The measured conversion loss agrees well with the simulated one with about 2–3 dB higher loss. It is believed that the higher loss is caused by lower LO power, which is reduced by the extra losses of the lumped capacitors of the diplexer and the SMA connector. In order to achieve low conversion loss, low loss coaxial line is needed to connect the SA and mixer to maintain high enough LO power.

The measured frequency response of the 2-port mixer is illustrated in Figure 13. The conversion loss is from 20 to 26 dB at full W-band. Typical conversion loss is about 23 dB. The PXA's LO power is fixed by the instrument, and verified by power meter of about 15 dBm. Thus, only the simulated conversion loss with 15 dBm LO power is given in Figure 13. It is found that the measured loss is in good consistent with the simulated one, which verifies the design methodology of this work.

The input 1 dB compression power of the harmonic mixer is also measured, as shown in Figure 14. The compression of 2-port mixer begins at the input power of −6 dBm, and the 1 dB compression power is about 0 dBm, which is similar to M1970W from Keysight. It is a reasonable value to guarantee the measurement dynamic range. The measured compression performance of 3-port mixer is almost the same as 2-port mixer with 2 dB higher LO power to compensate the loss of the diplexer.

Besides, in order to maintain good performance and reliability, the maximum RF input power of 5 dBm is recommended for the harmonic mixers.

Figure 15 presents the simulated and measured RF input return loss. The only difference between 3-port and 2-port harmonic mixer is that 3-port mixer has an extra diplexer at the LO/IF port, which has little impact on the return loss at RF port. Thus only the simulated RF return loss of 2-port mixer is shown in Figure 15, which is from 4.5 to 6.5 dB at full W-band.

The measured return losses include the mixer circuit, the waveguide to MSL transition, the gold wire bonding, and a section of waveguide, while the simulated one only

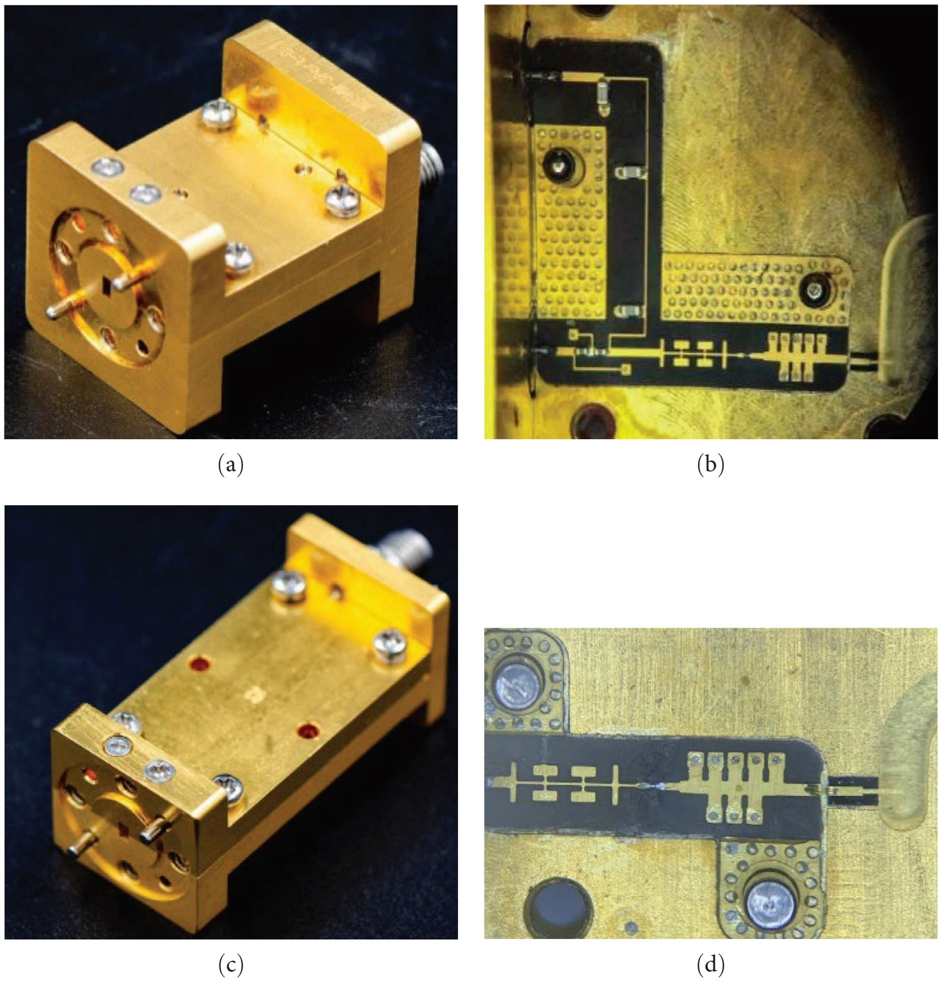


Figure 10: Photos of the mixer modules (a) 3-port mixer module, (b) lower half of the 3-port mixer module, (c) 2-port mixer module, and (d) lower half of the 2-port mixer module.

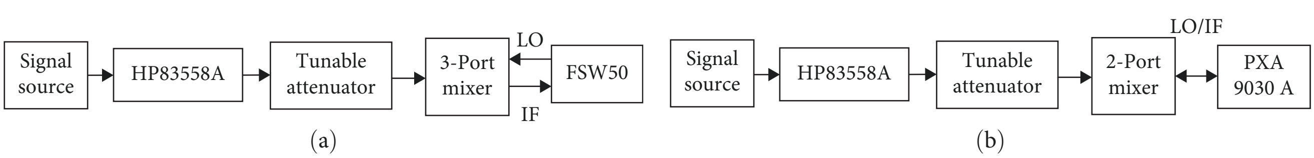


Figure 11: Test bench of (a) 3-port mixer and (b) 2-port mixer.

contains the mixer circuit. The measured return loss envelops of both 2-port and 3-port mixers agree well with the simulated one, which is about 6 dB. It indicates that these harmonic mixers have relatively poor RF return loss in order to maintain full band low conversion loss. Also, if these mixers are used for W-band components measurement, it is better to use isolators at the RF port to guarantee the full band gain flatness. Besides, it is found that the full band return loss is insensitive to LO frequency during the test, and the return loss remains about 4.5–6.5 dB with 75, 94, and 110 GHz LO.

The typical conversion losses of the designed harmonic mixers are compared with the reported ones, as shown in Table 2. A 7th harmonic mixer with about 20 dB conversion loss is designed by Schneiderbanger et al. [1]. This mixer utilizes waveguide as a balanced coupler, and a flip chip diode is adopted. While the mixers designed in this work are actually planar MSL circuits, and the waveguide is only used to couple the input signal, making it easy to integrate with other chip and circuits. Compared with other listed mixers, the proposed ones either have broader bandwidth, higher frequency, or have lower conversion loss. Besides, they have comparable or even better performance compared with the commercial mixers listed in Table 1, and these low-cost mixers are very helpful for the laboratory test of W-band components and systems.

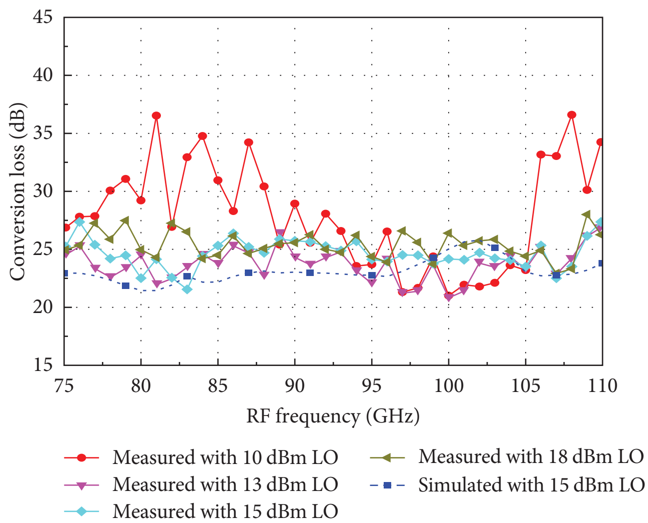


FIGURE 12: Measured frequency response of 3-port harmonic mixer with FSW50 together with simulated conversion loss.

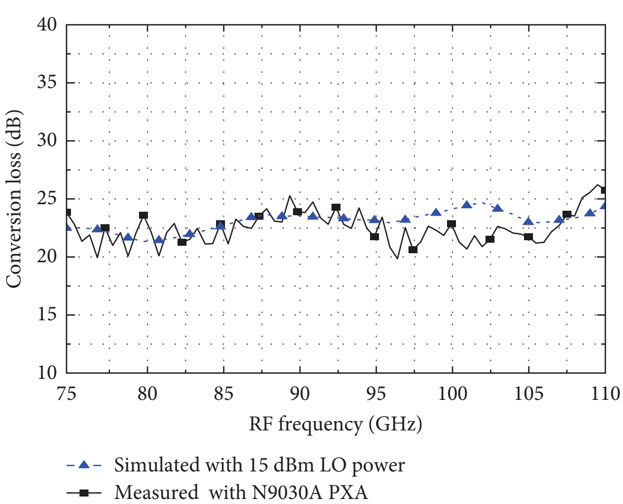


FIGURE 13: Measured conversion loss of 2-port harmonic mixer with PXA N9030A together with the simulated conversion loss.

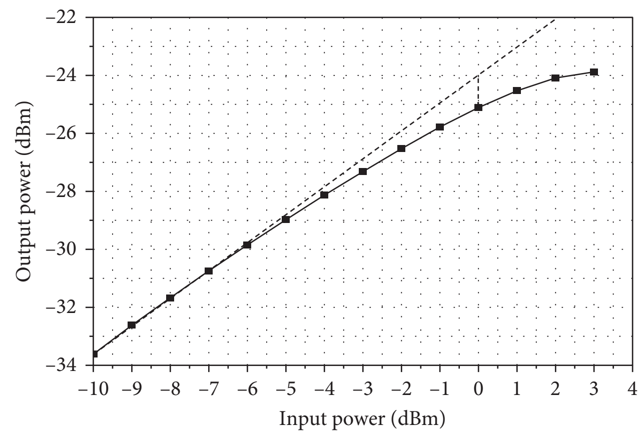


FIGURE 14: Measured input 1 dB compression power of the 2-port mixer at 94 GHz with 15 dBm LO power.

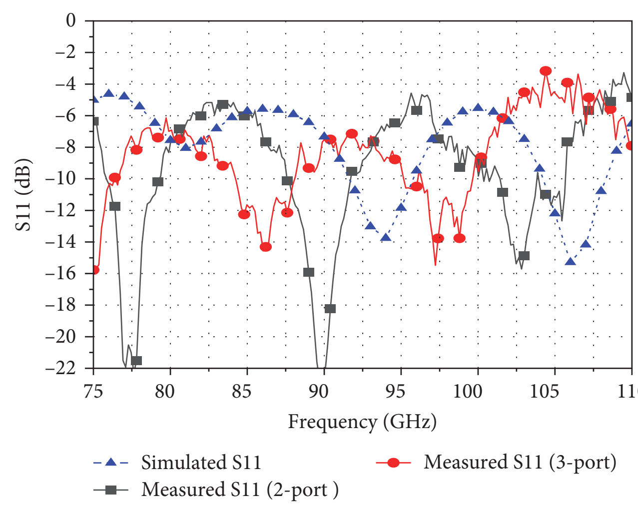


FIGURE 15: Simulated and measured RF input return loss with 15 dBm LO power at 94 GHz.

TABLE 2: Commercial harmonic mixers for SA frequency extension.

Ref	Frequency range (GHz)	Number of ports	Harmonic number	Typical conversion loss (dB)	Circuit type
Schneiderbanger et al. [1]	75–110	2	7	20	Hybrid, waveguide
11970 Series Harmonic Mixers [7]	80–105	3	8	36	Hybrid, MSL
Xue et al. [24]	37–39	3	8	23	Silicon based MMIC
This work	75–110	2	8	23	Hybrid, MSL
	75–110	3	8	25	Hybrid, MSL

4. Conclusion

The 2-port and 3-port 8th harmonic mixer design methods are proposed to extend the working frequency of SA in this work. The design concepts and steps are elaborated. The mixers are compatible with Keysight PXA and R&S FSW series SAs. W band 2-port and 3-port harmonic mixers are designed based on the proposed mechanism. The measured conversion loss of 2-port 8th harmonic mixer is from 20 to 26 dB, and 23 to 28 dB for 3-port mixer at 75–110 GHz. The measured results agree well with the simulated ones at full W-band, demonstrating that the design methods are effective. Furthermore, the design method is also feasible for harmonic mixer design at both MMW and THz bands.

Data Availability

The simulation models and design of the circuits can be requested from the corresponding author with the email address jguo@seu.edu.cn.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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