Design of a millimeter-wave third-harmonic mixer using substrate integrated waveguide balun

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Abstract: A planar millimeter-wave third-harmonic mixer with low conversion loss is proposed. The mixing circuit consists of a substrate-integrated waveguide (SIW) balun, a pair of diodes, a diplexer and microstrip matching circuit. The mixer is ideal for use as down-converter and up-converter. For a fixed intermediate frequency (IF) of 2 GHz, the mixer has an up-conversion loss of 14.5-15.6 dB and a down-conversion loss of 14-15.6 dB over the radio frequency (RF) band of 38-47 GHz. For a fixed local oscillation (LO) frequency of 13 GHz, the mixer has a conversion loss of 10-15.8 dB over the IF frequency band of DC-6.4 GHz. The proposed mixer offers an effective and low-cost solution for millimeter-wave applications.

Keywords: millimeter-wave, third-harmonic mixer, substrate-integrated waveguide (SIW) balun, down-conversion and up-conversion

Classification: Microwave and millimeter wave devices, circuits, and modules

References


1 Introduction

The harmonic mixer is widely used in millimeter-wave region, because it significantly reduces the frequency of the local oscillator (LO), thus simplifies the design of the LO source [1-4]. Compared with even harmonic mixer with a pair of antiparallel diodes, odd harmonic mixer has a better performance of radio frequency (RF)-to-LO isolation due to its balanced configuration. Odd harmonic waveguide mixers have been reported in the past years, and demonstrated having good performance [5-7]. However, these mixers are unsuitable for integrating with other planar circuits for their 3D structures. A Ka band monolithic microwave integrated circuit (MMIC) third-harmonic mixer has been reported [8], but the design of a MMIC mixer for a special application is an expensive and time-consuming task.

As a fundamental and important component, balun has been widely used in microwave and millimeter-wave circuits such as power combiners, balanced mixers and balanced amplifiers. Recently, substrate-integrated waveguide (SIW) technology has drawn much attention, and SIW is proved to preserves the advantages of rectangular waveguide and microstrip line. A broadband SIW balun has been realized [9], but the two balanced ports are not on the same side of the substrate. In this paper, a millimeter-wave SIW balun is proposed. Then, a millimeter-wave third-harmonic mixer based on the SIW balun is designed, fabricated and measured.
2 Design of the SIW balun

The SIW balun is composed of a power divider and a 180 degree phase shifter as shown in Fig. 1. Owing to the symmetrical structure, a wide band power divider is easily achieved by tuning the parameters $l_m$ and $d_m$. The broadband SIW compensating phase shifter [10] is adopted in this balun. The phase shift is generated by the length of delay line, and widths difference between two SIW lines. The length of the two SIW lines with different widths of $a_1$ and $a$ is $l_1$, and the length of the delay line is $l_p$. The phase shift at the center frequency $f_0$ is predicted by [10]:

$$\varphi(f_0) = l_1[\beta_1(f_0) - \beta_2(f_0)] - l_p \beta_2(f_0)$$

(1)

Where $\beta_1$ is the phase constant of up branch (width $a_1$), $\beta_2$ is the phase constant of down branch (width $a$). With proper values of $a_1$, $l_1$ and $l_p$, 180 degree phase shift can be achieved between the two output ports of the power divider.

Figure 2 shows the simulated results of the SIW balun with the following optimized values: $d = 0.3$ mm, $p = 0.6$ mm, $d_m = 0.4$ mm, $l_m = 2.4$ mm, $a = 3.5$ mm, $a_1 = 3.1$ mm, $l_p = 1.8$ mm, $l_1 = 7.2$ mm, $w_f = 12$ mm and $l_r = 3.5$ mm. The results are carried out through the commercial software Ansoft HFSS. It is observed that the simulated amplitude and phase imbalance are less than $\pm0.75$ dB and $\pm10^\circ$, respectively, across the frequency range of 40-50 GHz. In addition, the low loss property of SIW helps to achieve low conversion loss mixer.
This paper adopts several techniques to achieve low conversion loss mixer. First, the SIW balun proposed above is a low loss balun compared with traditional microstrip ones. Second, low loss diplexer is used to separate RF, LO and IF signals. The diplexer provides high isolation, preventing the signals from leaking to other ports, thus improving conversion loss too. Third, matching circuit is essential to get good port return loss, making full use of the available LO power. Last but not least, terminating some idle frequencies those containing nonnegligible power [1].

The circuit configuration of the proposed third-harmonic mixer is shown in Fig. 3. It consists of a SIW balun, a pair of diodes, a microstrip matching network and a diplexer. The two balanced diodes can effectively suppress the idle frequencies of the mixing products. The SIW balun divides/combines the RF signal, and rejects the LO and intermediate frequency (IF) signals. The diplexer separates the RF, LO and IF signal from each other. The diplexer is mainly composed of three filters, which are two low-pass filters and one band-pass filter. The low-pass filter following the matching circuit rejects the RF signal and some other spurious signals from leaking to LO and IF port. The band-pass filter at LO port rejects IF signal. Open stubs are used at the end of the parallel coupled lines to fulfill sharp rejection at the lower band of the band pass filter, and also lower loss is achieved compared with traditional band-pass filters with the same out-band rejection. The low-pass filter at IF port rejects LO and RF signals.

As described above, the diplexer adopts low order filters to separate the signals, and at the same time to guarantee lower loss. The low pass-filter at the RF port and the IF port both are 3-pole filter. In addition, the band-pass filter is actually a coupled line with short open stubs. These low order filters are key factors for low loss diplexer design.

### Table I. Spice model parameters of DMK2790

<table>
<thead>
<tr>
<th>$I_s$ (pA)</th>
<th>0.5</th>
<th>$R_s$ (Ω)</th>
<th>4</th>
<th>$XTI$</th>
<th>2</th>
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<td>n</td>
<td>1.05</td>
<td>$TD$ (sec)</td>
<td>1E-11</td>
<td>$FC$</td>
<td>0.5</td>
</tr>
<tr>
<td>$CJ0$ (pF)</td>
<td>0.05</td>
<td>$M$</td>
<td>0.26</td>
<td>$BV$ (V)</td>
<td>4</td>
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<tr>
<td>$EG$ (eV)</td>
<td>1.43</td>
<td>$VJ$ (V)</td>
<td>0.82</td>
<td>$IBV$ (uA)</td>
<td>10</td>
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</table>

Figure 4 shows the simulated results of the diplexer by HFSS. The cut-off
frequency of the low-pass filter is about 6.5 GHz, and the pass-band for LO is about 12 to 16 GHz. It is observed from Fig. 4 and Fig.2 that both the SIW coupler and the diplexer reflect the second harmonic of LO and mixing products with low order IF for up-conversion. This also helps to achieve low conversion loss mixer as described above.

![Simulated S parameters of the proposed diplexer](image)

**Fig. 4.** Simulated S parameters of the proposed diplexer

The adopted diode is commercial GaAs Schottky diode DMK2790 from Skyworks, Inc. Tab. I lists the SPICE model parameters of the diode.

As for the performance evaluation of the mixer, the simulated S-parameters results of SIW balun and diplexer are exported to the harmonic balance simulator as “sNp” data in Agilent ADS. The performance of the mixer is optimized by tuning the parameters of the matching network and the length of the transmission line ML1.

![Photograph of the proposed third-harmonic mixer](image)

**Fig. 5.** Photograph of the proposed third-harmonic mixer

### 4 Mixer implementation and measurement

The sample mixer is fabricated on a Rogers RT/Duriod 5880 substrate with substrate thickness of 0.254 mm and relative permittivity of 2.2. Figure 5 shows the photograph of the proposed mixer. A transition from microstrip line to
rectangular waveguide at the RF port is added for test. Figure 6 shows the measured conversion loss of the third-harmonic mixer using Agilent PNA Network Analyzer E8364C with PSG Analog Signal Generator E8257D providing the LO signal. Testing results show that the conversion loss is less than 15.8 dB in a wide IF frequency band (from DC to 6.4 GHz) with LO frequency fixed at 13 GHz. And the conversion loss is 14-15.6 dB in a RF frequency range of 38-47 GHz with IF frequency fixed at 2 GHz for both up and down conversion. During the test, LO power is fixed at 8 dBm. The rapid increase of conversion loss above 6.5 GHz is mainly caused by stopband of the low-pass filter used at the IF port. Figure 7 gives the dependence of conversion loss on LO power. The conversion loss increases drastically below +6 dBm LO power, and does not change much with higher LO power.

Table II depicts the performance comparison between the proposed third-harmonic mixer and some reported similar odd-harmonic mixers. It demonstrates that the proposed third-harmonic mixer has a low conversion loss, low LO power and wide frequency band.

![Fig. 6. (a) Measured conversion loss versus IF frequency with LO frequency fixed at 13 GHz, (b) Measured conversion loss versus RF frequency with IF frequency fixed at 2 GHz.](image)

![Fig. 7 Conversion loss vs. LO power of the mixer](image)
5 Conclusion
A wide-band millimeter-wave third-harmonic mixer with low conversion loss is proposed. An SIW balun and a microstrip diplexer are used to divider/combine the RF signal and separate the LO and IF signals, respectively. The measured results show a good performance. Furthermore, the proposed mixer is easy to be integrated with other circuits for its planar structure, and it maintains a low cost property for the PCB technology we used. This mixer can be widely used in millimeter-wave circuits and systems.

Acknowledgments
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<table>
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<tr>
<th>Reference</th>
<th>RF (GHz)</th>
<th>IF (GHz)</th>
<th>Harmonic number</th>
<th>LO power (dBm)</th>
<th>Conversion Loss (dB)</th>
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<tr>
<td>[6]</td>
<td>60-90</td>
<td>0.1</td>
<td>7</td>
<td>13.5</td>
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<tr>
<td>[7]</td>
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<td>0.75</td>
<td>7</td>
<td>14</td>
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<td>2</td>
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