Harmonic Dual-Band Diode Mixer for the X- and K-Bands

Jeong Hun Park · Moon-Que Lee*

Abstract

This paper presents a new dual-band diode mixer for the X- and K-bands. The proposed mixer consists of a pair of series-connected diodes and a frequency-dependent delay line that operates at 180° and 360° at the X-band of 10.525 GHz and at the K-band of 24.15 GHz, respectively. Without reconfigurable devices such as switches, the proposed mixer operates as a single-balanced diode mixer at the X-band and a subharmonically pumped antiparallel diode mixer at the K-band simultaneously. The designed circuit was implemented in a hybrid microwave integrated circuit using discretely packaged RF components on a microwave printed circuit board. The measurement results showed conversion losses of 6.5 dB and 16.6 dB at the X- and K-bands, respectively.

Key Words: Diode Mixer, Dual-Band, Radar.

I. INTRODUCTION

A radar detector is a passive device that receives the microwave emission signals of a speed measuring or warning radar. It can also be used to help prevent speed-related car accidents. The frequency of these radars ranges at a variety of wavelength bands, usually at the X-, K-, and/or Ka-bands. The X- and K-bands at 10.525 GHz and 24.15 GHz, respectively, are the most common frequencies for speed measuring or warning [1].

Various microwave mixers in radar detector architectures have been studied to detect multi-band radar signals effectively. One simple method is to use two mixers for each band reception, but this approach has the disadvantages of a large circuit size and high cost. Common radar detectors usually adopt the architecture of a multi-band mixer. A gate FET mixer with a tunable gate bias voltage for the X-, K-, and Ka-bands has been explored [2]. This circuit detects only one RF band with respect to the optimized gate voltage for one band among the X-, K-, and Ka-bands. In

addition to these approaches, some mixer schematics can be applied to a multi-band operation. A monolithic microwave integrated circuit (MMIC) mixer using a differential pair amplifier and a Gilbert cell mixer in a cascode configuration has been studied for multi-band wireless applications [3]. A dual-band subharmonic mixer making use of the second and fourth subharmonics of the local oscillator (LO) signal has been reported [4]. As a low-cost circuit, a dual-band self-oscillating mixer employing both the fundamental and harmonic signals has been proposed for the C- and X-bands [5].

This paper proposes a novel dual-band mixer without reconfigurable devices, which behaves as a single-balanced mixer at the X-band and a subharmonically pumped antiparallel diode mixer at the K-band simultaneously.

II. MIXING OPERATION AND CIRCUIT DESIGN

Fig. 1 presents a schematic diagram of the proposed dual-band

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Fig. 1. Schematic diagram of a harmonic dual-band mixer for the X- and K-bands.

mixer for the X- and K-bands. The RF port receives dual-band signals at the X-band of 10.525 GHz and the K-band of 24.1 GHz. The LO frequencies are 11.275 GHz and 11.285 GHz for the X- and K-bands RF signals, respectively. The proposed mixer consists of a frequency diplexer for the isolation between the LO and IF (intermediate frequency) ports, a pair of series-connected diodes, a compact delay line with frequency dependency, and an RF matching circuit including a DC path. For the dual-band RF operation, the DC path was designed to have an infinite or high impedance at the X- and K-bands.

The key component of the proposed mixer is the frequency-dependent delay line connected between the cathode of diode 1 and the anode of diode 2. The transmission phase of the delay line is designed to have approximately 180° at the X-band RF and LO signals and 360° at the K-band RF signal of 24.1 GHz simultaneously.

1. X-Band Operation

In the X-band RF operation, the transmission phase of the delay line is approximately 180° at both the RF and LO signals. The voltage $v_{1,X}$ between the anode and the cathode of diode D1 shown in Fig. 1 is denoted as

$$v_{1,X} = v_{LO} - \overline{v_{RF,X}} = v_{LO} + v_{RF,X}, \quad (1)$$

where the overbar of the symbol $v_{RF,X}$ is the phase reversal of $v_{RF,X}$ that occurs due to the delay line at the X-band. Similarly, the voltage $v_{2,X}$ between the anode and cathode of diode D2 can be described as

$$v_{2,X} = -v_{LO} + v_{RF,X}. \quad (2)$$

The V-I characteristics of a diode can be expressed as a power series.

$$i = a_0 + a_1 v + a_2 v^2 + a_3 v^3 + \dots \quad (3)$$

where a_0 , a_1 , a_2 , and a_3 are the constant power series coefficients. The base band IF components in the mixer are linked to a_2 and a_3 , which are related to the quadratic and cubic terms of the diode V-I characteristic, respectively. The quadratic term gives rise to the desired mixing product $\omega_{RF} - \omega_{LO}$, while the cubic term generates the subharmonic mixing component $\omega_{RF} -$

ω_{2LO} .

The current $i_{IF1,X}$ and $i_{IF2,X}$ of the diodes related to mixing are

$$i_{IF1,X} \propto v_{1,X}^2, \quad (4)$$

$$i_{IF2,X} \propto v_{2,X}^2. \quad (5)$$

Considering the polarities, the sum current $i_{IF,X}$ of the mixer is expressed as

$$i_{IF,X} = -i_{IF1,X} + i_{IF2,X} \propto (-v_{1,X}^2 + v_{2,X}^2). \quad (6)$$

After low-pass filtering, the IF component $v_{IF,X}$ of the mixer is obtained as

$$v_{IF,X} \propto \cos\{(\omega_{RF,X} - \omega_{LO})t\}. \quad (7)$$

This result is the same as the mixing component of a single-balanced diode mixer for the X-band RF signal.

2. K-Band Operation

In the case of the K-band RF operation, the voltage $v_{1,K}$ between the anode and the cathode of diode D1 can be described as

$$v_{1,K} = v_{LO} - v_{RF,K}. \quad (8)$$

Note that the RF voltage of the cathode of D1 $v_{X,RF}$ has the in-phase through the delay line with a transmission of 360° at the K-band. The voltage $v_{2,K}$ between the anode and the cathode of diode D2 is

$$v_{2,K} = -v_{LO} + v_{RF,K} = -v_{1,K}. \quad (9)$$

From the voltage relationship across the diodes, an antiparallel diode connection between D1 and D2 is achieved.

In the operation of the subharmonic mixer using an antiparallel diode connection, the IF components have no quadratic term because $v_{1,K}^2$ is identical to $v_{2,K}^2$ and is cancelled out.

In the subharmonic mixing, the current $i_{IF1,K}$ of diode D1 is

$$i_{IF1,K} \propto v_{1,K}^3. \quad (10)$$

Considering the polarity of D2, the current $i_{IF2,K}$ is

$$i_{IF2,K} \propto v_{2,K}^3 = -v_{1,K}^3. \quad (11)$$

The sum current $i_{IF,K}$ of the mixer is

$$i_{IF,K} = -i_{IF1,K} + i_{IF2,K} \propto (-v_{1,K}^3 + v_{2,K}^3) = -2v_{1,K}^3. \quad (12)$$

After low-pass filtering, the IF voltage component $v_{IF,K}$ is obtained as

$$v_{IF,K} \propto \cos\{(\omega_{RF,K} - 2\omega_{LO})t\}. \quad (13)$$

In this configuration, the behavior of the proposed mixer is the

same as that of a subharmonically pumped antiparallel diode mixer.

3. Delay Line with Frequency Dependency

The delay line between the cathode of D1 and the anode of D2 is implemented using a three-*stepped* impedance transmission line. The electrical length of the *normal* uniform transmission line with a phase of 360° at $f_{RF} = 24.1$ GHz has 157° at the X-band $f_{RF} = 10.525$ GHz, which is 23° away from the ideally required phase angle of 180° . This phase imbalance yields a poor LO to RF isolation (Fig. 2). To compensate for the phase imbalance at the dual-band RF signals, the authors propose the three-stepped transmission line, which has the required phase values at the X- and K-bands by adjusting the characteristic impedances and lengths of the three-stepped lines.

The voltage and currents on both sides of the proposed delay line can be expressed using the ABCD matrix:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}, \quad (14)$$

where

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos \theta_1 & jZ_1 \sin \theta_1 \\ jY_1 \sin \theta_1 & \cos \theta_1 \end{bmatrix} \cdot \begin{bmatrix} \cos \theta_2 & jZ_2 \sin \theta_2 \\ jY_2 \sin \theta_2 & \cos \theta_2 \end{bmatrix} \cdot \begin{bmatrix} \cos \theta_1 & jZ_1 \sin \theta_1 \\ jY_1 \sin \theta_1 & \cos \theta_1 \end{bmatrix}. \quad (15)$$

Among the ABCD, the trans-impedance parameter “A” is given by

$$A = \cos \theta_2 \cos 2\theta_1 - \frac{(Z_1 Y_2 + Y_1 Z_2)}{2} \sin \theta_2 \sin 2\theta_1. \quad (16)$$

The phase delay of each line section is given by

$$\theta_{X1,2} = \frac{\theta_{K1,2} f_X}{f_K}, \quad (17)$$

where $\theta_{X1,2}$ and $\theta_{K1,2}$ are the phase values at the X-band f_X and K-band f_K , respectively.

Fig. 3 shows the ideally required delay line at the X- and K-bands, where Z_X and Z_K are the characteristic impedances at the X- and K-bands, respectively. Their ABCD matrices are as follows:

Fig. 2. Delay line (a) the conventional and (b) the proposed compact delay line.

Fig. 3. Ideally required equivalent delay line at (a) the X-band and (b) the K-band.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_X = \begin{bmatrix} \cos \theta_X & jZ_X \sin \theta_X \\ jY_X \sin \theta_X & \cos \theta_X \end{bmatrix}, \quad (18)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_K = \begin{bmatrix} \cos \theta_K & jZ_K \sin \theta_K \\ jY_K \sin \theta_K & \cos \theta_K \end{bmatrix}. \quad (19)$$

From Eqs. (16) and (18), for $\theta_X = 180^\circ$, the trans-impedance parameter “A” of the ABCD matrix should satisfy the following equation:

$$\cos \theta_{X2} \cos 2\theta_{X1} - \frac{(Z_1 Y_2 + Y_1 Z_2)}{2} \sin \theta_{X2} \sin 2\theta_{X1} = -1. \quad (20)$$

Similarly, the required phase $\theta_K = 360^\circ$ for the K-band is applied as

$$\cos \theta_{K2} \cos 2\theta_{K1} - \frac{(Z_1 Y_2 + Y_1 Z_2)}{2} \sin \theta_{K2} \sin 2\theta_{K1} = 1. \quad (21)$$

With the aid of the commercially available software Keysight ADS, Z_1 , Z_2 , θ_{K1} , and θ_{K2} , which satisfy Eqs. (20) and (21), were extracted as 50Ω , 82Ω , 100° , and 165° , respectively.

Fig. 4 shows the phase characteristics of the conventional uniform and the proposed delay lines. The proposed line yields a more optimized performance of phase reversal in the X-band RF and LO frequency compared with the conventional one.

III. MEASUREMENT RESULTS

Fig. 5 shows the equivalent circuit model of the Schottky diodes SMS7621-006LF used in the design [6].

Two Schottky diodes are series connected in a surface-mount plastic package, which has parasitic effects of lead inductances of 1 nH, stray capacitance of 0.07 pF between leads, and bond wire inductance of 0.3 nH. The intrinsic Schottky diode is expressed as the SPICE parameters: parasitic series resistance $R_s = 12 \Omega$, zero-bias junction capacitance $C_{j0} = 0.10$ pF, and junction potential $V_j = 0.51$ V. Fig. 6 shows a photograph of the designed mixer fabricated on a Teflon substrate (TLC-30) of $\epsilon_r = 3.0$ and $h = 0.5$ mm.

Fig. 7 illustrates the simulated and measured performance of the mixer operating at the X-band RF signal. The conversion loss for the different LO input power from -10 dBm to $+15$ dBm is

Fig. 4. Transmission characteristics of (a) the uniform and (b) the proposed compact delay lines.

Fig. 5. Equivalent circuit model of SMS7621-006LF.

Fig. 6. Photograph of the proposed mixer.

shown in Fig. 7(a). The saturated conversion loss of 6.5 dB is measured at an LO power level of 10 dBm. Fig. 7(b) presents the conversion loss of less than 7.6 dB over the X-band RF frequency at a range of 10.025–11.125 GHz at a fixed LO power of 10 dBm.

Fig. 7. Simulated and measured responses for the X-band RF input: (a) conversion loss with respect to the LO power and (b) conversion loss vs. RF frequency at $f_{LO} = 11.275$ GHz and LO power of 10 dBm.

Fig. 8 shows the simulated and measurement results in the K-band RF operation. The saturated conversion loss of 16.6 dB was measured at the LO power level of 0 dBm. The conversion loss ranged from 15.5 to 22.2 dB over the RF frequency range of 23.6–24.5 GHz at the optimal LO power of 0 dBm. The measurement shows that conversion loss increases when driven by LO power of over 0 dBm. This is attributed to the higher order mixing components generated in an overdriven diode.

The proposed mixer has a single balance characteristic to the LO signal because of the traveling phase of 180° in the proposed compact delay line. Therefore, LO leakage in the RF port is canceled out. The LO-RF isolation was measured above 15.6 dB. The measured 1-dB compression points for the dual-band RF signal were 2 dBm and -9 dBm at 10.525 GHz and 24.1 GHz, respectively, as shown in Fig. 9.

The performance of the designed dual-band mixer is compared with other published single-band passive mixers at the X- and K-bands in Table 1. According to the summary, the designed

Fig. 8. Simulated and measured responses for the K-band RF input: (a) conversion loss with respect to the LO power and (b) conversion loss vs. RF frequency at $f_{LO} = 11.285$ GHz and LO power of 0 dBm.

Fig. 9. Simulated and measured responses for the X- and K-bands: (a) IF power with respect to the X-band RF power and (b) IF power with respect to the K-band RF power.

Table 1. Performance summary of the published mixers at the X- and K-bands

Ref.	RF (GHz)	CL (dB)	LO (dBm)	LO-RF isolation (dB)	P1dB (dBm)	Note
[7]	9–11	5	12	25–28	–	Diode
[8]	9.2–10.5	10	13	30	–	Diode
[9]	10–11.5	5.7–7.1	9	14	–	Diode
[10]	3.1–10.6	6.7–8.2	8	18	6	Diode
[11]	16.5–33	10–12	10	25	–	(MMIC) APDP mixer
[12]	23–37	9.4–12	13	22	6	(MMIC) APDP mixer
[13]	18–26	11–12	7	30	–	(MMIC) Resistive mixer
This work	10.025–11.125	6.5–7.6	10	15.6	2	Surface-mount packaged
	24.1	16.6	0	15.6	–9	Schottky diode

CL=conversion loss, APDP=anti-parallel diode pair.

mixer shows acceptable performance in conversion loss at the X-band operation. Moreover, the conversion loss at the K-band

seems acceptable, considering that the implementation uses packaged RF devices with a series lead inductance of 1 nH, which oped-

rates as a high impedance of $j151\ \Omega$ at the K-band. The conversion loss and LO-RF isolation can be improved if we use the flip chip device with low parasitics or fabricate using the MMIC process.

IV. CONCLUSION

A new topology for a dual-band diode mixer has been proposed. The proposed harmonic dual-band mixer operates as a single-balanced mixer and a subharmonically pumped antiparallel diode mixer at the X- and K-bands, respectively. The validity of the proposed mixer was demonstrated by measurement results showing acceptable conversion loss and LO-RF isolation at both the X- and K-bands. The proposed dual-band mixer without reconfigurable devices, such as switches, has the advantages of simplicity, circuit size, and cost over conventional ones.

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