A novel circuit architecture for fourth subharmonic mixers

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Abstract: A circuit topology for high-order subharmonic (SH) mixers is described. By phase cancellation of idle frequency components, the SH mixer circuit can eliminate the complicated design procedure of idle frequency circuits. Similarly, the SH mixer circuit can achieve a high port isolation by phase cancellation of the leakage LO, RF and idle frequency signals. Based on the high-order SH mixer architecture, a new Ka-band fourth SH mixer is analyzed and designed, it shows the lowest measured conversion loss of 8.3 dB at 38.4 GHz and the loss is lower than 10.3 dB in 34–39 GHz. Measured LO-IF, RF-LO, RF-IF port isolation are better than 30.7 dB, 22.9dB and 46.5 dB, respectively.

Key words: SH mixers; antiparallel diodes; conversion loss; harmonic balance analysis
DOI: 10.1088/1674-4926/33/6/065002 **EEACC:** 2570

1. Introduction

Millimeter and submillimeter wave SH mixers are widely used to extend the range of millimeter and submillimeter wave test and measurement equipment, such as spectrum analyzers, electronic warfare, frequency counters, power meters and other instruments. SH mixers can lower the LO frequency, which alleviates the difficulty in obtaining high performance and low cost high frequency millimeter and submillimeter wave sources. Research on SH mixers has a long history from earlier crossed waveguide configurations to recent hybrid integrated and monolithic configurations, and from an earlier one mixing diode to recent antiparallel diode pair SH mixers. Most of the published papers concentrated on the work of low-order SH mixers. To the best of our knowledge, there are few published works on high-order SH mixers, especially the recycling of LO, RF and idle frequency signals in high-order SH mixers for low conversion loss and high port isolation[1−12].

Examining published SH mixer literature, there are a significant number of SH mixer papers incorporating reflector networks, with proper terminations presented to RF, LO and idle frequency components, to lower conversion loss. The papers quantitatively assess the influences of input and output reflector networks simultaneously. The input network is designed to pass the operation frequency components and reflect partially undesired mixing frequencies. Minimum reflection is realized to the input signals by optimizing input matching networks. The output network reflects the operation frequencies and undesired mixing frequency components for low conversion loss[8−11]. The philosophy using reflector networks is similarly fit to implement high quality fundamental mixers. However, due to the difficulty in design reflector networks for maximum recycling of idle frequency components, using reflector networks for low conversion loss high-order SH mixers remains a great challenge.

In this paper, high-order SH mixer circuit topology is given and discussed. According to the designed SH mixer order, the specified mixing diode sub-arrays and corresponding power dividers, as well as phase shift networks for RF and LO signals are arranged. The SH mixer circuit topology eliminates the complicated design process of idle frequency circuits by phase cancellation of idle frequency components. Moreover, the circuit can also have a high port isolation by phase cancellation of the leakage signals. To phase-canceled undesired mixing products, the circuit presents a short circuit at the terminals with zero terminal voltage, which effectively reuses these idle frequencies[13]. Since diode series resistance is a dominant factor in mixer conversion loss, the number of diodes can be increased to reduce the effective series resistance for each mixing diode sub-array[12]. Based on high-order SH mixer topology, a new Ka-band fourth-order SH mixer is analyzed and implemented with two antiparallel mixing diode pair sub-arrays soldered in parallel. The LO signals propagate to the two sub-arrays with a phase difference of 90°, and the RF signals are in-phase to each sub-array. The measured conversion loss is lower than 10.3dB in 34–39 GHz and the lowest loss is 8.3 dB at 38.4 GHz. LO-IF port isolation is higher than 30.7 dB in 8.5–9.6 GHz, and RF-IF, RF-LO port isolation is better than 46.5 dB, 22.9 dB in 34–39 GHz, respectively.

2. SH mixer circuit topology

The basic SH mixer circuit configuration is given in Fig. 1, where n is the number of mixing diode sub-arrays. If the voltage amplitude of the LO signals are much larger than the RF signals ($V_{LO} \gg V_{RF}$), the conductance has a time-varying behavior that varies at the rate of the LO frequency. The main

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Received 6 December 2011

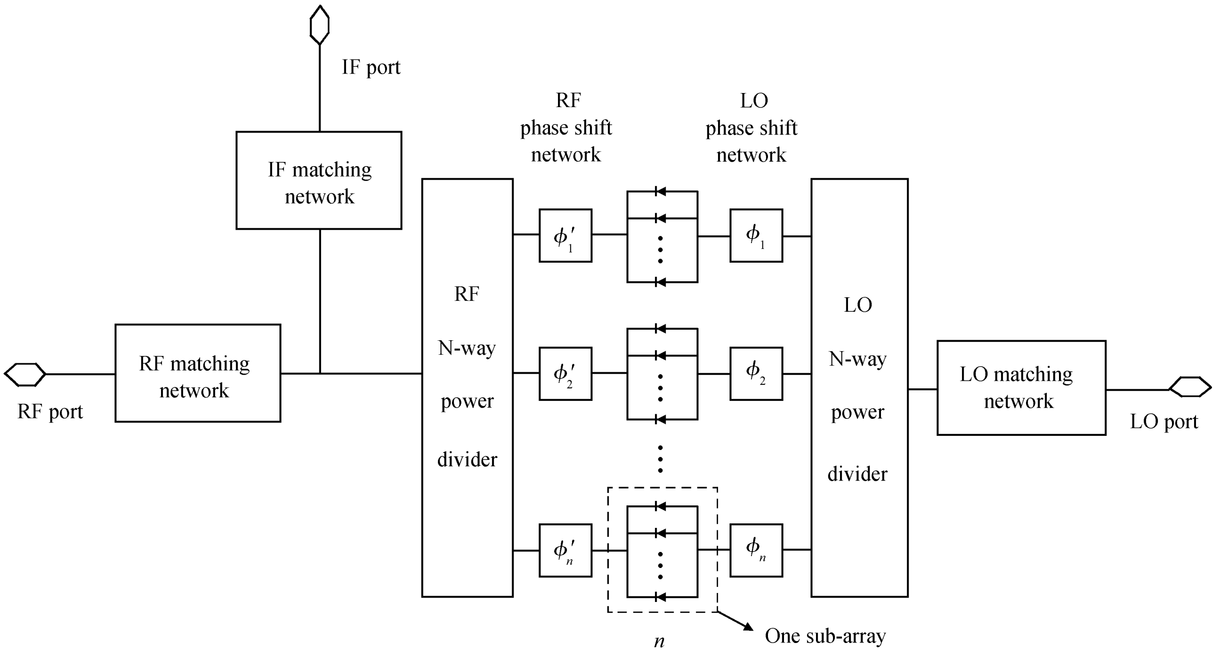

Fig. 1. SH mixer circuit topology.

current waveform of the Kth sub-array $I_{\rm K}(t)$ generated by the product of the signal voltage $V_{\rm RF}(t)$ and conductance $g(t)$ can be expressed as follows[14]:

$$I_{\rm K}(t) = V_{\rm RF}(t) \times g_K(t) = V_{\rm RF}\cos(\omega_{\rm RF}t + \phi'_K) \times \left[g_0 + 2\sum_{n=1}^{\infty} g_{\rm n}\cos(n\omega_{\rm LO}t + n\phi_k)\right]. \quad (1)$$

Assume a phase shift angle of $\phi_K = 2k\pi/n$ and $\phi'_K = 0$, the output total mixing current can be presented as:

$$I(t) = \sum_{k=1}^{n} I_K(t) = \sum_{k=1}^{n}\left\{V_{\rm RF}\cos(\omega_{\rm RF}t + \phi'_k) \times \left[g_0 + 2\sum_{n=1}^{\infty} g_n\cos(n\omega_{\rm LO}t + n\phi_k)\right]\right\}, \quad (2)$$

and the identity

$$\sum_{k=1}^{n}\cos\left(\frac{2k\pi}{n}C\right) = 0, \quad (3)$$

in which C is $cn+1$, $cn+2$, $cn+3$, $\ldots$, $(c+1)n-1$, where the $c = 0, 1, 2, 3, \ldots$. Therefore, the output total current can be deduced as:

$$I(t) = nV_{\rm RF}\cos(\omega_{\rm RF}t)\{g_0 + 2g_{n(c+1)}\cos[n(c+1)\omega_{\rm LO}t]\}. \quad (4)$$

Based on the derived equation (4), it can be concluded that the output mixing products of the SH mixer are merely $\omega_{\rm RF} \pm n(c+1)\omega_{\rm LO}$. Other frequency mixing components are recycled by phase cancellation of the circuit. To the mixing diode sub-arrays as shown in Fig. 1, at the condition of equal leakage power of LO signals, the total phase shift angle of the leakage LO signals to RF/IF port is $2k\pi/n$, it can be derived that the sum of the leakage LO signals power to RF/IF port is also eliminated by phase cancellation according to Eq. (3) with $C = 1$, infinite isolation of the LO-RF/IF port can be achieved in theory.

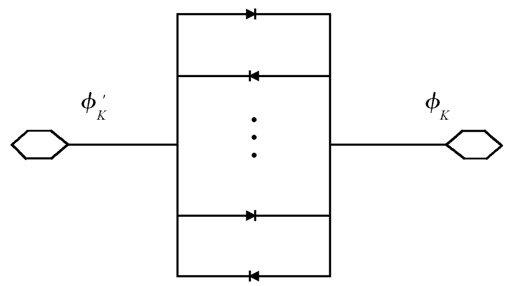

Fig. 2. Antiparallel diode pair sub-array.

So far, we have assumed that the voltage and current controlled circuit elements are only the function of the LO voltage and current. This is normally the case when the LO signals are much larger than the RF signals, as its sole function is to generate the time-varying circuit element waveform. When the RF signal amplitude increases, these circuit elements can be a function of both the LO and RF signal amplitudes. In this case, the time-varying waveform will contain harmonics of both LO and RF signals. Consequently, the SH mixer output spectrum will contain mixing products of all harmonics of the LO and RF signals. These frequencies can be expressed in the general form: $m\omega_{\rm RF} \pm n\omega_{\rm LO}$, where the m and n are 1, 2, 3, 4, $\cdots$. Assuming a phase shift angle of $\phi_K = \phi'_K = 2k\pi/n$, it can also be derived that idle frequency components are maximally

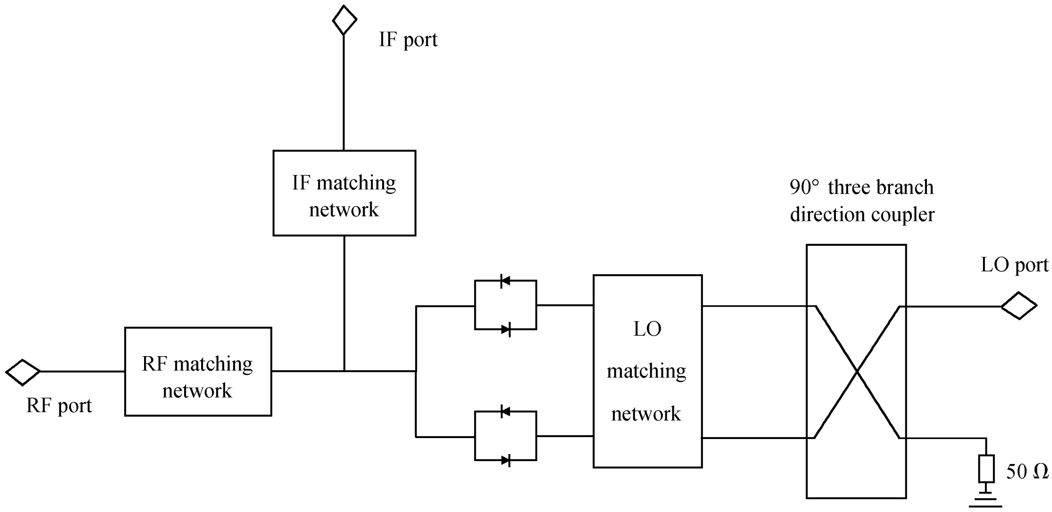

Fig. 3. Circuit schematic of the fourth-order SH mixer.

recycled. Since $\omega_{RF} = n\omega_{LO}$, to each mixing diode sub-array, the total phase shift angle of the leakage RF signals to LO port is $2k\pi + 2k\pi/n$, it can be concluded from Eq. (3) that the RF-LO port isolation is infinite in theory. Of course, the total phase shift of the leakage LO signal to RF/IF port is $2k\pi/n^2 + 2k\pi/n$, which can be simplified as a phase shift angle of $2k\pi/n$ with large n. For high-order SH mixers, we can also improve LO-RF/IF isolation.

In the SH mixer circuit topology Fig. 1, while the mixing diode sub-arrays are replaced by an antiparallel diode pair sub-array as given in Fig. 2, with corresponding power dividers and phase shift networks, the even-order SH mixer is realized with recycled idle frequency components. The even-order SH mixer circuit can be seen as a special case of circuit topology Fig. 1. When the mixing diodes are pumped by LO signals ($V_{LO} \gg V_{RF}$), with the phase shift angle of $\phi_K = k\pi/n$ and $\phi'_K = 0$, it can be found that the output total current is derived as follows:

$$I(t) = 2n\alpha i_S V_{RF} \cos(\omega_{RF} t)\{I_0(\alpha V_{LO}) + 2I_{2n(c+1)}(\alpha V_{LO}) \cos[2n(c+1)\omega_{LO} t]\}, \quad (5)$$

where the $I_n(aV_{LO})$ are modified Bessel functions of the second kind. Based on Eq. (5), it can be found that the output mixing components are $\omega_{RF} \pm 2n(c+1)\omega_{LO}$. Undesired idle frequencies are recycled by phase cancellation of the circuit. The leakage RF signals to the LO port is in-phase, the RF-LO isolation can be improved by adding a simple reflection network. The isolation of LO-RF/IF can also be enhanced in the same way as discussed above.

When the RF signal amplitude increases, voltage and current controlled circuit elements are a function of both the LO and RF signal amplitudes. In this case, the output mixing frequencies can be expressed in the general form: $m\omega_{RF} \pm n\omega_{LO}$, where $m + n$ is an odd integer ($m + n = 1, 3, 5, 7, \ldots$). Assume the phase shift angle of $\phi_K = \phi'_K = k\pi/n$, it can also be derived that idle frequency components are also maximally recycled.

3. Ka-band fourth SH mixer design

In order to investigate the SH mixer circuit topology described above, a novel fourth SH mixer circuit is designed, its circuit schematic is shown in Fig. 3, where the mixing diodes are pumped by LO signals. The RF port is a standard WR-28 rectangular waveguide. The RF signals are transferred via waveguide (WG)-finline-microstip transition, metallic via holes are applied along the mounting edge of the substrate to suppress high-order modes[15]. The IF and LO ports are connected with SMA. The LO signals are divided equally by a three branch coupler with an output phase difference of 90°, and the coupler isolation port is terminated by a thin-film resistor with 50 Ω, which has a wide coupling bandwidth and high port isolation compared with a conventional two branch directional coupler. The IF block is realized by an interdigital coupler to prevent the leakage of IF signals to the RF port, and the IF return path is provided by a short $\lambda_{LO}/4$ high impedance microstrip line. The circuit substrate is RT/duroid5880 with a dielectric constant of 2.22 and thickness of 0.254 mm. A flip-chip Schottky barrier diode (SBD) DMK2308 of Skyworks inc. is used. The important diode SPICE parameters are $R_S = 4\ \Omega$, $n = 1.05$, $C_{j0} = 0.05$ pF, $I_S = 0.5$ pA, $M = 0.26$, $V_j = 0.82$ eV, $B_V = 4.0$ V, and $I_{BV} = 0.01$ mA[16]. The mixer circuit and the diode chip are soldered using silver epoxy.

All passive parts of the fourth SH mixer are simulated by HFSS and the S-parameters are exported for conversion loss analysis in ADS. The analysis process is repeated to optimize the whole circuit for the lowest conversion loss and flat response in the designed frequency band. The simulated conversion loss results are depicted in Fig. 4. In the frequency band 34–39 GHz, the simulated conversion loss is flat and the typical loss is 8.5 dB.

4. Measurements

In the measurement setup, the RF signals are generated by an Agilent E8267D signal generator, and the LO signals are generated by an Agilent E8251A with the output power of 13.5 dBm. The output IF signals of the SH mixer are moni-

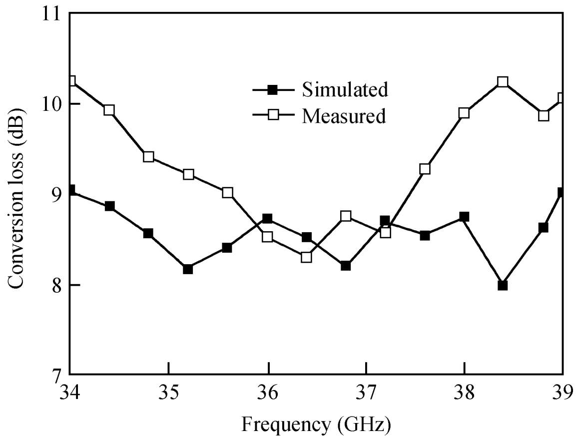

Fig. 4. The measured and simulated conversion loss.

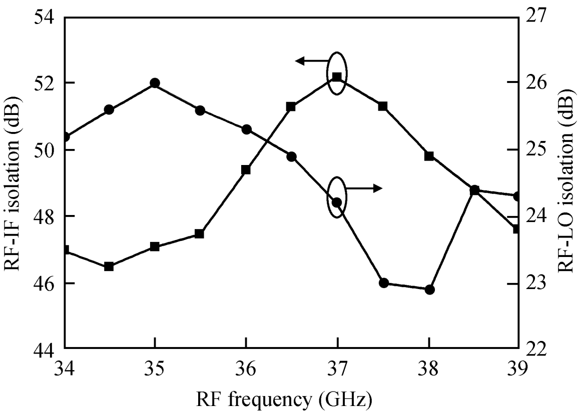

Fig. 5. The measured RF-IF and RF-LO port isolation.

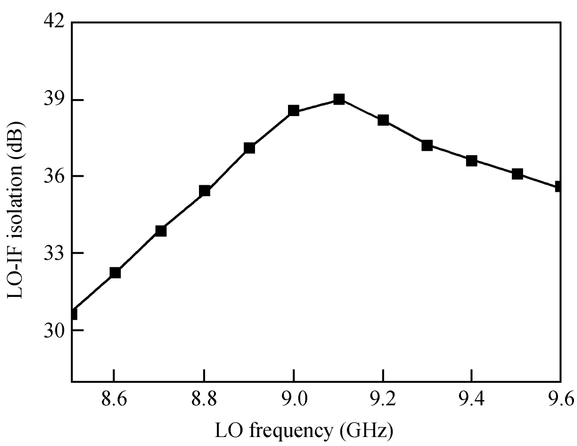

Fig. 6. The measured LO-IF port isolation.

tored by an Agilent E4447A spectrum analyzer. The measured conversion loss results of the fourth SH mixer are also plotted in Fig. 4. It can be found that the measured conversion loss is lower than 10.3 dB and the response is flat in 34–39 GHz, and the lowest measured loss is 8.3 dB at 38.4 GHz. Figure 5 shows that the measured RF-IF port isolation is better than 46.5 dB and the RF-LO isolation is higher than 22.9 dB in 34–39 GHz at an LO frequency fixed at 9.1 GHz. In Fig. 6, the tested LO-IF port isolation is higher than 30.7 dB from 8.5–9.6GHz with

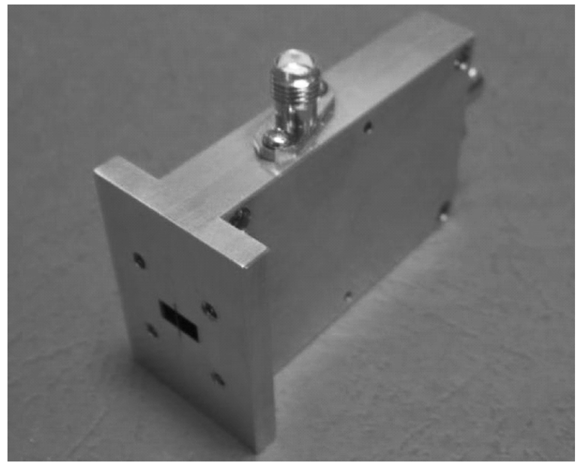

Fig. 7. Photo of the fourth-order SH mixer.

the RF frequency fixed at 36 GHz. The photo of the designed novel Ka-band fourth SH mixer is shown in Fig. 7.

5. Conclusions

In this paper, a novel circuit topology for high-order SH mixers is described. The SH mixer circuit structure can eliminate undesired idle frequency components by phase cancellation of the circuit and lower conversion loss. Similarly, the SH mixer circuit can get high port isolation. A new Ka-band fourth SH mixer is analyzed and designed. As the measured results show, the fourth SH mixer achieves the lowest measured conversion loss of 8.3 dB at 38.4 GHz and the loss is lower than 10.3 dB with a flat response at 34–39 GHz. The maximum isolation of LO-IF, RF-LO and RF-IF reaches 30.7 dB, 22.9 dB and 46.5 dB, respectively. The novel Ka-band fourth SH mixer presents a low cost solution and a very promising performance, which is very attractive in millimeter and submillimeter wave application systems.

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