Design of Single Balanced Millimeter-Wave Sub-Harmonic Mixer Circuits

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***Abstract*-As the demand of broadband and high speed communication increases, high performance sub-harmonic mixer solution becomes more and more important for millimeter-wave frequency applications. Low Conversion Loss (CL), high LO to RF/IF isolation, low spurs leakage and high linearity are desired features that are challenging to reach at the same time in SHM designs. This paper briefly reviews three designs of passive single balanced sub-harmonic mixers and identify promising topologies that could further improve SHM performances in terms of CL, isolation and spurs level.**

I. INTRODUCTION

With required LO frequency only at half or less of the RF frequency, sub-harmonic mixer (SHMs) demonstrates several advantages over fundamental mixing operation in that, at lower LO frequency, it is easier to generate the desired LO drive level with less phase noise. Therefore, sub-harmonic mixer is often the preferred solution over fundamental mixers in the millimeter-wave applications.

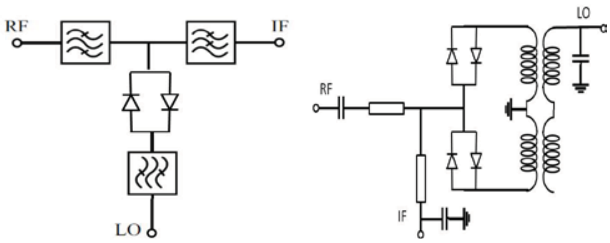
The widely adopted sub-harmonic mixer (SHM) topology is the anti-parallel diode pair (APDP) with filtering networks at LO, RF and IF ports [1] - [3]. Filters used in this approach usually limits the operation bandwidth. Other topologies include passive field effect transistor (FET) based SHM and active Gilbert-cell based design. The passive FET approach employs resistive FET biased at triode region and differential LO/RF signals are applied to the gates to achieve the mixed signal via modulations of the FET's channel resistance [4]. The active Gilbert-cell approach requires LO signals are driven with precise quadrature offsets, which can only be achieved at lower frequencies [5]-[6].

This paper briefly reviews three designs of passive sub-harmonic mixers (SHMs) to illustrate the state of arts development of SHM design techniques, which includes one example for APDP based SHM; one example for trans-condutance SHM [7]; and one example for passive distributed SHM [8].

II. DESIGN THEORY

A. Single-Balanced APDP Sub-Harmonic Mixer (SHM)

The conventional sub-harmonic mixer (SHM) topology is shown in Fig 1(a). The anti-parallel diode arrangement inherently double the LO frequency by switching on the APDP at both the positive and negative half-cycles of the LO signal. The filter networks typically are required to achieve certain level of isolation between LO-RF and LO-IF ports. However, those filter networks also limit the operation bandwidth and consume relatively large area since multiple quarter-wave length transmission lines are often used for bandpass filtering [2]. Single balanced SHM using spiral Marchand balun is a better choice to overcome those problem especially for designs using planar GaAs process where low substrate loss and air-bridge-lifted metal capacity make high quality balun possible at these high frequencies.



(a) (b)

Figure 1. (a) Conventional APDP Sub-Harmonic Mixer; (b) Schematic of single Balanced SHM based on Spiral Marchand Balun

As shown in Fig. 1(b), the LO signal is converted to balanced differential signal to drive two APDP cores. The virtual LO ground at the center of APDP cores is used to connect RF and IF networks. This topology is verified on a 4-mil thick GaAs process that provides Schottky diode with anode length of 1 um and cut-off frequency f_c of 3 THz. The spiral Marchand balun covering 34 - 45 GHz can be designed using top-layer metal which is partially lifted as air-bridged structure (Fig. 2). This practice improves the balun's operation frequency and reduces the substrate loss as well.

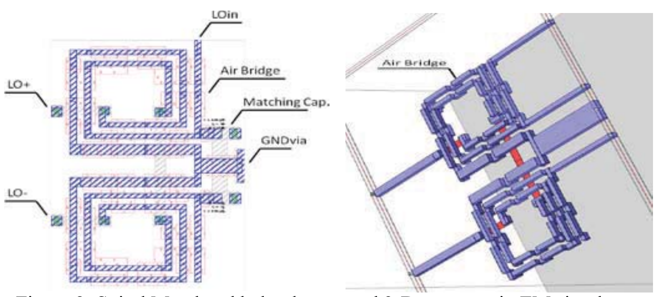


Figure 2. Spiral Marchand balun layout and 3-D structure in EM simulator.

Preliminary measured data of this SHM show lower than 12.5 dB Conversion Loss (CL) for up conversion (RF=2xLO-

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IF, LO = 9 dBm, IF=0.5 GHz) and RF frequencies between 65 - 86 GHz with min. CL of 8 dB around 75 GHz. The balanced operation also improved LO isolations to RF and IF ports with LO leakage at those ports lower than -30 dBm and 2xLO spurs at RF port lower than -26 dBm over the entire operation band.

B. Single Balanced Transconductance SHM

In principle, any nonlinear device can be used as sub-harmonic mixer, however, the cut-off frequency f_c of Schottky diode needs to be 3-5 times higher than operating frequency to maintain low conversion loss in SHM designs, however most low cost GaAs or SiGe process cannot provide such high f_c for millimeter-wave operations. Therefore, to solve this challenge on low cost commercial process, Hung et al. [7] proposed a novel SHM design using single balanced transconductance mixing approach. This design is verified for a 77 GHz SHM application using a SiGe technology with diode f_c only ~50 GHz and HBT device f_T ~ 80 GHz.

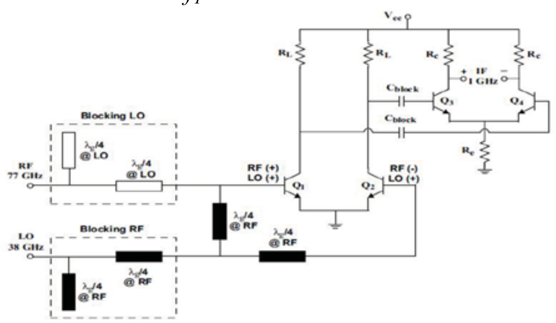

Figure 3. Schematic of single balanced Transconductance SHM. [7]

In this design (Fig. 3), the large signal LO signal across the base and emitter junctions creates a periodically varying transconductance, which modulates the collector current and generates harmonics. When the device is biased close to turn-on point, the 2nd harmonic product reaches its maximum value. To isolate the LO and RF ports and prevent 2xLO harmonics reflected back to RF port, dedicated filtering and cancellation circuits are implemented as shown in Fig.3. Two quarter-wave length transmission lines between bases of Q1 and Q2 creates 180-degree offset for RF signal and provide 0 degree offset for LO signals. In addition, those two lines provide 180-degree cancellation for 2xLO spurs that are generated at the bases of Q1 and Q2. All of above quarter-wave lines can be realized using LC lumped element networks around the operation frequencies to reduce the circuit area. This design demonstrates a measured CL of 10.3 dB without IF buffer stage at 77 GHz (LO=10 dBm at 38 GHz), LO to RF leakage less than -20 dBm and 2LO leakage at RF port less than -15 dBm.

C. Distributed SHM Based On Reduced-Size Rat-Race Coupler

Distributed concept has been widely used in amplifier and mixer designs to accommodate multi-octave wide bandwidth. However, it is usually very challenging to provide the desired differential signal driving the distributed SHM network. Kuo et al. proposed a modified Rat-Race coupler based on broadside coupling and spiral Marchand balun structure (Fig. 4) on 0.13um CMOS process [8].

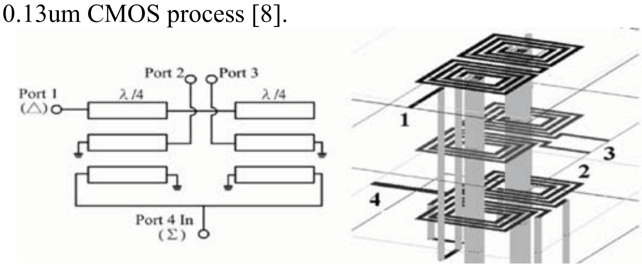

Figure 4. Modified Rat-Race coupler provide wide-band in-phase RF and differential LO driving for a distributed SHM design. [8]

TABLE I
V- AND W-BAND SUB-HARMONIC MIXER PERFORMANCES

Device / f_T or f_c (GHz)	f_{RF} (GHz)	LO harm.	Conv. Loss (dB)	LO/RF & IF Iso. (dB)	2xLO Leakage (dBm)	Ref.
GaAs Schottky Diode/f_c=3000	65-86	X2	Min. 8, Max. 12.5	>39	<-26	This work
GaAs Schottky Diode/f_c=1500	94	X2	>7	LO-RF: >40 LO-IF: >30	N.A.	[2]
0.15um GaAs PHEMT	75-88	X2	14 - 18	LO-IF: 40	N.A.	[4]
0.5um SiGe HBT/f_T=80	77	x2	>10.3	LO-RF: >30	<-15	[7]
0.13um CMOS/f_T=91	32–70	x2	11-13	LO-IF: >30; LO-RF:>25;	<-12	[8]

III. SUMMARY

A comparison of some of the reported V- and W-band SHM is presented in Table I. Single balance SHM designs have demonstrated preferable advantages for millimeter-wave applications, such as high LO-RF/IF isolation, low 2xLO leakage and suppressions of the LO AM noise. With advances of semiconductor process such as InP HBT in [9], more SHM designs for higher frequencies can be found in recent publications. Meanwhile, innovations in topologies and design techniques will continue to be major driver of the SHM designs.

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