HF-VHF-UHF IQ Mixer with a Single SPDT Switch

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Abstract  -- An I Q mixer topology using passive components and a single SPDT switch is described with simulations and measurements at 7 MHz and 144 MHz. A test fixture permits experiments with a variety of switch candidates. Results are presented for MOSFET switches and an SPDT switch using a hybrid coil and ring of Schottky diodes. SSB conversion loss is near 6 dB. Measured IIP3 is +16 dBm for a MOSFET switch and +6 dBm for the diodes. The Schottky version exhibits much better 2nd order performance and stability of amplitude and phase differences between I and Q ports. Results at VHF using surface mount components suggest that the Schottky diode/hybrid coil switch is a promising candidate for low power near-zero IF applications.

Frequency Conversion, Mixers, Receivers, Schottky Diodes

I. Introduction

The frequency converter block commonly known as a mixer has Radio Frequency (RF), Intermediate Frequency (IF) and Local Oscillator (LO) ports. A signal at the RF or IF port is multiplied by the LO to obtain sum and difference frequencies at the remaining port. Reactive filters are commonly used on the RF and IF ports to suppress undesired mixing products. Mixers are often configured in In-Phase and Quadrature (I and Q) pairs to suppress selected undesired sum or difference frequencies using basic sine and cosine product identities. IQ mixers are particularly attractive when RF and LO frequencies are high and the IF is at a near-zero baseband frequency. Although general purpose wide-bandwidth mixers are attractive, mixers are commonly preceded by bandpass filters, and optimization for a particular RF/LO frequency range may improve an important specification. The IQ mixer described in this paper was initially designed for a narrow-band starved-current off-grid application, but the resulting topology presents other interesting possibilities.

To implement an image-reject mixer, the IQ mixer may be configured with a quadrature hybrid network on the IF port and a second quadrature hybrid on either the RF or LO port. An in-phase splitter on the RF ports with quadrature LO drive is common in wideband applications, and integrated LO signal generators with I and Q outputs facilitate this approach. The alternate configuration shown here with a quadrature hybrid on the RF ports normally carries a bandwidth penalty, but for many applications the band of interest is narrow. In a mixer optimized for narrow band operation, passive components may serve a dual purpose of enhancing mixer performance while providing front-end selectivity and low-pass filtering in both down converter and up converter applications.

II. The Basic Switch Mixer

The switch mixer shown in figure 1 has been described in basic form by Maas [1], in high frequency balanced form by Hayward [2], and in configurations without ground and balanced I Q forms by Campbell [3] and [4]. Operation is conceptually simple: the waveform at a is multiplied by 1 or 0 at the LO frequency, and the difference product appears after a low-pass filter at the IF port. Switch devices have been GaAs MESFETs, silicon MOSFETs and JFETs, all operated in the triode region. Such shunt-FET mixers are now common in integrated form, but less familiar with discrete components below 1 GHz.

Many configurations with in-phase I and quadrature Q IF ports are possible, but the intriguing arrangement in figure 2 has only a single SPDT switch. Reactive components depend on the RF and LO frequency range. Since the only active component is the switch, operating frequency is limited only by switch characteristics—the basic block diagram works from millihertz to terahertz.

The input block in present experiments is a variation on the twisted wire hybrid described by Fisher [5]. At higher frequencies transmission line and waveguide structures become attractive. The twisted wire hybrid has some useful properties: impedance is 50 ohms when impedances at ports 2 and 3 are equal, and ports 2 and 3 exhibit a 90 degree phase difference over a wide bandwidth. Port 2 and 3 amplitudes are equal only at the design center frequency, but amplitude differences are easily trimmed in the baseband signal processor. A pair of lumped element impedance inverters labeled 1/z follows the quadrature hybrid. The impedance inverters provide desirable low-pass filtering in the RF path and a convenient place to trim out any phase errors between the I and Q channels.
III Simulations with Various Switches

A 7 MHz test fixture was built, and the measured component values extracted for LTspice simulations. The schematic in figure 3 serves for both measurements and simulations. A 20 kHz IF quadrature hybrid combines the I and Q ports with equal amplitude and 90 degree phase shift in the simulations. The resulting single sideband mixer facilitates comparisons between simulations and measurements. The only change between all the different switches is the circuitry inside the dotted line on the schematic. Figures 4 and 5 show variations using MOSFETs and a hybrid coil/diode combination. Table 1 shows simulation results with an ideal voltage-controlled SPDT switch, a pair of VN10 MOSFETs, and a hybrid coil with a ring of diodes. Using a diode ring and hybrid coil to implement an SPDT RF switch may be unfamiliar. Careful analysis of signal flow and LO current in the hybrid coil and diodes reveals that LO and RF are isolated in the hybrid coil, and the two RF ports are alternately connected to ground. The three switches substituted inside the dotted line of figure 3 show similar results. A number of other JFET and MOSFETs have been simulated.

Table 1. Simulation Results with Different Switches

<table>
<thead>
<tr>
<th></th>
<th>Ideal Switch</th>
<th>MOSFET</th>
<th>Hybrid/Diode</th>
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<tbody>
<tr>
<td>Conversion Loss</td>
<td>4.1 dB</td>
<td>5.3 dB</td>
<td>5.9 dB</td>
</tr>
<tr>
<td>Input 3rd Order</td>
<td>+22.8 dBm</td>
<td>+21.2 dBm</td>
<td>+6.9 dBm</td>
</tr>
<tr>
<td>LO Drive</td>
<td>N/A</td>
<td>+10 dBm</td>
<td>+4 dBm</td>
</tr>
<tr>
<td>2nd Order Performance</td>
<td>perfect</td>
<td>poor</td>
<td>perfect</td>
</tr>
<tr>
<td>I Q stability</td>
<td>excellent</td>
<td>excellent</td>
<td>excellent</td>
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Table 1 is a brief summary of simulation results. MOSFET and hybrid/diode combinations both perform well, except for significant 2nd order products with MOSFETs.

IV. Measurements at 7 MHz

An experimental test fixture was built to measure performance with a selection of different switches. VN10 MOSFETs, J310 JFETs, 5200-2835 Schottky diodes and 1N4148s have all been tried. The same coil: 8 trifilar turns on an FT37-43 ferrite toroid core, has been used as a hybrid coil with the diodes and for differential gate drive to the FETs.

Figure 4 and Photo 2 show the schematic and construction of the dual-mode hybrid coil and Schottky diode ring SPDT switch. LO drive is applied to the diodes in differential mode, and points a and b are alternately connected to ground through the low-loss hybrid coil common mode.

Figure 5 and Photo 3 show straightforward construction of the dual MOSFET switch. Variable gate bias is applied as shown.
Table 2 summarizes the measured performance of the VN10 and 5200-2835 mixers at 7 MHz. The simulations are included for comparison. As expected, real diodes and FET switches are non-ideal—but they are non-ideal in interesting and important ways. As expected, 3rd order dynamic range is better for the VN10 switches: large MOSFETs have low on resistance with forward bias well above threshold, and high off resistance when the gates are driven into deep sub-threshold. In contrast, the Schottky diodes have modest dynamic resistance when conducting a few mA, and reverse bias is clamped to the forward voltage on the opposite branch in the figure 4 circuit. Schottky diode reverse bias clamping may improve balance and reduce I Q error dependence on LO drive level.

<table>
<thead>
<tr>
<th>Simulated vs Measured Performance</th>
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<tbody>
<tr>
<td>Ideal</td>
</tr>
<tr>
<td>sim</td>
</tr>
<tr>
<td>Loss dB</td>
</tr>
<tr>
<td>IIP3 dBm</td>
</tr>
<tr>
<td>LO dBm</td>
</tr>
<tr>
<td>2nd Order</td>
</tr>
<tr>
<td>I Q stability</td>
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</tbody>
</table>

*see text for more detail

Table 2. Measured Results with Different Switches

The 2nd Order and I Q stability results in Table 2 are presented as relative terms, and some explanation is in order. 2nd order performance was simulated and measured by injecting a signal 10 dB below the LO level into the RF port and observing 2nd order products on the baseband output port, and also by observing the level of LO present at the RF port. For ideal switches and the hybrid/diode case with ideal transformers and four identical diode models, 2nd order products are below the simulation noise floor. 2nd order products are also below the measurement noise floor for the hybrid/diode combination in photo 2. LO levels at the RF port of the hybrid/diode mixer are construction limited, and lower than -40 dBm. Note that it is possible to null the LO at the RF port by introducing a few millivolts of dc offset at the I and Q baseband ports. 2nd order performance of the MOSFET switch mixer was poor in both simulation and measurement. During two-tone simulations and measurements for IIP3, 2nd order products were often larger than 3rd order products. Furthermore, dc offsets at the baseband I and Q ports are many millivolts, and vary with LO drive level and across the frequency range. This precludes using fixed trim for LO-RF suppression with MOSFETs.

I Q stability presents interesting challenges in both simulation and measurement. In all cases, the I Q outputs drive a set of conventional third order all-pass networks, capable of opposite sideband suppression greater than 50 dB. Amplitude and phase offsets are trimmed at an RF-LO center frequency for opposite sideband suppression greater than 40 dB across a decade baseband frequency range from 300 to 3000 Hz. RF-LO frequency, and LO drive level are then varied to observe stability of the offset trim. With the hybrid/diode mixer, 40 dB suppression holds for LO levels between 0 dBm and +10 dBm, across a 1% RF-LO frequency range. The MOSFET mixer requires amplitude and phase trimming with LO changes of 1 dB, and much smaller LO-RF frequency excursions.

2nd order performance and I Q phase stability are still being investigated for the MOSFETs. Trifilar toroid differential drive to an unmatched pair of large, highly variable and non-linear voltage-dependent gate capacitors offers a rich area for exploration. Cgs is roughly 22pF on the VN10FET data sheet. The VN10 SPICE model appears overly simplified in the triode region, but relatively poor 2nd order performance appears in the simulations as well. In contrast, measured 2nd order performance and I Q amplitude and phase stability of the hybrid coil/diode configuration are consistently good in measurements, and simulated 2nd order products are below the discrete math noise floor.

Since a critically important performance criterion for I Q mixers is stability and repeatability of amplitude and phase errors between the I and Q channels, the hybrid/diode switch may be a better choice for the near-zero IF applications. An experimental starved-current VHF receiver system maintains opposite sideband suppression greater than 40 dB over wide ranges of LO drive level and day-to-day changes in the lab. A few measurements are listed in the following paragraph.

V. Measurements at 144 MHz

Results at 7 MHz warrented a second set of experiments at 144 MHz using surface mount components and microwave diodes and transformers. Photos 4 and 5 show top and bottom views of an experimental I Q mixer using an SPDT switch built with a surface mount trifilar coil and two pair of Agilent HSMS 2817 diodes. Preliminary results are encouraging. A starved-current receiver system using the experimental I Q mixer without an LNA exhibits an input intercept of +2 dBm, 14 dB noise figure, and draws 10 mA from a 9v battery.

VHF I Q mixer

VHF underside
VI. Conclusions

An IQ mixer topology using passive components and a single SPDT switch is presented along with simulations and measurements. Results are presented for MOSFET switches and an SPDT switch using a hybrid coil and ring of Schottky diodes. Conversion loss is similar for either switch. 3rd order intercept is superior for the MOSFETs, but the Schottky version exhibits much better 2nd order performance and stability of amplitude and phase differences between I and Q ports. The Schottky diode version maintains low loss and modest 3rd order performance at 0 dBm LO drive, and is attractive for low current near-zero IF applications at HF-VHF-UHF.

The hybrid/diode combination provides useful performance and agreement between basic understanding, simulation, and measured results. The large MOSFET IQ mixers described here provide significantly improved 3rd order performance, but are not competitive for either 2nd order performance or IQ stability. More work is needed to understand performance limitations when using MOSFET switches in the triode region as frequency conversion elements in IQ mixers. Suggested areas for study are the reactive networks connected to the drains, perhaps by extending the techniques used for PA waveform engineering, and exploring the precision of on-off MOSFET zero crossings by digging into the device physics.

VII. Acknowledgements

This work follows a natural progression starting with lunch table discussions of switch mixers at Bell Labs, Murray Hill, in the 1970s. The hybrid/diode IQ topology was initially sketched following starved-current mixer conversations with Wes Hayward, Bob Larkin, Bob Culter, and Allison Parent.

References


