Terahertz RF Front-End Employing Even-Order Subharmonic MOS Symmetric Varactor Mixers in 65-nm CMOS for Hydration Measurements at 560 GHz

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Abstract

A 560-GHz RF front-end employing MOS symmetric varactor (SVAR) subharmonic mixers achieves a minimum SSB noise figure (NF) of 35 dB in the 4th order subharmonic mixing (SHM) mode which is 5-7 dB lower than that of SiGe HBT mixers. The front-end fabricated in 65-nm CMOS also achieves 45-dB SSB NF for 6th order SHM at RF=810 GHz and 60-dB SSB NF for 10th order SHM at RF=1.2 THz. Use of SVAR’s in a mixer is the first and the 1.2-THz RF is the highest among the silicon coherent RF front-ends.

Keywords: Terahertz, CMOS, reactive mixer, and SVAR

Introduction

The electro-magnetic spectrum near 560 GHz strongly absorbs water, and this property can be used to monitor water contents/hydration levels in materials, tissues and cornea [1]. The sensitivity can be improved by many orders of magnitudes using a coherent detector using a mixer instead of an incoherent detector. For coherent detection in silicon technologies, a low to no power gain at above ~0.3 THz requires passive mixing, which suffers from high conversion loss (CL) and noise figure (NF). The power gain limitation also makes it challenging to implement local oscillators (LO’s). Use of higher order subharmonic mixing (SHM) eases the LO implementation at the expense of even higher CL and NF. The highest operating frequency of resistive subharmonic mixer in CMOS is 410 GHz [2], while that using SiGe HBT’s is 1 THz [3]. This paper reports an RF front-end employing even-order subharmonic mixers using accumulation mode MOS symmetric varactors (SVAR’s) [4], which achieves a 5-7 dB lower SSB NF than that of the SiGe HBT mixer operating around 600 GHz [5]. The front-end when its mixers are used in a 6th order SHM mode, achieves the same SSB NF at 820 GHz as the SiGe HBT mixer with NF of 45 dB [3]. Using the mixers as 10th order subharmonic mixers, operation up to 1.2 THz which is the highest among the silicon RF front-ends is demonstrated. The mixer is also the first to use MOS SVAR’s for SHM. The SSB NF of 35 dB at 560 GHz and 60 dB at 1.2 THz corresponds to more than 10,000 and 100X lower equivalent noise equivalent power (NEP), respectively for a 1-kHz signal bandwidth than that of incoherent detectors operating at similar frequencies.

Varactor Based Receiver Design

Reactive mixing using varactors has multiple advantages over resistive mixing. First, the loss of varactors is lower than that of NMOS transistors. A dynamic cut-off frequency, \(f_{\text{dc}} = (C_{\text{min}}^{-1} - C_{\text{max}}^{-1})/2nR_s\) of SVAR’s that suppress even-order harmonic generation (\(C_{\text{min}}\) and \(C_{\text{max}}\) are the minimum and maximum capacitance, and \(R_s\) is the series resistance) can be close to 2 THz in 65-nm CMOS [7]. Additionally, according to the Manley-Rowe relation [6], the minimum CL of an upper sideband varactor mixer is IF (Intermediate Frequency)/RF (Radio Frequency) regardless of the order of SHM suggesting the potential for better performance of higher order SHM.

An RF front-end circuit schematic is shown in Fig. 1(a). The intended RF is between 550 and 570 GHz, and IF is 20 GHz. The receiver picks up an RF signal using an on-chip dipole antenna (half-wave at 560 GHz) with a metal reflector formed on a printed circuit board. The integrated circuit thickness is 275 \(\mu\)m which is \(\sim 7\lambda_{XG}/4\) at 560 GHz. The mixer hybrid is based on low-loss transmission lines and the IF amplifier is a two-stage cascode transformer coupled amplifier with simulated gain and NF of 20 and 2dB. An SVAR is formed by parallel connecting an n-type accumulation mode MOS varactor (n-VAR) and a p-type accumulation mode MOS varactor (p-VAR) (Fig. 1(b)). The n-well of n-VAR (Vq) and gate of SVAR (VG) can be DC biased independently to control its capacitance-voltage curve [4]. Biasing \(V_N=2V_G\) results in the optimal even-order harmonic mixing and suppression of odd-order harmonic mixing. The measured optimum point in Fig. 1(b) is \(V_G=0.45\) and \(V_N=1V\) for an LO voltage of 2V peak-to-peak, which is close to that expected from the theory.

The lowest mixer CL that can be achieved using varactors
according to Manley-Rowe is IF (20 GHz)/RF=−14 dB at RF=550 GHz and 18 dB at RF=1.27 THz with the assumption that the mixer is properly terminated at the all other signal frequencies resulting from mixing. The hybrid design that suppresses the significant harmonic mixing terms especially from the strong 2nd order subharmonic mixing and frequency multiplication of LO signals is a key to good performance. As shown in Fig. 2(a), the hybrid is a cascade of a grounded coplanar waveguide (G-CPW) and differential transmission lines with a transition at the junction. The hybrid is intended to work down to RF of 550 GHz. The equivalent circuit for the RF path is shown in Fig. 2(b). The RF signal is fed to the hybrid using a differential line in odd mode. The transition area acts as a virtual ground for the RF signal, and differential lines L1’s in Fig. 2(b) are shorted stubs for an RF signal. The electrical length (EL) of L1 is around $\lambda_{RF}/4$ at 550 GHz which presents high impedance at RF and is absorbed into the RF matching between the antenna and SVAR’s. The EL of L1 is less than $\lambda_{RF}/2LO/8$ at the 2nd subharmonic mixing frequency of RF-2fLO for suppression of this signal. LO is fed to the hybrid using a G-CPW in even mode and it is split into 2 in-phase signals. The strong in-phase signals at fLO and its odd harmonic frequencies generated by two SVAR’s [4] must be controlled to ensure that these signals are not radiated through the antenna. Although the dipole antenna does not radiate when its two arms are driven by the same signals, unintended circuit imbalances will cause common to differential mode conversion that generates leakage of signals at these frequencies. To alleviate this, the differential line L2 length is chosen in such a way that the combined EL including that of antenna is close to $\lambda_{LO}/4$ which in turn presents high impedance at odd multiples of LO frequency while not disturbing the antenna impedance at RF. Fig. 2(c) shows the equivalent IF signal path. A differential line, L2 combined with the antenna arm acts as an open stub and is absorbed into the IF matching.

### Measurement Results

The measurement setup is shown in Fig. 3. The RF front-end is placed 5 cm away from a signal source, and a far-field operation is verified by observing the 1/R² dependence of received power. An RF signal at 550 GHz is generated using a VDI WR 1.9 amplifier multiplier chain (AMC). Four sets of LO signals are generated from a VDI WR 1.2 and a broadband AMC. The table in Fig. 3 summarizes the mixing orders and the LO signals are generated from a VDI WR 1.9 broadband AMC. Four sets of LO signals are generated from a VDI WR 1.9, 1.2 THz broadband AMC. The electromagnetic power for the 8th order SHM. The measured conversion gain (CG (dB) = Pout at IF - (TX power + TX horn antenna gain - propagation loss) and NF at fIF=550 GHz versus LO power for 4th and 8th order SHM is shown in Fig. 4(b). The minimum NF is 35 dB. The RF front-end saturates at an available LO power at the pad of 14 dBm. A reason for the high LO power is the mismatch loss of LO port due to the pad parasitics. With proper matching, co-optimization of the mixer and an integrated LO driver, the required LO power can be reduced by ~4 dB [7]. The CG difference from 4th and 8th order SHM at RF of ~550 GHz is only 2 dB. This is expected from the fact that varactor mixer performance is ideally not dependent on the SHM order.

Although the receiver was designed for operation at 560 GHz, it was also characterized at RF of 810 GHz (6th order SHM) and 1.2 THz (10th order SHM). A VDI WR 1.2 and a WR 0.65 AMC’s are used to generate the RF signal at 810 GHz and 1.2 THz. The measured CG and NF versus frequency plots are shown in Fig. 5. Despite the fact that the antenna matching, thickness of substrate and suppression of unwanted mixing products are not shown in Fig. 5, the performance at 810 GHz is comparable to that of the SiGe HBT subharmonic mixer in [3]. Table I compares the performance of the RF front-end using SVA mixers to that of the previously reported THz silicon coherent receivers.

### References