CMOS I/Q Subharmonic Mixer for Millimeter-Wave Atmospheric Remote Sensing

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Abstract—A compact second harmonic 180 GHz I/Q balanced resistive mixer is realized in a 32-nm SOI CMOS technology for atmospheric remote sensing applications. The MMIC further includes two on-chip IF amplifiers at the mixer's I and Q channels. A conversion gain of +8 dB is achieved with 74 mW of dc power consumption using a 1.2 V supply. The measured IF frequency range is from 1 to 10 GHz. The mixer achieves a 20 dB image-rejection (IR) ratio with an LO input power of +4 dBm. The chip size is 0.75 mm² including probing pads.

Index Terms—CMOS integrated circuit, millimeter-wave integrated circuit, mixers, MMICs, remote sensing.

I. INTRODUCTION

CMOS has been the favored technology for high volume and low cost applications due to its capability of high level of integration and high yield. There has been enormous development in the field of CMOS circuits operating at millimeter-wave frequencies [1], [2]. Besides low noise (temperature), miniature size, low power consumption, and light weight are desirable features for large array radiometers, such as Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) [3]. These features have been traditionally obtained using III–V compound semiconductors. The possibility to integrate more functions on a single silicon chip would enable reducing the size and mass of the synthetic array radiometers and small satellites (CubeSats) [4].

The aim of this letter is to study the feasibility of using CMOS technology in atmospheric remote sensing receiver front-ends operating at an atmospheric window channel of 183 GHz. In general, the gain and noise performance of the CMOS technology is not competitive with that of III–V semiconductor technologies. However, CMOS circuitry could be utilized by employing preceding III–V high-gain low-noise amplifiers determining the required receiver noise figure. Bearing this receiver architecture in mind, in this letter we present the design of a compact wideband CMOS 180 GHz second harmonic balanced I/Q resistive mixer along with two IF amplifiers at the mixer’s I and Q channel.

II. CIRCUIT DESIGN AND REALIZATION

The concept of a subharmonically pumped resistive mixer was first demonstrated at X-band in [5]. It has a number of advantages over the fundamental mixers, especially in millimeter-wave frequencies. For example, it requires only half of the LO frequency compared to a fundamental mixer and increases the LO to RF isolation significantly. Therefore, subharmonically pumped resistive mixer topology is utilized in this design. The design methodology applied for the second harmonic I/Q balanced resistive mixer is similar to the one realized in Indium Phosphide (InP) HEMT technology [3].

The simplified circuit schematic of the designed image-rejection subharmonic resistive mixer with integrated IF amplifiers is shown in Fig. 1. The mixer consists of two single-balanced unit resistive mixers where each unit has two 11 × 1 μm NMOS transistors. The LO signal is applied from a coplanar waveguide and split up into two spiral transmission lines.
line baluns. The spiral baluns provide the required 180° phase shift to the transistor gates of each unit mixer [6]. A short circuited differential shunt stub together with a series line is used to transform the low-impedance of the transistor gate to a higher impedance level which helps to obtain better LO port matching [7].

The RF-signal is applied through a Lange coupler to generate the required wideband 90° phase shift for good image-rejection performance at the drains of the unit mixers. The generated in-phase IF signals are combined by connecting the transistor drains of each unit mixer. The connection points are virtual grounds for the LO signals. Quarter-wavelength short-circuited shunt stubs at RF frequency are used to prevent the millimeter-wave signals from entering into the IF circuitry. Finally, the IF signals from the two channels (I and Q) are combined by connecting the transistor drains of each unit mixer. The connection points are virtual grounds for the LO signals. Quarter-wavelength short-circuited shunt stubs at RF frequency are used to prevent the millimeter-wave signals from entering into the IF circuitry. Finally, the IF signals from the two channels (I and Q) are combined by connecting the transistor drains of each unit mixer. The connection points are virtual grounds for the LO signals. Quarter-wavelength short-circuited shunt stubs at RF frequency are used to prevent the millimeter-wave signals from entering into the IF circuitry. Finally, the IF signals from the two channels (I and Q) are combined by connecting the transistor drains of each unit mixer. The connection points are virtual grounds for the LO signals. Quarter-wavelength short-circuited shunt stubs at RF frequency are used to prevent the millimeter-wave signals from entering into the IF circuitry. Finally, the IF signals from the two channels (I and Q) are combined by connecting the transistor drains of each unit mixer. The connection points are virtual grounds for the LO signals. Quarter-wavelength short-circuited shunt stubs at RF frequency are used to prevent the millimeter-wave signals from entering into the IF circuitry. Finally, the IF signals from the two channels (I and Q) are combined by connecting the transistor drains of each unit mixer. The connection points are virtual grounds for the LO signals. Quarter-wavelength short-circuited shunt stubs at RF frequency are used to prevent the millimeter-wave signals from entering into the IF circuitry. Finally, the IF signals from the two channels (I and Q) are combined by connecting the transistor drains of each unit mixer. The connection points are virtual grounds for the LO signals. Quarter-wavelength short-circuited shunt stubs at RF frequency are used to prevent the millimeter-wave signals from entering into the IF circuitry. Finally, the IF signals from the two channels (I and Q) are combined by connecting the transistor drains of each unit mixer. The connection points are virtual grounds for the LO signals. Quarter-wavelength short-circuited shunt stubs at RF frequency are used to prevent the millimeter-wave signals from entering into the IF circuitry. Finally, the IF signals from the two channels (I and Q) are combined by connecting the transistor drains of each unit mixer. The connection points are virtual grounds for the LO signals. Quarter-wavelength short-circuited shunt stubs at RF frequency are used to prevent the millimeter-wave signals from entering into the IF circuitry.

The transistor modeling relies on the $RC$ parasitic extraction of the transistor layout and the EM simulation of the drain, gate, and source accesses. The Lange coupler is implemented in the microstrip environment [8]. The matching networks for the RF side are also realized in the microstrip environment and modeled through an EM simulator. EM simulations are also carried out for modeling the LO and RF probe pads and spiral transmission line baluns. Finger capacitors are used in the circuit design and their models are taken from the design kit’s library model. The chip was fabricated in a 32-nm SOI CMOS technology. The chip area including the probing pads is 0.75 mm². A micrograph of the chip is shown in Fig. 2.

### III. Measured Mixer Performance

On-wafer measurements were carried out to characterize the mixer performance. The required LO signal was obtained from a signal source together with a $4 \times$ W-band multiplier chain. The RF-signal was also generated by multiplying the signal from a signal generator using a G-band $12 \times$ multiplier. Coplanar (ground-signal-ground) RF probes are used for delivering the LO and RF signal to the chip. The LO signal power from the multiplier chains was calibrated using a power meter along with a W-band power sensor and the RF signal was calibrated with an Erickson calorimeter. The output IF signal spectrums were measured with a spectrum analyzer and the time domain IF signals were measured with an oscilloscope. The mixer gates were biased to 0.16 V which is below the pinch-off for optimum mixing performance. The resistive mixer does not draw any current but the IF amplifiers consume a total current of 62 mA using a 1.2 V supply.

The conversion gain was measured as a function of the LO power and as can be seen from Fig. 3, a +4 dBm LO power level is enough for optimum mixing operation. A low LO power performance is very important since it will simplify the LO system development and reduce the receiver power requirements [3].

The down-converted quadrature response of the designed mixer is shown in Fig. 4. The response was recorded from 1 to 6 GHz where the upper frequency limit was set by the measuring equipment. The mixer along with the IF amplifiers exhibits an amplitude imbalance of less than 2 dB and the phase imbalance of maximum 5° between the IF channels.

The measured upper and lower side-band conversion gain at a fixed IF frequency of 2 GHz is presented in Fig. 5. An RF frequency range from 158 to 182 GHz is achieved with a conversion gain of 8 to 5.6 dB. The measured conversion gain and image-rejection ratio as a function of IF frequency are shown in Fig. 6. A 3 dB IF bandwidth is realized from 1 to 6 GHz with 20 dB IR ratio. The conversion gain is limited at...
lower frequencies because of on-chip DC-blocking capacitors, C5 (Fig. 1) used between the mixer channels (I and Q) and the IF amplifiers to simplify the mixer circuit design. Although not tested in this work, off-chip capacitors shown in Fig. 1 can be used to extend the lower frequency bandwidth. Nevertheless, the measurement results show that the designed MMIC is capable of providing an IF bandwidth from 1 to 10 GHz which is required for certain atmospheric radiometer systems [9].

The mixer and IF amplifier chain has a simulated noise figure of 26 dB which should be adequate for the intended application assuming high-gain low-noise InP HEMT amplifiers in the preceding stages.

IV. CONCLUSION

In this letter, we have presented the design of a CMOS millimeter-wave subharmonic I/Q balanced resistive mixer in the 180-GHz frequency band. This compact design includes on-chip LO power division, required phase shift for the IF signals, and IF amplification. The state-of-the-art results published for MMIC subharmonic I/Q mixers around 180 GHz are shown in Table I. The presented results show record conversion gain at 180 GHz using a +4 dBm LO power.

<table>
<thead>
<tr>
<th>Table I</th>
<th>STATE-OF-THE-ART PERFORMANCE OF mm-Wave I/Q Subharmonic Mixers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref.</td>
<td>This work</td>
</tr>
<tr>
<td>Technology</td>
<td>32-nm SOI CMOS</td>
</tr>
<tr>
<td>Circuit topology</td>
<td>2x mixer + IF amplifier</td>
</tr>
<tr>
<td>RF frequency (GHz)</td>
<td>158-182</td>
</tr>
<tr>
<td>LO frequency (GHz)</td>
<td>80-90</td>
</tr>
<tr>
<td>Peak conversion gain (dB)</td>
<td>+8*</td>
</tr>
<tr>
<td>IR ratio (dB)</td>
<td>&gt;20</td>
</tr>
<tr>
<td>IF bandwidth (GHz)</td>
<td>1-10</td>
</tr>
<tr>
<td>LO power (dBm)</td>
<td>4</td>
</tr>
<tr>
<td>DC power (mW)</td>
<td>74</td>
</tr>
</tbody>
</table>

*Simulated conversion gain of the stand-alone mixer is -23 dB.  
Estimated mixer conversion gain.

HEMT mixer reported in [3], and demonstrates the potential of the CMOS technology for designing 180 GHz receiver front-ends suitable for atmospheric remote sensing applications.

REFERENCES


