An X-Band Doppler Motion Sensor With a Two-Ports Oscillator

Young-Gi Kim, Hyoun-Kyou Dam, Jin-Woo Lee, Jung-Hyung Bae, Jae-Yeon Hwang, Hyun-Jin Kim, Patrick Roblin, Senior Member, IEEE, and Chang-Woo Kim, Member, IEEE

Abstract—In this paper, we propose an X-band Doppler motion sensor based on a high-efficiency dual-output oscillator circuit integrated with a common resonator and a passive mixer. The oscillator provides two output signals with different power levels. The oscillator and mixer circuits are implemented in a 0.5 μm AlGaAs/InGaAs depletion-mode pseudomorphic high electron mobility transistor process. The oscillator shows a high output power of 21.15 dBm at 11.2 GHz and a peak efficiency of 41.1 % at 10.7 GHz. For a 10.3 GHz oscillation, a phase noise of −132 dBc/Hz is obtained at a 10 MHz offset. The output power centered at 10.58 GHz is 11.67 dBm at one port and 9.12 dBm at the other port, and a phase noise of −105.8 dBc/Hz at 1 MHz offset when providing a 2.55 V supply with 28 mA consumption for practical Doppler motion sensor application that detects human motion at a distance of 13 m. A detection range of 30 m has been proven for human motion. This paper demonstrates the feasibility of a compact high efficiency Doppler motion sensor without a bulky power divider or amplifier by monolithic combining the proposed oscillator and mixer circuit.

Index Terms—Doppler radar, sensor systems, microwave single integrated circuits (MMICs).

I. INTRODUCTION

DOPPLER theory detecting the frequency shift in a reflected wave signal is applied to detect tiny body movements without any sensors attached to the body. Based on the Doppler theory, microwave Doppler radars monitoring of biomedical sign signals, such as respiratory, cardiac, arterial movements, and sleeping status have been demonstrated with commercially available devices since the late 1980s [1]–[3]. However, most of these radar systems are bulky, consume significant power and are not suitable for portable systems. Today, especially in space-constrained portable battery-operated radar systems, there is a growing demand for circuits that meet low power and low chip area requirements. In some systems, circuit space and power savings can be important design goals rather than very high performance unless performance loss is excessive.

There has been much research and development of microwave single integrated circuits (MMICs) based on CMOS technology for Doppler sensors as a preparation for increasing demands [4], [5]. The design approach of conventional Doppler RF transceivers requires multiple RF sub-blocks such as power dividers, phase shifters, and baluns. However, these sub-blocks contain large size and significant insertion loss to supply RF signals to the Tx and Rx blocks.

This paper presents a pseudo-high electron mobility transistor (PHEMT) integrated Doppler sensor composed of an oscillator with two output ports and a passive mixer. One output port of the oscillator is connected to the transmit antenna and the other port is connected to the local oscillator (LO) port of the mixer to reduce the strain on the die area and bulk power splitter or balun.

The sensor IC was fabricated in a 0.5 μm AlGaAs/InGaAs depletion-mode PHEMT process. The overall performance of the sensor will be described.

II. DOPPLER SENSORS

Fig. 1 shows a simplified schematic explanation for the principle of a Doppler sensor. The equation for Doppler frequency shift, \( f_d \), of object moving with speed of \( v \) with respect to a stationary transmitter is

\[
\begin{align*}
    f_d &= \frac{v}{c} (\cos \theta_{in} + \cos \theta_{out}) \\
\end{align*}
\]

where \( f \) is the transmitted signal, \( \theta_{in} \) is the angle between the moving object velocity and the incoming wave, \( \theta_{out} \) is the angle between the moving object velocity and the outgoing wave, and \( c \) is the speed of the wave. Typically \( \theta_{in} \) is approximately equal to \( \theta_{out} \) for mono-static measurement and (1) reduces to [6]:

\[
\begin{align*}
    f_d &= 2 \frac{v}{c} \cos \theta_{in} \\
\end{align*}
\]

Fig. 2 depicts a comparison of the conventional Doppler sensor and presented Doppler sensor. In the conventional Doppler sensors power splitters, baluns or phase shifters are used to provide high frequency signal generated from a one output port oscillator to both a transmitting antenna as a RF signal and down converting mixer as a LO signal.
The circuitry of splitters, baluns or phase shifters occupy a lot of die area since they need transmission lines of quarter wave length or matching networks, which are big burdens against integration of the circuits. We present a compact sensor by removing the power splitter using a two ports oscillator shown in Fig. 2 (a) as compared with the conventional circuit shown in Fig. 2 (b).

A previous Doppler sensor chip driven by an oscillator having one output port has three buffer amplifiers and occupies a large chip area [4].

System-on-chip based Doppler sensors in [7] and [8] used a bulky power divider to drive the mixer and send RF signals to the transmit antenna.

Differential oscillators or push-push oscillators can be used without a power splitter. However, the output is not sufficient to pump the mixer. Therefore, a buffer amplifier or a power amplifier circuit is required [9], [10].

This paper presents a two output port oscillator circuit sharing a resonator to provide RF signal power to the transmitting antenna at one port and to drive the mixer from the other port without any power splitter in the Doppler motion sensor application.

### III. Circuit Design

Two negative resistance generating circuits are connected to a common resonator for the proposed two port oscillator as shown in Fig 3.

The resonator consists of a planar inductor $L_r$ and a parasitic capacitor $C_r$. The gate feedback inductors $L_{g1}$ and $L_{g2}$ drive $Q1$ and $Q2$ to induce the negative resistance. The source resistors $R_{b1}$ and $R_{b2}$ provide self-biasing and temperature stabilization. $C_{b1}$ and $C_{b2}$ are by-pass capacitors. $L_1$ and $L_2$ are matching inductors. $R_{l1}$ and $R_{l2}$ are load resistances. The total large signal admittance exhibited by the negative resistance circuits and resonator is zero for steady-state oscillations according to following balance condition

$$
G_{\text{resonator}} = - (G_{\text{negative1}} + G_{\text{negative2}}) \tag{3}
$$

$$
B_{\text{resonator}} = - (B_{\text{negative1}} + B_{\text{negative2}}) \tag{4}
$$

where $G_{\text{resonator}}$, $G_{\text{negative1}}$, and $G_{\text{negative2}}$ represent the large-signal conductances of the resonator, negative resistance generating circuit 1, and negative resistance generating circuit 2, respectively. $B_{\text{resonator}}$, $B_{\text{negative1}}$, and $B_{\text{negative2}}$ represent the large-signal susceptances of the resonator, the negative resistance generating circuit 1, and the negative resistance generating circuit 2, respectively.

The oscillation power is shared with the two active devices in the negative-resistance generating circuits. Therefore the total oscillator output power obtained is larger than is possible from an oscillator with a single active device without inflicting any damage to the active devices. The negative resistance part is connected with reduced resistance by parallel load resistances and active devices. Real part of the resonator impedance can be kept as low as 1.6 ohm for a high Q and a high efficiency [11]. Each active device is optimized to have 4 fingered 75 um gate under the condition (3) and (4) for a high efficiency and a high power oscillation.

The output signal frequencies at each port are locked, regardless of the circuit parameter differences, i.e. impedances of loads, transistor sizes, and micro-strip lines geometry, between the negative-resistance generating circuits.
The circuit layout was designed so as to provide a minimum distance between the active devices and to have a ground via and the resonator shared by both of the negative resistance generating circuits to minimize the phase difference. Different power levels from each output port were synthesized with a careful layout assisted by EM simulations. The output power difference between the ports is caused by asymmetry of layout and bond wire length. All the interferences from each part are included in the repeated EM simulations and layout modifications.

Fig. 4 depicts a simplified circuit of the designed mixer. Two HEMTs with 10 um gate and one HEMT with two fingered 25 um gates are connected in parallel for the passive resistive mixer. A shunt 803 ohm resistor is connected to the gate to avoid gate floating. Drain, source and gate are connected to IF, RF and LO respectively.

IV. EXPERIMENTAL RESULTS

The proposed monolithic oscillator and a passive resistive mixer circuits based on a 0.5 μm AlGaAs/InGaAs HEMT process are fabricated on the same die. Fig. 5 shows the fabricated die, where the circuits inside the dotted polygons present the oscillator and mixer. The chip sizes are 0.26 mm² for the oscillator and 0.09 mm² for the mixer.

Fig. 6 shows the output spectrum at one of the output port in the circuit. The oscillator provides a maximum power of a 21.15 dBm at 9.16 V supply with 47 mA current when accounting for a connector loss of 0.12 dB. The center frequency is 11.24 GHz with a free running phase noise of 118 dBc/Hz at 10 MHz offset. The second harmonic is suppressed by 33.12 dB. The other port shows an output power of 18.31 dBm. When the oscillator is locked by a phase locking loop (PLL) and the supply voltage drops to 2.45 V for low-voltage phase performance, as shown in Figure 7, phase noise improves to −132 dBc/Hz at 10 MHz offset.

The measured and simulated oscillation output powers, efficiencies, 2nd harmonic suppressions, frequencies, and phase noises with supply voltages are plotted in Fig. 8. The lower supply voltage forces the output power level, second harmonic suppression and oscillation frequency shift to lower values. The oscillator exhibits a high efficiency of 41.14 % for a 3 V supply. The total output power is 15.53 dBm with a phase noise of −106.8 dBc at 1 MHz offset and −22.55 dB 2nd harmonic suppression at this point.

Table I gives a summary of the most significant measured results compared with other high power Si or GaAs based...
Fig. 9. Measured RF and LO return losses of mixer.

Fig. 10. Measured conversion gains versus applied LO powers with IF frequency variation of the mixer.

oscillators that have been reported. The proposed oscillator exhibits the highest power and peak efficiency in silicon or GaAs processes above the X frequency band compared to the previously reported results.

The supply voltage is reduced to 2.55 V with 28 mA for practical Doppler motion sensor applications subject to regulation. Then the oscillator provides output powers of 11.67 dBm at one port and 9.12 dBm at the other port. The center frequency is 10.58 GHz with a phase noise of $-105.8$ dBc/Hz at 1 MHz offset.

The return losses of RF and LO ports for the mixer are measured and plotted in Fig. 9. The return losses of both ports are maintained less than $-10$ dB from 10.4 GHz to 10.7 GHz.

The conversion gains for various LO powers are plotted in Fig. 10. The converted If frequencies are changed from 4 kHz to 500 kHz in the figure. The optimum LO power for the highest conversion gain is 4 dBm for 4 kHz of If frequency. The optimum power increases as the IF frequency is changed to higher frequency up to 100 kHz. The conversion gain reaches maximum value of $-10.87$ dB when LO power is 9 dBm with 100 kHz of the IF frequency.

The passive resistive mixer with a $-11.8$ dB conversion gain and a 2.3 dBm 1 dB compression point on the same die, a planar transmitting antenna, a receiving antenna with an antenna gain of 5.1 dBi, an active low-pass filter with an 85.7 dB gain and a 96 Hz unity-gain frequency are designed and connected to the oscillator for Doppler motion sensor test as shown in Fig. 11. The transmitting antenna is connected to the high power output port and the LO port of the mixer is internally connected to the other port of the oscillator. A photograph of the RF transceiver with the transmitter and receiver antennas of the sensor is shown in Fig. 12.

Fig. 13 shows the resulting down-converted wave stimulated by very slow moving motions of a metal plate located 0.5 m to 1 m away from the antenna. In this figure the low frequency pulse corresponds to a slower motion and the high frequency to a faster motion. The signal converted from a very slow human motion 13m away from the sensor can be detected with a current of 28 mA at 2.55 V supply voltage.
TABLE I

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Output Power (dBm)</th>
<th>Freq. (GHz)</th>
<th>Efficiency (%)</th>
<th>Phase Noise (dBc/Hz)</th>
<th>DC Power (mW)</th>
<th>FOM</th>
<th>Area (mm²)</th>
<th>Process</th>
<th>Topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>[10]</td>
<td>19.68</td>
<td>9.8</td>
<td>30</td>
<td>-65 @ 0.1 MHz</td>
<td>310</td>
<td>-140</td>
<td>2</td>
<td>AlGaAs GaAs HBT</td>
<td>CB Buffer (Cascade)</td>
</tr>
<tr>
<td>[12]</td>
<td>10.6</td>
<td>46.2</td>
<td>16.1</td>
<td>-104 @ 1 MHz</td>
<td>71</td>
<td>-180</td>
<td>0.29</td>
<td>90 nm CMOS</td>
<td>Cascode-</td>
</tr>
<tr>
<td>[13]</td>
<td>16</td>
<td>24.1</td>
<td>25</td>
<td>-93 @ 1 MHz</td>
<td>159</td>
<td>-159</td>
<td>0.2 μm MHEMT</td>
<td>Common Gate</td>
<td></td>
</tr>
<tr>
<td>[14]</td>
<td>18</td>
<td>36.2</td>
<td>22</td>
<td>-87 @ 1 MHz</td>
<td>287</td>
<td>143</td>
<td>2.8</td>
<td>AlGaAs/InGaAs HEMT</td>
<td>Sub-resonator</td>
</tr>
</tbody>
</table>

This work in high power measurement: 21.15 11.2 30.5 -118 @ 10 MHz 430 -153 0.26 0.5 μm HEMT Common Resonator
This work in high efficiency measurement: 15.53 10.7 41.1 -114 @ 10 MHz 87 -156 0.26 0.5 μm HEMT Common Resonator
This work in low phase noise measurement: 11.12 10.3 20.3 -132 @ 10 MHz 63 -174 0.26 0.5 μm HEMT Common Resonator

V. CONCLUSION

This paper proposes a two-port oscillator based on a common resonator and demonstrates the feasibility of an X-band Doppler motion sensor composed of this oscillator. The proposed oscillator provides different high power RF outputs at two output ports.

The proposed oscillator exhibits the best power and peak efficiency among all the reported integrated oscillators in silicon or GaAs based integrated oscillators for frequencies higher than X band.

The proposed circuit simplifies the transmitter by eliminating the disadvantages of bulky power dividers, low noise amplifiers or power amplifiers in conventional Doppler detectors.

VI. ACKNOWLEDGMENT

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REFERENCES


Fig. 14. Time domain waveforms in 100 ms reading converted at 30 m distance from the Doppler motion sensor (a) with human motion and (b) without motion.

The maximum detection range extends to 30 m by changing the supply to 5 V at 35 mA. Fig. 14 (a) shows the signal with a human motion from a 30 m distance. Fig. 14 (b) shows the signal without any motion at the same distance. The active low pass filter shows peak gain at a few Hz. The peak occurs when the Doppler shifted frequency, converted from the moving velocity, is matched to the filter’s peak frequency. Comparing the waveform to the waveform in (b), we can see that there are several smaller pulses in addition to the peak pulse in Figure 14 (a). The peak corresponds to the matched frequency and the small peaks match weakly.

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