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Reprinted from
*IEEE 12th Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems
(SiRF), 16. – 18. January 2012
in Santa Clara, California*

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Dual-Band Millimeter-Wave VCO with Embedded RF-MEMS Switch Module in BiCMOS Technology

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Abstract—This paper presents a dual-band millimeter-wave VCO utilizing RF-MEMS switches fully integrated into a standard BiCMOS process. The switch and associated transmission line form a reconfigurable inductor in the VCO core. Depending on the state of the switch, the VCO frequency can be tuned either from 48 to 52 GHz, or from 64 to 72 GHz. The VCO provides both fundamental and frequency-divided (divide by 64) outputs, with integrated frequency dividers. The fundamental output power is 4/5 dBm and the phase noise at 1 MHz offset is -84/-86 dBc/Hz for the lower/upper bands. To the authors' knowledge, this is the first millimeter-wave, dual-band VCO with fully integrated RF-MEMS switches.

Index Terms—Silicon bipolar/BiCMOS process technology, Voltage-controlled oscillators, Microelectromechanical systems.

I. INTRODUCTION

Typical millimeter-wave circuits (short range wideband wireless communication at 60 GHz, 71-76 GHz and 81-86 GHz, automotive radar at 77/79 GHz, image sensing at 94 GHz and etc.) occupy wide bandwidth and operate in well separated frequency bands. Multi-band circuits that can switch between different frequency bands are advantageous as they may provide a solution for several, frequently low market volume, mm-wave applications at the same time. This paper presents a dual-band millimeter-wave VCO. Other than the common method to achieve multi-band circuits, where circuits for different bands are combined and switched on and off [1], band switching in this VCO is achieved through a reconfigurable inductor formed by a transmission line and a capacitive shunt switch. The RF-MEMS switch module has been developed in a standard BiCMOS technology for millimeter-wave applications and has achieved promising results [2] - [4]. By changing the state of the switch, the center frequency of the VCO can be switched between 50 and 68 GHz. The frequency tuning ranges for the two bands are 4 and 8 GHz, respectively. As a proof-of-concept circuit, the VCO demonstrates the possibility of integrating RF-MEMS switch in millimeter-wave circuits, which is the first step towards multi-band T/R systems for millimeter-wave applications.

II. TECHNOLOGY OVERVIEW

The VCO is fabricated in a standard 0.25 μm BiCMOS technology (IHP SG25H1). The transistor features f_T/f_{max} of 190/200 GHz. Five metal layers (including two thick top metal layers) are provided for passive elements and interconnects. The RF-MEMS switch module is implemented in the lowest three metal layers. Fig. 1 [2] shows the SEM image and schematic cross-section of the switch. The membrane is realized with metal 3 and the signal line is on metal 2. The high voltage electrode under the membrane is on metal 1. A thin Si₃N₄/TiN layer stack, which is part of the MIM capacitor of the process, forms the switch down-state contact region. The “up/down” state capacitance is about 25/250 fF. More information of the switch is provided in [2] - [4].

III. CIRCUIT DESIGN AND SIMULATION

The VCO is based on a negative resistance topology [5]. Fig. 2 shows a simplified schematic diagram of the circuit. Capacitive emitter degeneration (C_{VAR}) is used to generate the negative resistance. The switch (together with the signal line) forms a reconfigurable inductor and completes the resonance. Changing the state of the switch achieves the change between the two bands of operation, while the continuous frequency tuning within each band is done by tuning the variable capacitor (C_{VAR}). A common base stage is cascaded with the VCO core to improve the output power and isolate the VCO core from the load. All inductors (except for the switch) are realized with thin-film microstrip lines (TFMLs). The TFMLs are modeled using a length-scalable lumped-element model based on EM simulation results, as in [6].

To ease the characterization of the circuit and enable future use of the VCO in a PLL, a divide-by-64 frequency divider is designed and integrated together with the VCO. The divider consists of six divide-by-two static frequency dividers based on master-slave D-flip-flops. The first stage is optimized for maximum speed and can divide up to 80 GHz (in simulation), which covers the complete tuning range of the VCO. Speed of latter stages are reduced for lower power consumption. The final circuit provides a

Fig. 1. SEM image (a) and schematic cross-section (b) of the RF-MEMS switch.

Fig. 2. Simplified schematic of the VCO.

differential output at the oscillation frequency and a single-ended output at 1/64 of the oscillation frequency.

The circuit is simulated in Agilent ADS. The foundry provided model of the switch is used in the simulation. To determine the oscillation condition, the impedances looking into the base of transistor T_1 and the switch are first analyzed. Fig. 3 show the simulated real and imaginary parts of the impedances. The oscillation will start at the frequency where the imaginary parts of the impedances (X_1 and X_S) cancel out (at around 53 GHz for the “up” state and 68 GHz for the “down” state). For both states, the negative impedance (R_1) is much larger than the impedance of the switch (R_S), which guarantees the start-up of the oscillation. The signal line and the switch capacitance form a resonator, therefore, the imaginary part of the impedance looking into the switch is different from that of an ideal inductor, where both the real and imaginary part of the impedance increase linearly as the frequency increase. The “up” state inductance of the resonator increases as the frequency increases, which will result in a smaller frequency tuning range (compared with a normal inductor), while the “down” state inductance decreases as the frequency increases, which will increase the frequency tuning range. After the frequency is determined, Harmonic Balance simulation is used to check the final performance (tuning range, output power, phase noise etc.) of the VCO. The simulation results will be shown in Section IV.

IV. MEASUREMENT RESULTS

Fig. 4 shows a micrograph of the realized VCO. The complete circuit (including pads) occupies 0.68 mm^2 area. “V1” pads are the supply voltages of the VCO and divider and “V2” pads are the high voltage electrodes for the switches.

A. Static Characterization

The circuit is characterized on wafer. The divided output is connected to a spectrum analyzer to measure the frequency and phase noise. The fundamental output is connected to a V-band power meter to measure the output power. DC voltages are supplied with DC wedges. The VCO and the frequency divider consume 17 mA and 40 mA current from a 3.3 V supply, respectively. 28 V is applied on the switch for the “down” state measurement and 0 V is applied for the “up” state measurement.

Fig. 5 show the measured and simulated tuning behavior of the VCO for the “up” and “down” state. The frequency can be tuned from 48 to 52 GHz, when the membrane is up, and from 64 to 72 GHz, when the membrane is down. The difference between the simulation and measurement in the tuning behavior is mainly due to the parasitics in the layout (vias etc.) and the modeling of the transmission lines. The output power is 4 dBm for the “up” state and 5 dBm for the “down” state, which is close to simulation.

Fig. 3. Simulated real (a) and imaginary (b) parts of the impedances looking into transistor T_1 and the switch.

Fig. 4. Micrograph of the realized VCO. The size is $1 \times 0.86 \text{ mm}^2$, including pads.

Fig. 5. Simulated and measured frequency versus tuning voltage for the “up” state (a) and “down” state (b).

The phase noise is measured at the divided output and the results are shown in Fig. 6. Because of the frequency division, the measured phase noise is improved by 36 dB ($20\log(64)$), thus the estimated phase noise of the fundamental output is -86 dBc/Hz and -84 dBc/Hz at 1 MHz offset for the “up” and “down” state, which is close to simulation (-87 dBc/Hz).

B. Dynamic Characterization

To check the dynamic behavior of the circuit and the switch, rectangular pulses (50% duty cycle, around 2 ns rising/falling time) are applied to the high voltage electrode of the switch. Due to the lack of time domain measurement equipment capable of 70 GHz operation, it is difficult to measure the transient response of the VCO directly. However, the divided output can be easily monitored using a signal source analyzer. Fig. 10 shows the measured oscillation frequency (after division) versus time. As the switch is continuously switched “on” and “off”, the divided frequency also switches periodically between 800 MHz (51.2 GHz fundamental frequency) and

Fig. 6. Measured phase noise from the divide-by-64 output.

Fig. 7. Measured frequency from the divided output when periodic pulses are applied to the switch.

1.11 GHz (71.04 GHz fundamental frequency).

To better understand the behavior of the VCO and the switch, a laser Doppler vibrometer was used to simultaneously monitor the movement at the center of the membrane. Fig. 8 shows the measured membrane deflection and oscillation frequency (divided) versus time for different pulse voltages. For 28 V pulse, the switching time is roughly 40 μ s and it decreases to 10 μ s for 34 V pulse and 4 μ s for 40 V pulse. When the membrane starts to move down, the output frequency first decreases to the self oscillation frequency of the frequency divider, because the VCO output power at the switching transient is not sufficient to drive the frequency divider. Then the output frequency follows the VCO and starts to increase, as the membrane continues to move down. When the membrane is completely down, the output frequency remains constant, which shows that the VCO operation is very stable.

V. CONCLUSION

A dual-band millimeter-wave VCO with integrated RF-MEMS switch modules has been realized in a 0.25 μ m

Fig. 8. Measured deflection of the membrane and output frequency versus time for different pulse voltages. The total deflection is about 1.4 μ m.

BiCMOS technology. The circuit shows good performance in both frequency bands, which demonstrates the possibility of realizing millimeter-wave multi-band circuits and systems with integrated RF-MEMS switches.

ACKNOWLEDGMENT

The authors wish to acknowledge Johannes Borngräber and Matthias Wietstruck for the measurement of the IC. This work is funded by the European Commission through the FP7 project FLEXWIN.

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