192 GHz push–push VCO in 0.13 μm CMOS

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A 192 GHz cross-coupled push-push voltage controlled oscillator (VCO) is fabricated using the UMC 0.13 μm CMOS logic process. The VCO can be tuned from 191.4 to 192.7 GHz. The VCO provides output power of ~20 dBm and phase noise ~100 dBc/Hz at 10 MHz offset, while consuming 11 mA from a 1.5 V supply.

Introduction: With the rapid advance of high frequency capability for CMOS technology, millimetre-wave CMOS VCOs with ~100 GHz fundamental operating frequency have been reported [1, 2]. The fundamental oscillation frequency is limited by unity power gain frequency $f_{\text{max}}$ of the transistor. To obtain even higher frequencies, push-push VCOs [3–5] using the second harmonic operating at up to 131 GHz have been demonstrated in a 90 nm CMOS technology [5]. In push–push VCOs, besides higher device gain, varactor and capacitor $Q$ factors are higher, while the transmission line loss is lower at a given output frequency since the fundamental frequency of the oscillator is one half of the output frequency. In this Letter we report a 192 GHz push–push VCO fabricated using the 0.13 μm UMC logic process with eight copper layers. Oscillators such as this can be used in remote sensing and advanced imaging applications [6] and suggest that THz CMOS circuits will be available in the near future.

Circuit design: Fig. 1 shows the schematic of the VCO. Cross-coupled transistors $M_1$ and $M_2$ form the VCO core. Inductors $L_1$ and $L_2$ (~45 pH), accumulation node MOS capacitors, and the capacitances associated with $M_1$ and $M_2$ serve as the LC resonant tank. A key to achieving high fundamental operating frequency is minimising the parasitic capacitances connected to the LC tank [2]. At the virtual ground nodes, the anti-phase fundamental signals cancel out and the second-harmonic signal can be extracted. The middle point of Inductors $L_1$ and $L_2$ has the lowest parasitic capacitance to ground among the common-mode nodes. This makes the impedance looking into the transmission line is inductive to resonate with the capacitances from the pad and other metal interconnections. The characteristic impedance of the line is ~65 Ω. The length of lines is 150 μm. This length is slightly shorter than λ/4, so that the impedance looking into the transmission line is inductive to resonate the capacitances from the pad and other metal interconnections. The 2 pf bypass capacitors ($C_{l,a}$, $C_{l,b}$, in Fig. 1) serve as a short around 190 GHz. They are formed using the parasitic capacitance between adjacent metal layers [9]. The metal 8, 6, 4 and 2 layers form the top plate, and metal 7, 5, 3 and 1 layers form the bottom plate. The capacitance density is 0.55 fF/μm². The transmission lines and bypass capacitors are simulated using the Ansoft HFSS, a 3D EM simulator. Two VCOs are implemented. In the first version, to achieve higher oscillation frequency, the output buffers and bond pads for the fundamental output were not included. The chip occupies 450 × 390 μm including the bond pads. A micrograph is shown in Fig. 3. The second VCO, including the buffers for both the fundamental and push–push port, was also fabricated. Owing to the capacitance from output buffer, the measured fundamental oscillation frequency is about 4 GHz lower.

The oscillation frequency can be tuned from 191.4 to 192.7 GHz by increasing the output level, the circuit is measured with 11 mA bias current above 8 mA owing to the detection limit of the measurement setup. To increase the output level, the circuit is measured with 11 mA bias current from a 1.5 V supply. Fig. 4 shows the output spectrum and the measured signal level is ~82 dBm. The conversion loss of the harmonic mixer is ~60 dB at 190 GHz. The insertion loss of the probe is about 2 dB. Thus, the signal is estimated to be about ~20 dBm. The oscillation frequency can be tuned from 191.4 to 192.7 GHz by

Experiment results: The chip was measured on-wafer using a GGB WR-5 (140–220 GHz) waveguide probe. The cutoff frequency of the TE10 mode in the WR-5 waveguide is 115.7 GHz, which attenuates the fundamental signal entering the harmonic mixer. The VCO output spectrum is measured using an OML M05HWD (140–220 GHz) harmonic mixer and an Agilent E4448A 50 GHz spectrum analyser. An Agilent 11970W (75–110 GHz) harmonic mixer has also been used to evaluate the fundamental output. The circuit starts to oscillate with 3.2 mA current. However, no signal was detected at the push–push port until the bias current is increased to above 8 mA owing to the detection limit of the measurement setup. To increase the output level, the circuit is measured with 11 mA bias current from a 1.5 V supply. Fig. 4 shows the output spectrum and the measured signal level is ~82 dBm. The conversion loss of the harmonic mixer is ~60 dB at 190 GHz. The insertion loss of the probe is about 2 dB. Thus, the signal is estimated to be about ~20 dBm. The oscillation frequency can be tuned from 191.4 to 192.7 GHz by

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**Fig. 1 Schematic of push–push VCO**

The transmission line structure is shown in Fig. 2 and is formed using the grounded coplanar waveguide (CPW) structure [7, 8]. Compared to the conventional CPW, the ground plane isolates the line from the lossy silicon substrate and reduces the insertion loss. The lines are formed using the top metal (8) layer and the ground plane is formed by metal 1. The transmission line width and gap are 3 and 4 μm, respectively.

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**Fig. 2 Grounded coplanar waveguide transmission line**

**Fig. 3 Micrograph of chip**

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changing $F_{\text{TUNE}}$ from 0 to 1.8 V. Because the output of harmonic mixer
is weak, the phase noise could not be directly measured. The phase
noise of the fundamental output is $-106$ dBc/Hz at 10 MHz offset for
the VCO with the output buffer. The phase noise at the push–push port
is expected to be 6 dB higher. Owing to the coupling through the
substrate and metal interconnection, the fundamental signal also
appears at the push-push port. The measured fundamental signal is
about $-30$ to $-25$ dBm at the push-push port after calibrating the
losses. As expected, the frequency range of the fundamental signal is
exactly one half of the second harmonic.

**Fig. 4** Measured VCO output spectrum

**Conclusions:** A 192 GHz push–push VCO fabricated in the UMC
0.13 μm CMOS process is presented. 192 GHz is the highest operat-
ing frequency for any silicon-based circuits. Given that the state of the
art is 65 nm, generation of THz signals using CMOS technology
cannot be far in the future.

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