Generating Terahertz Signals in 65nm CMOS with Negative-Resistance Resonator Boosting and Selective Harmonic Suppression

Qun Jane Gu, Zhiwei Xu, Heng-Yu Jian, Xiaojin Xu, Mau-Chung Frank Chang,
Wei Liu and Harold Fetterman
Department of Electrical Engineering, University of California, Los Angeles, CA, 90095, USA
Tel: 310-794-9958, Fax: 310-206-849, E-mail: qung@ee.ucla.edu

Abstract

Terahertz signals have been successfully generated in 65nm CMOS by: 1) stacking a negative-resistance resonator in parallel to the conventional resonant tank to boost the fundamental oscillation to 0.22 THz; and by 2) selectively suppressing the odd and 2nd harmonics to boost the 4th and 6th harmonics in the terahertz regime. Consequently, we have detected 4th and 6th harmonic signals through on-chip antenna radiation at 0.87 and 1.31 THz, respectively, by using a Michelson interferometer. To our best knowledge, this is the first time a signal beyond 1 THz is generated by silicon based semiconductor.

Introduction

Terahertz imaging and spectroscopic systems have drawn increased attention recently due to their unique abilities in detecting and analyzing concealed objects and chemicals [1]. Digital CMOS technologies have not been seriously considered for applications in such spectrum range due to limited device cut-off frequencies (both f_t and f_{max}). To push CMOS operation further into the missing "Terahertz Gap" (0.3-3THz) and to realize highly integrated systems, we devise a new oscillator circuitry by adding a negative-resistance resonator in parallel to the conventional resonant tank to boost the fundamental oscillation beyond the device cut-off frequencies (about 0.2THz) and selectively boost their 4th and 6th harmonics beyond 1THz for the first time in silicon based semiconductor.

Circuit Analysis and Operation Mechanism

Physical drawbacks in super-scaled CMOS technologies such as substrate loss, gate resistance, and circuit parasitic, etc., have considerably limited their maximum operation frequencies. Traditional cross coupled type oscillators were heavily loaded by both active and passive device/interconnect parasitics. For instance, a cross coupled pair with 5μm gate width needs to resonate with < 20pH inductance to attain self-resonance > 200GHz, which nevertheless could render the resonant tank impedance too low to start the oscillation.

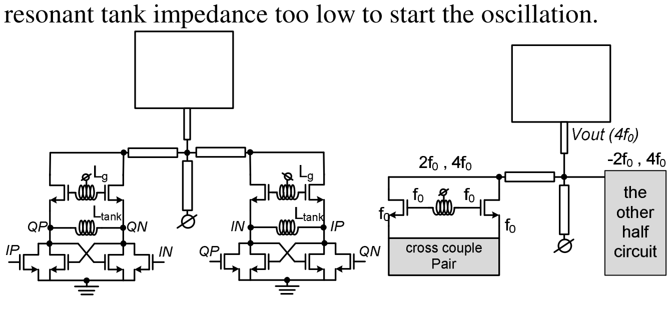


Fig. 1 (a) Terahertz oscillator with stacking resonator tank and on-chip antenna; (b) Illustration of boosted 4th order harmonic at expense of suppressed odd-order and 2nd order harmonics.

To overcome CMOS technology drawbacks for terahertz operations requires a new circuitry to increase the tank resonant impedance in concurrent with a sufficiently low tank inductance. Such oscillator circuitry is devised and demonstrated in Fig. 1(a) by stacking a negative-resistance resonator in parallel to the traditional resonant tank in each of the I/Q paths to boost the fundamental oscillation frequency. Differential feature suppresses odd-order harmonics at the common drain node [2, 3]. By subsequently combining outputs from the two cross coupled pairs with I/Q imaging to each other (Fig. 1(b)), the in-phase 4th harmonic will be constructively boosted at the expense of the out-of-phase 2nd harmonic at the antenna input (V_{out}). The generated signal is then radiated via an on-chip patch antenna for characterization. The detailed circuit operation mechanism can be analyzed as follows.

First, the stacking resonant tank consists of a primary tank with L_{tank} shunt between the drains of the bottom cross coupled pair and a parallel negative-resistance resonator with L_g shunt between cascode devices at the top in each of the I/Q oscillator units. This devised stacking architecture not only allows large L_{tank} and L_g inductances, but also combines them via cascode circuit to form a hybrid tank with a low overall inductance that can support oscillations at the terahertz spectrum. Second, the negative-resistance resonator also boosts the overall stacking resonator impedance, which eases the demand on cross coupled device's g_m to permit using smaller NMOS to further increase the oscillation frequency. Finally, the added negative resistance resonator vertically shares the same current with the regular tank and thus does not consume additional power.

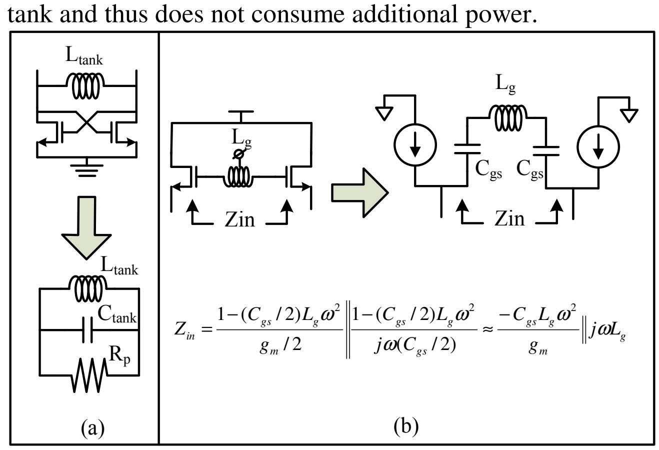


Fig. 2 Stacking resonant tank consisting of: (a) Regular tank at the bottom with L_{tank} shunt cross coupled drains and its equivalent circuit; (b) Negative-resistance parallel tank shunt between the gates of cascode devices at the top and its equivalent circuit.

The effect of the top negative-resistance resonator in the overall stacking resonant tank can be understood further by analyzing its small signal input impedance looking into the cascode source (Fig. 2(b)):

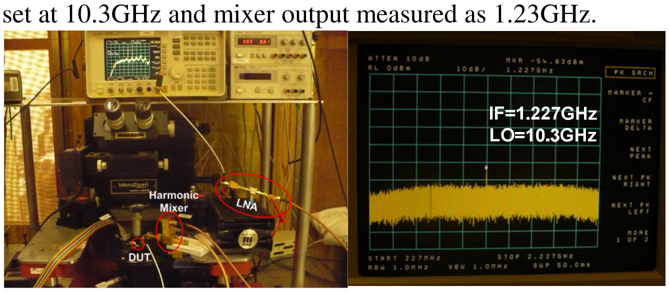
$$Z_{in} = \frac{1-(C_{gs}/2)L_g\omega^2}{g_m/2} \Big\| \frac{1-(C_{gs}/2)L_g\omega^2}{j\omega(C_{gs}/2)} \approx \frac{-C_{gs}L_g\omega^2}{g_m} \Big\| j\omega L_g \qquad (1)$$

At operating frequencies beyond $\omega > \sqrt{2/L_g C_{gs}}$, the imaginary part of Eq. (1) designates an inductor with effective inductance of L_g . When operating in parallel with the regular tank inductor $L_{\tan k}$, the combined inductance $L'_{\tan k} = L_{\tan k} // L_g$ can be substantially reduced to enable a much higher resonant frequency even beyond the cut-off frequency of the device. Meanwhile, its real part has resulted in a negative impedance which can be exploited to boost the equivalent tank impedance, $R'_p = R_p \| \left(-C_{gs} L_g \varpi^2 / g_m\right)$, to allow the use of smaller cross coupled devices to sustain stable oscillation with a relaxed g_m requirement.

Consequently, the large fundamental frequency signals present at both gates and sources will mix nonlinearly to generate higher order harmonics and intermodulations. Under ideal conditions, when phases and amplitudes are perfectly matched, the 4th harmonic will be boosted at the expense of other lower harmonics.

Measurement Results

Fig. 3(a) shows the setup for measuring the fundamental resonance frequency**.** The oscillator output is mixed with an external LO's high-order harmonic before feeding to a LNA and then to a spectrum analyzer. As the LO shifts by 5MHz, the mixed IF shifts by 105MHz, which confirms LO's 21st-harmonic being utilized. With this information, we identify the fundamental frequency as 217.5GHz in Fig. 3(b) with LO set at 10.3GHz and mixer output measured as 1.23GHz.



(a) (b)

$$f_o = N \times f_{lo} - f_{IF} = 21 \times 10.3 + 1.227 = 217.5GHz$$

Fig. 3 (a) Setup to measure fundamental resonant frequency (f_o) with an external LO and a harmonic mixer; (b) Measured fundamental oscillation at 217.5GHz (or roughly 0.22THz).

However, the typical electronic apparatus is not suitable for measuring terahertz frequencies due to immense setup losses. To overcome such obstacles, a Michelson interferometer based quasi-optical measurement approach is adopted. As shown in Fig. 4, the output signal, radiating from the vertically mounted CMOS oscillator designed with on-chip antenna, is detected through an interferometer followed by a bolometer. The signal spectrum is then recovered through the FFT, as shown in Fig. 5.

It is noteworthy that the power measurement results are un-calibrated and therefore the strengths of higher harmonics (4th and 6th harmonics at 0.87 and 1.31THz, respectively) may be substantially underestimated due to excessive water and oxygen absorption and setup losses at these frequencies. However, the results clearly show the 5th harmonic being heavily suppressed, and the 1st harmonic or fundamental being suppressed so that it is almost equal to the 2nd harmonic. The 2nd harmonic exists due to inevitable phase and amplitude mismatches of I/Q paths. Consequently, non-linearity and inter-modulation generate higher order harmonics, such as 3rd and 6th harmonics. All are with measurable strengths. In order to achieve accurate power profiles at different frequencies, the blackbody based calibration is currently under progress. The oscillator draws 12mA current from 1.4V power supply with its die photo shown in Fig. 6.

In summary, by using stacking negative-resistance resonator and selective harmonic suppression techniques, we have pushed CMOS operation well into the "Terahertz Gap". This is the first time for a silicon based semiconductor circuit or device to deliver higher than THz signals.

Acknowledgements

We thank TSMC for its excellent 65nm CMOS foundry support.

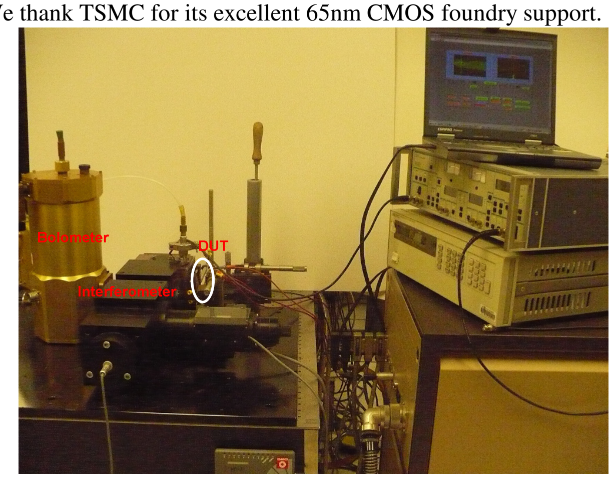


Fig. 4 Quasi-optical setup for measuring terahertz signal outputs.

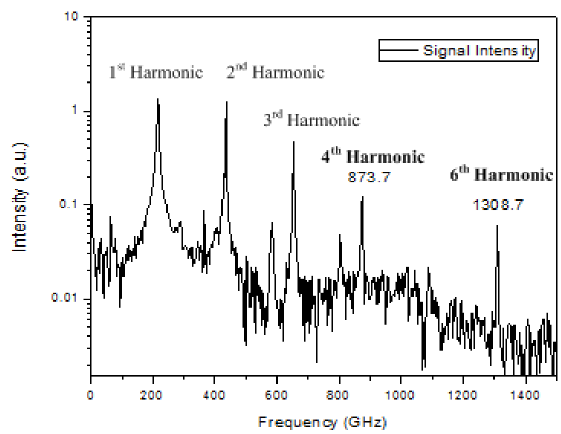


Fig. 5 Measured signal spectrum through Michelson interferometer.

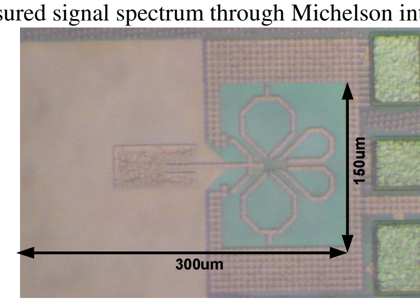


Fig. 6 Die photo of terahertz oscillator with on-chip antenna.

References

[1] P. H. Siegel, "Terahertz technology," *IEEE Trans. MTT*, vol. 50, no. 3, pp. 910-928, Mar. 2002.

[2] D. Huang, et al, "324GHz CMOS Frequency Generator Using Linear Superposition Technique," *ISSCC Dig. Tech. Papers*, pp.476-477, Feb. 2008.

[3] E. Seok1, et. al., "A 410GHz CMOS Push-Push Oscillator with an On- Chip Patch Antenna,**"** *ISSCC Dig. Tech. Papers*, pp.472-473, Feb. 2008.