

# The Design Of Single-Ended & Differential MMIC VCOs

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## Abstract

This paper describes design techniques for both single-ended and differential VCOs, with examples shown fabricated in GaAs MMIC processes. The potential uses and advantages of the differential over the conventional single-ended approach are discussed.

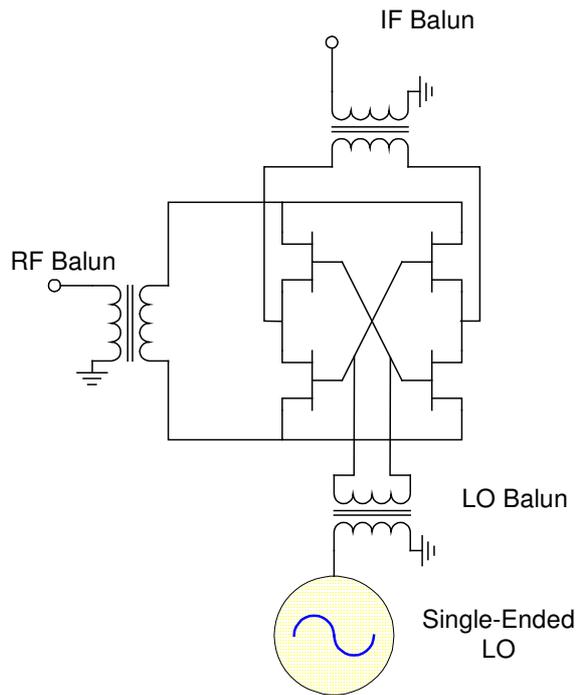
## Introduction

Voltage Controlled Oscillators (VCOs) are widely used as signal sources in RF and microwave communication systems. Fully monolithic VCO ICs are rarely encountered as stand-alone components, mainly due to the low Q of the resonators and poor tuning performance of the available varactor technology. Their use in multi-function ICs is, however, now relatively common, as pressure to reduce the number of external components needed by the IC increases. This paper aims to show that the use of monolithic differential VCOs has several advantages in transceiver ICs over a conventional single-ended approach.

In monolithic transceiver circuits the use of double balanced mixers also offers important advantages (Ref. 1) These include:

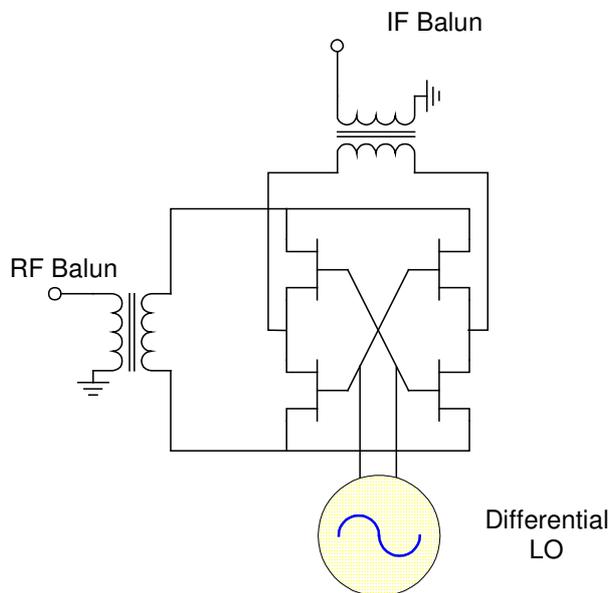
- Rejection of the LO signal
- Suppression of even-order products of the LO and/or RF
- Inherent isolation between all three ports
- Improved linearity

However, double balanced mixers also require differential, rather than single-ended, drives. Figure 1 shows a block level schematic of a double balanced quad-ring resistive FET mixer driven with a single-ended LO (VCO). A balun (or differential amplifier) is required at all three ports.



**Figure 1: Conventional Schematic of Quad-FET Ring Mixer with Single-Ended VCO**

Figure 2 shows how the LO balun can be eliminated by the use of a differential oscillator. This can have very positive implications for MMIC size (as well as performance), and therefore cost. In monolithic implementation the quad-ring and single-ended VCO are relatively small in area compared to the baluns.



**Figure 2: Schematic of Quad-FET Ring Mixer with Differential VCO**

## Single-Ended and Differential VCO Design

A typical single-ended VCO topology, this one using a FET as the active device, is illustrated in Figure 3. The topology is essentially a Colpitts (or Clapp) arrangement with the capacitive divider formed by the source capacitor and the internal  $C_{gs}$  of the device. The performance of this VCO topology, especially at high frequencies, can be degraded by the presence of the inductance of the grounding via holes. However, a potentially more serious performance degradation arises from the grounding inductance of the package and, when lower cost via-free processes are used, the inductance of grounding bondwires. In addition to VCO performance degradation, the fact that LO signal is flowing through bondwires and package pins to ground can result in increased LO leakage and an increased risk of interference with surrounding circuitry.

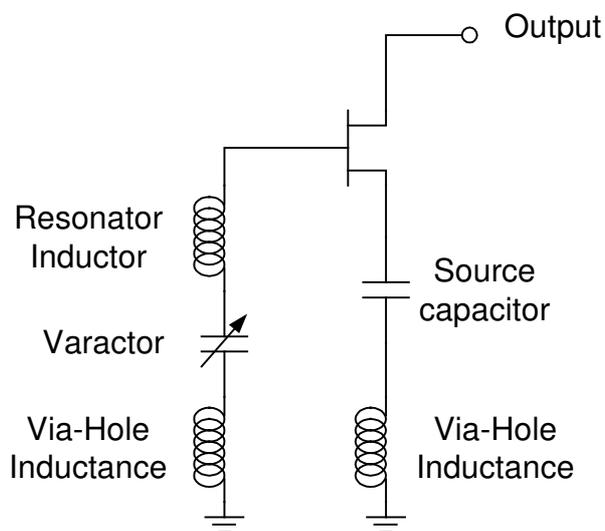
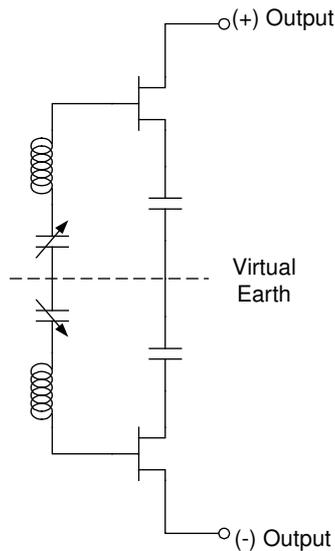


Figure 3: Simple Schematic of Single-Ended FET-Based VCO

The equivalent schematic of a differential version of this oscillator is shown in Figure 4. Two identical versions of the core oscillator are essentially used in a “Push-pull” mode. When correctly symmetrical the two outputs can be shown to be locked in frequency, but  $180^\circ$  out of phase. Differential circuitry relies on “virtual earths” and does not require low inductance RF paths to ground. This gives rise to a number of important advantages for the differential VCO:

- High frequency performance is no longer degraded by via-hole/bondwire inductance
- Fabrication on a simple, cheap via free process can be considered
- Rejection of common mode interference
- The differential signals required to drive balanced mixers are directly generated by the VCO, dispensing with the need for a potentially large, LO balun
- LO signal does not flow through the bondwires and package pins to ground resulting in less LO leakage and reduced risk of interference
- Bias de-coupling is easier

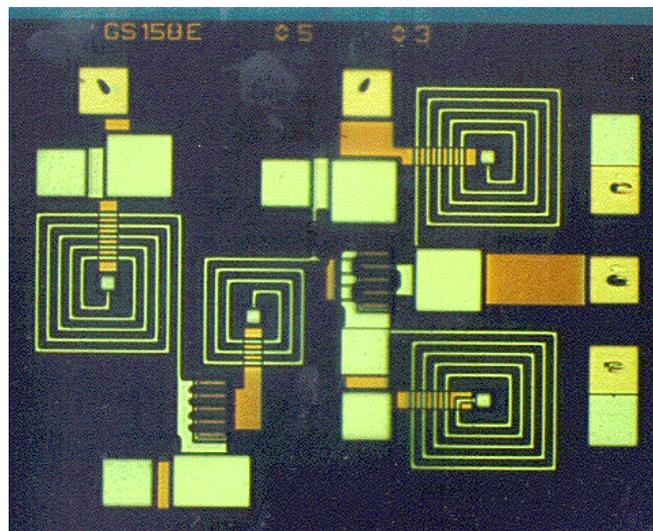


**Figure 4: Equivalent Schematic of Differential FET-Based VCO**

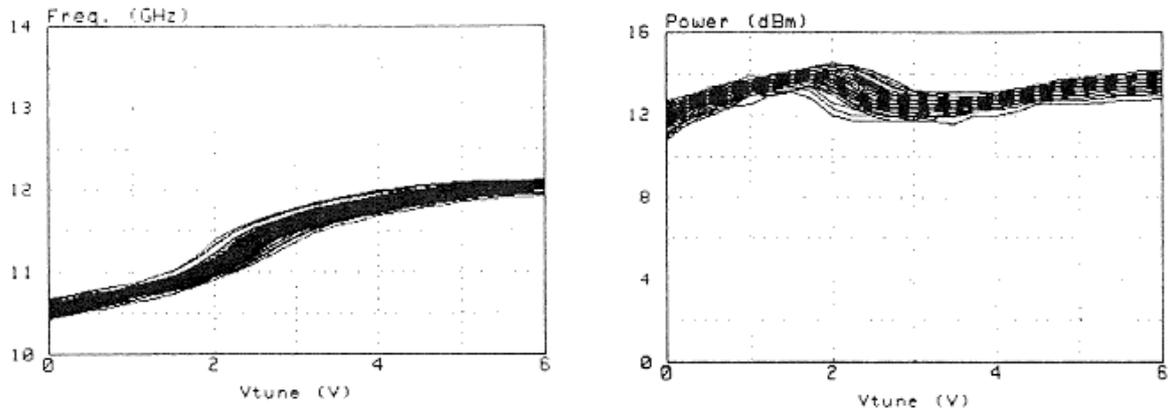
The simplest approach to designing a differential VCO is to design a single-ended oscillator (using either a small-signal approximation or full non-linear analysis – Ref. 2), using ideal grounds, and then simply combine two circuits symmetrically at the layout stage. The ideal grounds in the single-ended simulation become virtual earths in the differential implementation. A full Harmonic Balance of the complete differential oscillator can, of course, be performed, if desired.

### Single-Ended VCO Examples

An example of a single-ended FET-based MMIC VCO with a RF schematic identical to that shown in Figure 3 is illustrated in the photograph of Figure 5. Additional components on the IC are for DC bias of the FET and the application of the tuning voltage to the varactor. This particular example tunes 10.5 to 11.9 GHz, as shown in Figure 6. The measured phase noise is  $-75\text{dBc/Hz}$  at 100KHz offset.

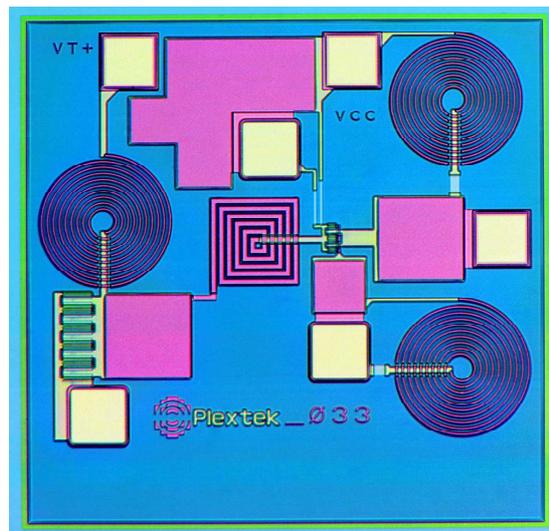


**Figure 5: Photograph of MMIC FET-Based VCO (Courtesy of GEC-Marconi)**



**Figure 6: Measured Tuning Range & Output Power of Single-ended FET VCO**

A similar VCO, but utilising a bipolar rather than a field-effect transistor, is shown in Figure 7(Ref. 3). This particular MMIC uses an InGaP HBT process from GCS semiconductors, based in the US. This example operates at approximately half the frequency of the previous example. The measured tuning range is given in Figure 8. The percentage tuning range of the HBT VCO is much less than that of the FET version, and is also less linear. This is due to the poor varactors on the HBT process, which are derived from a transistor's base-collector capacitance. The phase noise of the bipolar circuit, however, is far superior to the FET version, and was measured as  $-105\text{dBc/Hz}$  at the same offset frequency of 100KHz. This is shown in Figure 9. Adjusting for the frequency difference this is an improvement of approximately 24dB.



**Figure 7: Photograph of MMIC HBT-Based VCO (Courtesy of Pilextek)**

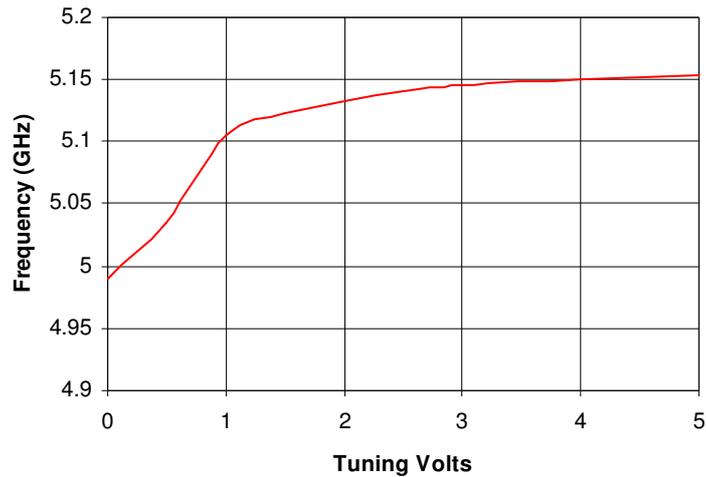


Figure 8: Measured Tuning Range of MMIC HBT-Based VCO (Courtesy of Plextek)

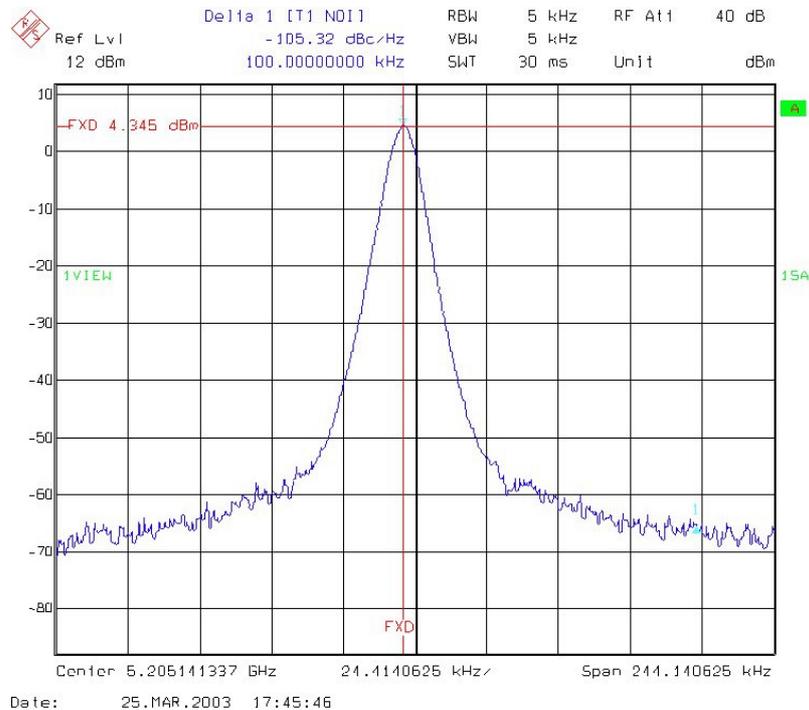
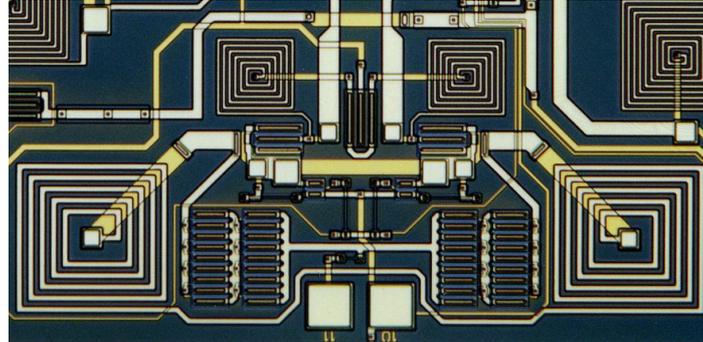


Figure 9: Output Spectrum of HBT MMIC VCO Showing Measured Phase Noise (Courtesy of Plextek)

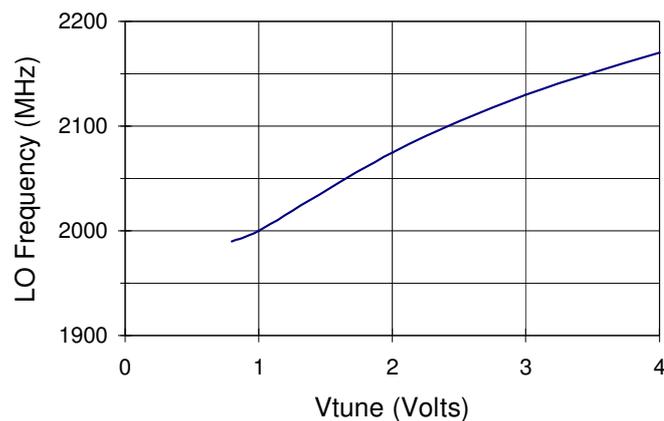
## Differential VCO Examples

A differential VCO, used as the Local Oscillator (LO) within a complete 2.4GHz transceiver IC, is shown in Figure 10 (Ref. 4). This circuit was fabricated at the GEC-Marconi GaAs MMIC fab at Caswell. The circuit is 0.5 $\mu$ m MESFET-based, through-GaAs via free, and plastic packaged. The exploitation of virtual earths in the VCO circuit meant that low inductance RF grounding of the VCO through the package leads was not necessary. A single-ended VCO does not benefit from virtual earths and would need to be grounded through bond-wires and the package ground. This would almost certainly have killed oscillation, or at the very least significantly degraded the performance. The tuning range is

illustrated in Figure 11. The measured phase noise was  $-87\text{dBc/Hz}$  at  $100\text{KHz}$  offset. This is equivalent to that of the aforementioned FET single-ended VCO, when compensating for the different output frequencies. ( $-75\text{dBc/Hz}$  at a frequency of  $10\text{GHz}$  is equivalent to  $-87\text{dBc/Hz}$  at  $2.5\text{GHz}$ , allowing  $6\text{dB/octave}$ ).



**Figure 10: Photograph of MMIC FET-Based Differential 2.4GHz VCO (Courtesy of GEC-Marconi)**



**Figure 11: Tuning Range of MMIC FET-Based Differential LO (Courtesy of GEC-Marconi)**

Figure 12 illustrates a similar differential VCO used within a  $5\text{GHz}$  transceiver MMIC, again fabricated by GEC-Marconi (Ref. 5). This particular transceiver MMIC is neither via-free nor plastic packaged due to its higher frequency of operation. The differential VCO, however, does exploit the use of virtual earths throughout. This ensures that the oscillation is not degraded by parasitic inductance and removes the need for on-chip bias de-coupling capacitors. The measured tuning range and buffered output power of several of the VCOs (measured on-wafer) is presented in Figure 13.

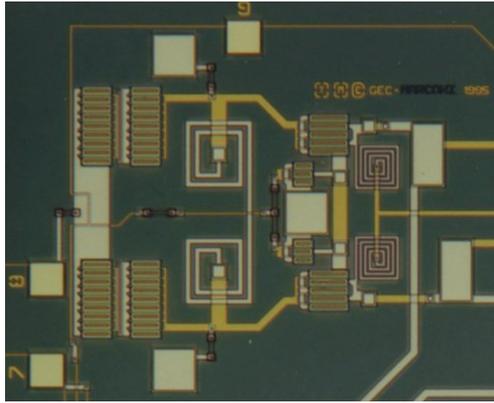


Figure 12: Photograph of MMIC FET-Based Differential 5GHz VCO (Courtesy of GEC-Marconi)

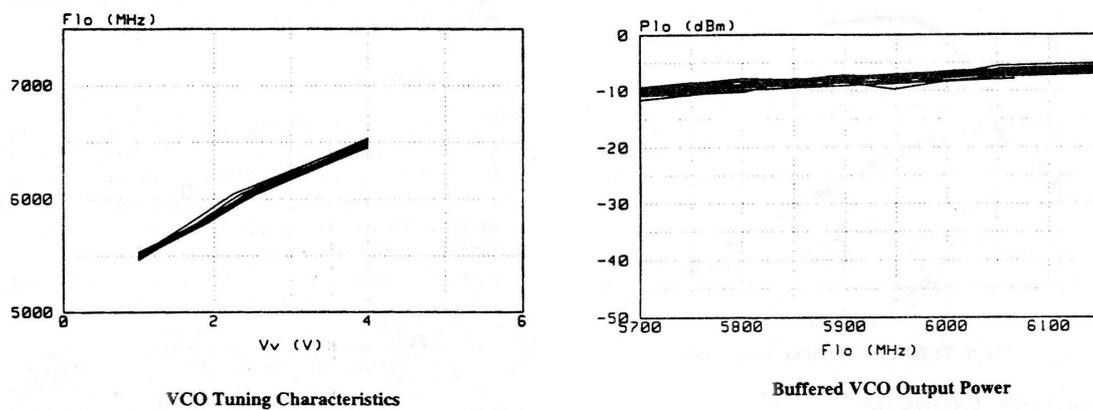


Figure 13: Measured Performance of MMIC FET-Based Differential 5GHz VCO (Courtesy of GEC-Marconi)

## Conclusions

The design and measured results of several MMIC single-ended and differential VCOs have been presented. All of the VCOs are fully monolithic and require no external resonators or bias components. When utilised in monolithic multi-function transceiver circuits the differential VCO approach holds several advantages over a single-ended LO/balun approach. These include:

- The chip area occupied by a dual-output VCO exploiting virtual earths is (generally) less than that of a similar VCO using via-holes in combination with a balun structure
- The via-free design is smaller, cheaper and higher yield, and less parasitic inductance means higher possible frequencies of oscillation
- Symmetrical oscillator design guarantees outputs with  $180^\circ$  phase difference for driving balanced mixers
- Rejection of common mode interference
- LO signal does not flow through the bondwires and package pins to ground resulting in less LO leakage and reduced risk of interference

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