KEITHLEY

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Making Ring Oscillator Measurements with the Model S530 Parametric Test System's Frequency Measurement Option

Introduction

In the world of CMOS wafer parametric testing, the ring oscillator is one of the more important test structures because its test data helps confirm that logic gates are meeting their speed design criteria. This application note discusses techniques for testing these devices using Keithley's Model S530 Parametric Test System.

Background

A growing number of semiconductor fabs are incorporating ring oscillators into their overall process control monitoring test structures. Frequency measurements on ring oscillator structures are used to determine gate propagation delay, one of the critical parameters that determines how quickly a digital circuit can operate. Every logic gate has input capacitance, so no device can switch instantaneously because the input capacitance limits the speed at which a gate can switch. However, this gate propagation delay is too short for most test equipment to measure directly, so test systems measure oscillation frequency instead and the gate propagation delay is calculated from this frequency measurement.

In a CMOS fabrication process, a ring oscillator test structure is typically designed and constructed with an odd number of inverter stages. Rather than cell libraries or gates, a ring oscillator test structure is usually constructed from transistors in order to ensure an accurate representation of the parameters of interest.

The structure is designed to be as compact as possible to ensure that its performance is dominated by the transistors rather than by the interconnects. The device channel length of the transistors is usually the minimum length that the process design rules will support.

Figure 1a is a high-level schematic view of a typical ring oscillator circuit; ***Figure 1b*** is a block diagram of a ring oscillator.

The ring oscillator shown in ***Figure 1a*** (like all ring oscillators) consists of an odd number of inverter stages. The input can consist of a 2-input NAND gate that can serve as an externally controlled trigger. Once triggered, the ring oscillator will free-run at a frequency that's dependent on the propagation delay between the stages. Because the ring oscillator will natively oscillate at a frequency much higher than a typical parametric test system can measure directly, the output of the test structure is usually isolated with a buffer (in order to deal with the effects of test system capacitance) and its output signal divided using

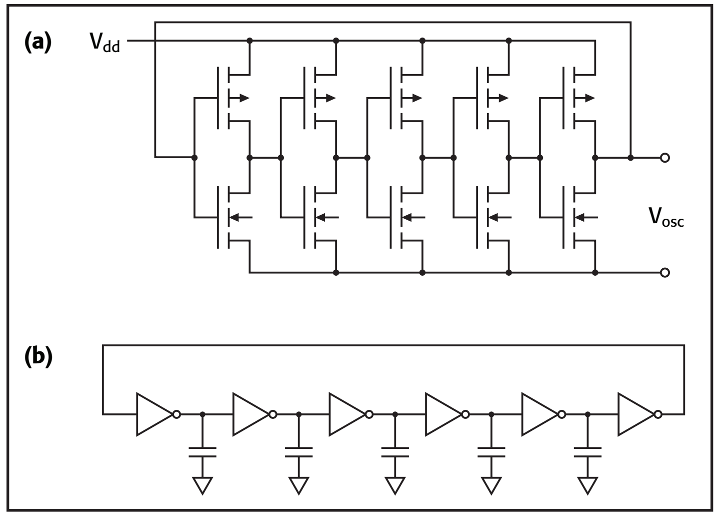

Figure 1. Schematic (a) and block diagram (b) representation of a CMOS ring oscillator (without trigger or buffer stage).

a D-type flip-flop by a factor of 256 (or as high as 1024 for processes 0.25µm or smaller). The measured frequency (after the signal is divided) is typically on the order of 1–50MHz.

Given that the oscillation frequency is what's being measured but the propagation delay is the actual parameter of interest, the next step is to calculate the propagation delay from the frequency measurement using this equation:

$$t_{delay} = \frac{1}{2nf_{osc}}$$

where: n is the number of inverter stages and

f_{osc} is the measured frequency of oscillation

Measurement Considerations

Parametric test systems have always been optimized to perform accurate, low-level DC measurements. However, AC performance for these systems is also important for supporting C-V measurement, pulse generation, and frequency analysis of ring oscillator structures. So although the S530 is ideally suited for DC measurements, it has also been designed with an AC signal bandwidth of 20–30MHz.

A frequency counter is often thought of as the best instrument for measuring frequency. However, given that frequency counters count crossings (through zero, etc.), they can often produce erroneous readings in situations where the signal has to be extracted from a noisy AC environment. That's why frequency measurements are often best performed using a spectrum analyzer or an oscilloscope using spectrum analysis techniques.

Spectrum analyzers operate by converting a signal from the time domain to the frequency domain using Fourier analysis. Each frequency in the signal's spectrum is plotted versus its signal amplitude (***Figure 2***). That means, in a noisy signal environment, the signal of interest is often the one with the highest amplitude. Of course, in some instances, even spectrum analysis fails, such as when the amplitude of the signal of interest is below the noise floor of the system.

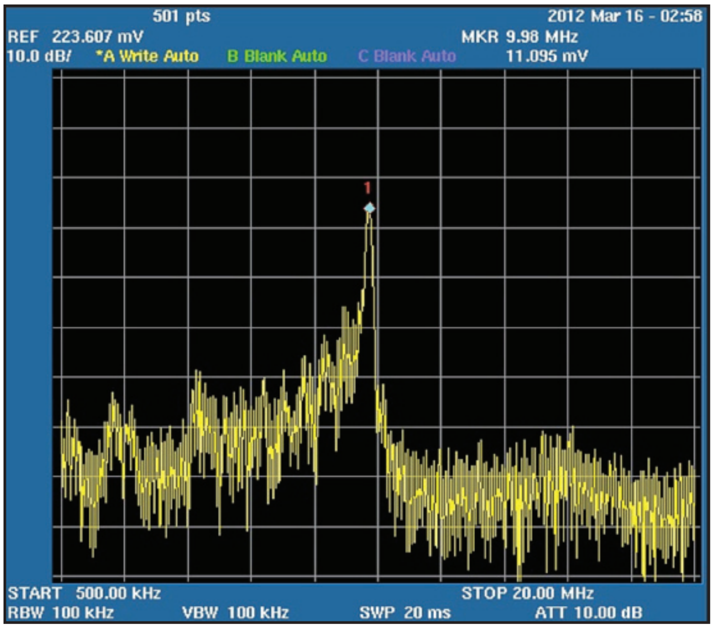

Figure 2. Ring oscillator signal spectrum through the S530 switch matrix.

In applications outside the general-purpose parametric test environment, test system designers strive to ensure that the impedances of the DUT, transmission lines, and measurement equipment are matched and that there are no open signal paths, thereby minimizing the major causes of AC signal distortion: insertion loss and reflections. However, this is not always possible to accomplish in a DC parametric test environment. This is another situation in which a spectrum analyzer will produce more accurate readings than a frequency counter because the amplitude of the frequency of oscillation will usually stand out despite these distortions.

S530 Frequency Measurement Hardware

Keithley's S530 Parametric Test System supports characterizing ring oscillators using the frequency measurement option. This measurement option is oscilloscope-based and connects to an instrument port on the S530 switch matrix, just like the system's source measurement units (SMUs), C-V unit, pulse generator units, and digital multimeter (DMM.) Once connected to the switch matrix, the frequency measurements can be switched to any one of the matrix's DUT pins.

The instrument driver for the frequency measurement option measures the frequency of a ring oscillator signal by using Fourier analysis to convert the signal from the time domain to the frequency domain. The various software commands return the measurement in the form of pairs of results, corresponding to the frequency and amplitude of the strongest signals.

The S530 frequency measurement option can accurately measure AC signals with signal levels above 25mVp-p and frequencies up to 20MHz.

S530 Frequency Measurement Software

The S530 frequency measurement option supports a variety of measurement commands:

`ring _ max`	Detects the frequency with the highest amplitude.
`ring _ ref`	Detects the frequency that is closest to the specified reference frequency.
`ring _ Icc`	Detects the 5 frequencies whose amplitudes are larger than the specified threshold.
`ring _ meas`	Determines the ring oscillator frequency and amplitude.
`freq _ init`	Initializes the oscilloscope card to its default state.
`freq _ setup`	Sets the start frequency and end frequency of the scan as well as the resolution bandwidth.
`freq _ measure`	Measures the frequency and amplitude of the strongest signal.
`freq _ measure _ next`	Measures the frequency and amplitude of the next strongest signal as compared to the measurement returned by the `freq _ measure` command.
`freq _ detect _ peaks`	Returns the frequencies and amplitude of the specified number of peaks.
`freq _ selftest`	Places the oscilloscope card in self-test mode and returns the status.

Making a Ring Oscillator Measurement with an S530

To illustrate the process of making a ring oscillator measurement with the Model S530, let's begin by assuming a ring oscillator like the one shown in ***Figure 3***.

The `freq _ init`, `freq _ setup`, and `freq _ measure` commands described previously provide one way to measure the ring oscillator frequency and signal amplitude. For the purposes of this example, let's assume that the ring oscillator frequency is 10MHz and that its V_{ss}, V_{cc}, V_{ccb}, and output pads are connected to pins 1, 2, 3, and 4 respectively. Let's further assume this device requires 5V to power it and 5V to trigger the oscillation. For this example, the following command sequence (provided in an S530 KITT macro) could be used to perform this measurement:

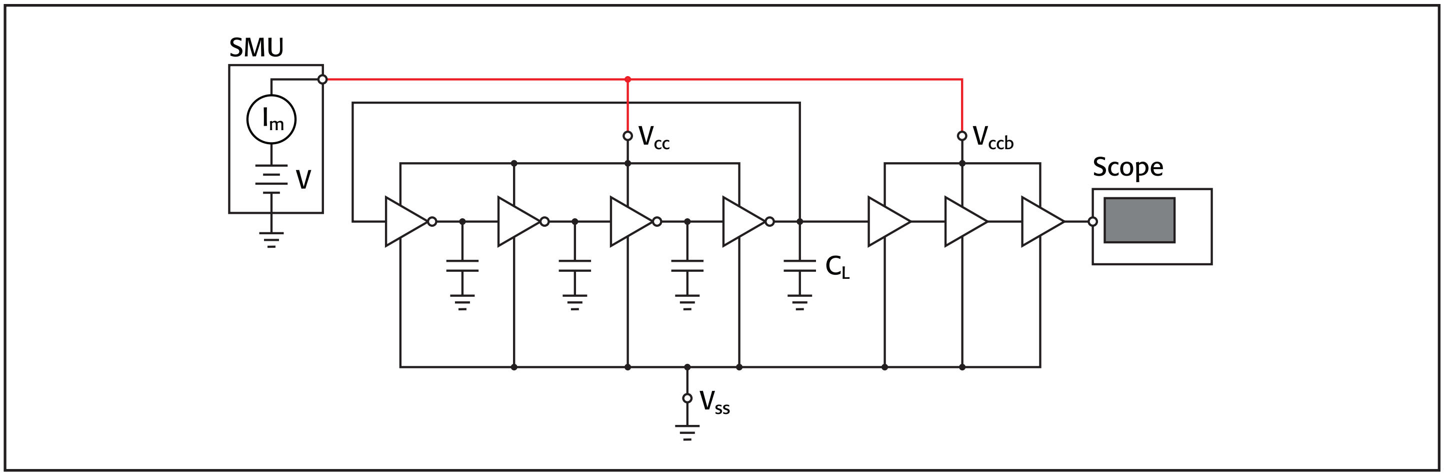

Figure 3. Generalized CMOS ring oscillator.

```
vss _ pin = 1
vcc _ pin = 2
vccb _ pin = 3
output _ pin = 4
vcc = 5.0
conpin(SMU1, vcc _ pin, vccb _ pin, 0)
conpin(vss _ pin, GND, 0)
conpin(SCP1A, output _ pin, 0)
forcev(SMU1, vcc)
init _ status = freq _ init()
setup _ status = freq _ setup( 0e6, 15e6, 1e6)
meas _ status = freq _ measure(frequency, level)
```

Here is what this test sequence does:

`vss _ pin = 1` `vcc _ pin = 2` `vccb _ pin = 3` `output _ pin = 4`	Defines the DUT pins.
`vcc = 5.0`	Defines the voltages required to power and trigger the ring oscillator.
`conpin(SMU1, vcc _ pin, vccb _ pin, 0)` `conpin(vss _ pin, GND, 0)` `conpin(SCP1A, output _ pin, 0)`	Makes the connections to the DUT.
`forcev(SMU1, vcc)`	Powers the device and triggers the oscillation.
`init _ status = freq _ init()`	Initializes the oscilloscope card. This command is always required to use the scope card!
`setup _ status = freq _ setup( 0e6, 15e6, 1e6)`	Defines the frequency scan and resolution bandwidth. Because the oscillator frequency is 10MHz, it's essential to make sure that it is within the scan boundaries. In this case, the start frequency is set to 0Hz, the end frequency to 15MHz, and the resolution bandwidth (or scan resolution) to 1MHz. This would give a frequency measurement that is accurate to 1MHz.
`meas _ status = freq _ measure(frequency, level)`	Performs the measurement and returns the frequency (in Hz) and amplitude (in Vp-p) of the strongest signal found.

This example required a total of seven commands to perform the ring oscillator measurement. However, the `ring _ max` command offers a simpler way to perform this same measurement, as the next example shows:

```
vss _ pin = 1
vcc _ pin = 2
vccb _ pin = 3
output _ pin = 4
vcc = 5.0
meas _ status = ring _ max(vcc _ pin, vccb _ pin, vss _
pin, output _ pin, vcc, 10e6, 0.5, 25e-3, frequency,
level, meas _ status)
```

The second test sequence example accomplishes the same functions as the first but with fewer commands:

`vss _ pin = 1` `vcc _ pin = 2` `vccb _ pin = 3` `output _ pin = 4`	Defines the DUT pins.
`vcc = 5.0`	Defines the voltages required to power and trigger the ring oscillator.
`meas _ status = ring _ max(vcc _ pin, vccb _ pin, vss _ pin, output _ pin, vcc, 10e6, 0.5, 25e-3, frequency, level, meas _ status)`	Performs the measurement and returns the frequency (in Hz) and amplitude (in Vp-p) of the strongest signal found. The `ring _ max` command simplifies things a bit. Although most of the arguments are self-explanatory when compared to the previous example, the 6th, 7th, and 8th arguments (…10e6, 0.5, 25e-3…) require some explanation: • 10e6 is the expected frequency of oscillation. • 0.5 is the measurement tolerance. This parameter tells the function how to know that it has measured the desired frequency. The measurement stops when the following condition is met: $\frac{(f_{meas} - f_{expected})}{f_{expected}} < tolerance$ • 25e-3 is the minimum acceptable signal level in Vp-p.

Summary

This application note has offered an overview of how to perform ring oscillator measurements using the S530 parametric test system's frequency measurement option. For further information on this option, consult the user documentation provided with the test system or contact a local Keithley applications engineer.

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