Switching Speed Measurements of Barium Strontium Titanate (BST) Varactors

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[Summary] Varactors are used in a wide variety of adaptive and reconfigurable RF and Microwave circuits. For applications that require circuits to have fast re-configurability, characterization of the device's switching speed is typically required. This paper describes switching speed measurements of Barium Strontium Titanate (BST) varactors using a Vector Network Analyzer over a broad range of frequencies.

1 Introduction

In the past couple of decades, the radio spectrum has expanded and become crowded as it continues to support a wide variety of services and applications. Spectrum resources continue to grow as new spectrum allocations and communication standards are defined and made available for use. Reconfigurable or adaptive radios and radio front ends offer a scalable approach in simplifying hardware by tuning to a frequency and standard that is least used at a given moment in time[1),2)]. Tunable passive RF/Microwave devices are the building blocks of reconfigurable or adaptive electronics and modern radio front ends. These devices are also critically important in the use of steerable antennas, antenna arrays and tunable filters.

The speed or state transition time at which a passive RF/Microwave device can change states is important since this will, in most cases, impact system level performance specifications. Ideally, the measured speed in which a device changes states is not limited by the measurement system. Often for tunable devices which exhibit fast switching characteristics such as BST devices, it is the measurement system that will limit the Device Under Test (DUT) characteristics observed. In this paper, an Anritsu MS464XB Vector Network Analyzer is used to measure the rise/fall time characteristics of varactors. This measurement process can be applied to any switching device but is specifically interesting when phase carries the transition information.

2 Measurement Block Diagram

2.1 Pulse Measurement VNA options

The switching speed measurement block diagram shown in Figure 1 uses an Anritsu MS464XB Vector Network Analyzer (VNA) with options 035 and 042[3)]. Option 035 is the IF digitizer option that receives, processes and records digitally the analog IF information for specific measurement time durations. Option 042 called PulseView™ is a User Interface (UI) that adds the capability to generate, trigger and measure pulsed signals. The VNA uses an external pulse generator[4)] and pulse amplifier[5),6)] to drive the varactor from 0 V to +20 V DC. An oscilloscope monitors the pulse input leading and trailing edges to the varactor. At any given CW frequency, the VNA is controlled to digitally capture the change in magnitude and phase of the transmission parameter S21 as the varactor pulse input transitions from 0 V to +20 V and +20 V to 0 V. The S21 magnitude and phase 10%-90% transition times are compared with those observed on the oscilloscope. Since the VNA measures the relative change in transmission magnitude and phase over each pulse transition, a VNA receiver calibration is not necessary. Also, either the change in transmission magnitude or phase (not necessarily both) is needed to quantify actual DUT switching speeds.

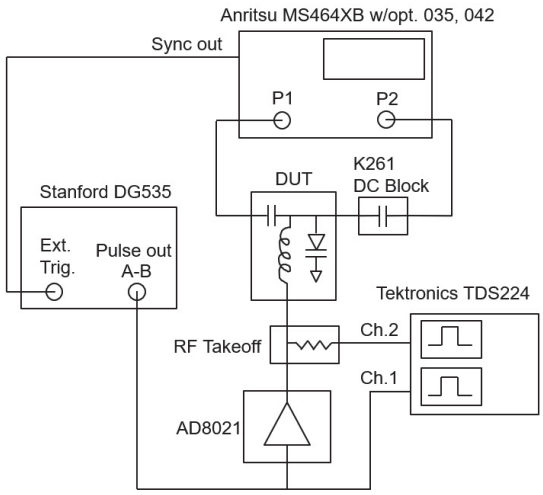

Figure 1 Switching speed measurement block diagram using Anritsu MS464XB w/options 035 and 042

2.2 Pulse Generation

Measuring and quantifying varactor switching speed over its full tuning voltage range of 0 to +25 V is desirable. The VNA externally triggers an external pulse generator which only has an output of 4 V peak and approximately 10 nS rise and fall times. A high-speed amplifier increases the pulse generator's output voltage amplitude to bring the signal level to +20 V while trying to preserve rise and fall times of the pulse generator. For the high-speed amplifier selection, compromises were made of both peak amplitude and rise/fall times. Analog Devices AD8021 was selected with a voltage gain of 5 giving a peak voltage output of +20 V and rise/fall times of about 450 nS and 150 nS, respectively. This amplifier was assembled and evaluated on an evaluation printed circuit board (PCB).

3 Varactor DUT Model Development

3.1 Electrical Models

Previous work[7] characterized Tecdia Varactors[8] to derive electrical models as a function of tuning voltage. This data was used to create an electrical model in AWR Microwave Office[9] to evaluate the change in transmission magnitude and phase vs. frequency over a range of tuning voltages.

Figure 2 shows a simplified electrical model of the DUT circuit. The tuning voltage is applied to "Pulse In" end of the RF choke (RFC). The RFC is modeled as a 3.5 mm long bond wire to provide sufficient inductance above 2-3 GHz but not so much inductance to limit the input pulse edge rise and fall times. Figures 3 and 4 show the change in transmission magnitude and phase respectively of the HBC2R2KY20X10X5A02 (2.2pF) varactor design. The absolute values in Magnitude and Phase are not so much of a concern but it is the relative change in magnitude and phase that gives confidence the VNA will be able make the measurement with enough vertical scale resolution. Note in Figure 4, the phase change at 10 GHz is small so measurement resolution will be limited. Determining the rise/fall times may be difficult at this frequency. This is not a problem, however, since the transmission magnitude shows sufficient relative change at this frequency. Again, measurement of either transmission magnitude or phase is necessary to determine DUT switching speed. The transmission magnitude and phase electrical model results of the HBCR22AY20X10X5A02 (0.22pF) varactor are similar and not shown.

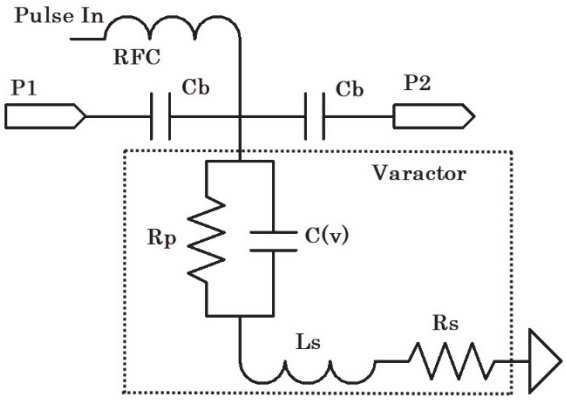

Figure 2 DUT electrical model

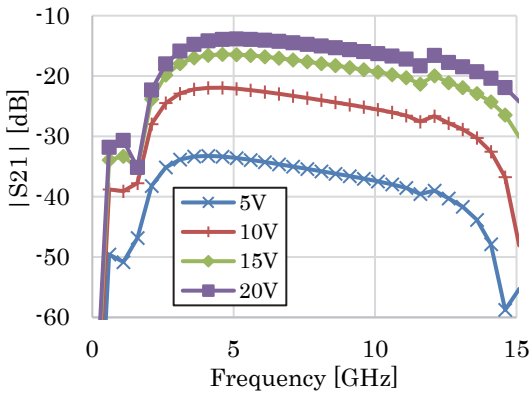

Figure 3 Transmission Magnitude vs. frequency vs. varactor voltage

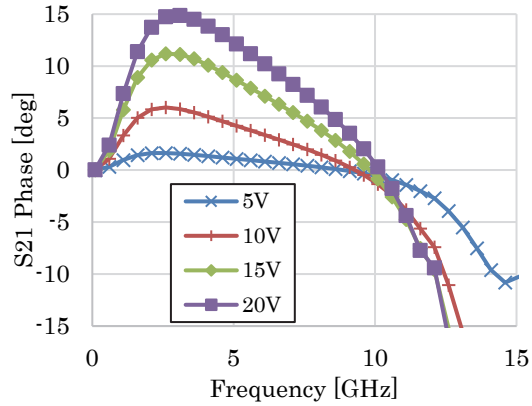

Figure 4 Transmission Phase vs. frequency vs. varactor voltage

3.2 Varactor DUT Modules

DUT physical models were built using a 10-mil thick Alumina circuit using 2.2 pF and 0.22 pF shunt mounted varactors. Segmented wire bonds were necessary to achieve the 3.5 mm bond wire length and required inductance value. Anritsu K connectors were used with a ribbon wrap pin-substrate connection on the connector's backside. An SMA connector was used to connect to the Bondwire RFC. Figure 5 shows the DUT internal circuit.

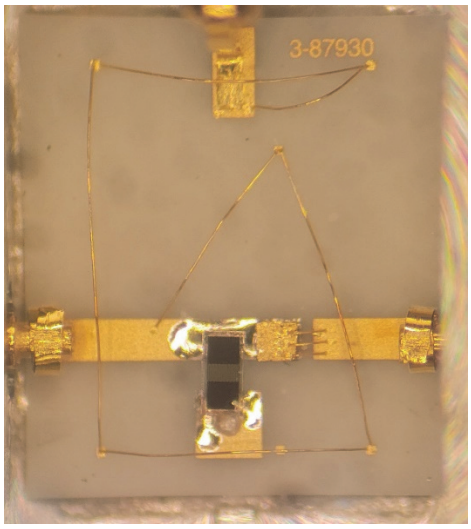

Figure 5 Shunt mounted varactor on 10-mil Alumina Substrate

4 Switching Speed Measurements

4.1 Instrument Settings

The Anritsu MS464XB VNA Option 042 PulseView™ (Option 042) UI settings are shown in Table 1. The measurement mode is selected as Pulse profile since structure of the data within the pulse is of interest. In this measurement, S21 magnitude and phase vs. time is captured at the pulse rising and falling edges. In this mode, both frequency and power are held constant. The pulse amplifier's 10%-90% rise and fall times are approximately 100 nS so the Measurement Width parameter is set to 10% of this value. It is expected the pulse amplifier will limit how fast the varactor can be switched. The VNA receiver is set to b2 (Port 2) which implies S21 Magnitude and Phase will is measured.

The Pulse Repetition Interval (PRI) describes the period of the pulse input to the DUT. The first half of the interval the pulse to the DUT will be at a high state and the last half of the interval, the pulse will be at a low state as a 50% duty cycle was employed. The Start/Stop interval of 99 uS to 101 uS captures the falling-edge state of the measurement. Conversely, a Start/Stop interval of 0 uS to 2 uS captures the rising-edge state of the measurement. The DG535 pulse generator's pulse repetition interval is set to 200 uS, with a duty cycle of 50% and a pulse amplitude of 4 V. Changing the duty cycle of the pulse generator requires a change in Start/Stop interval when measuring the falling-edge state of the DUT.

Table 1 Anritsu MS464XB PulseView™ configuration settings

Parameter	Value
Measurement Mode	Pulse Profile
Receiver	b2
# of Points	401
Measurement Width	10 nS
Start	99 uS
Stop	101 uS
Control Type	Synch
Pulse Repetition Interval	200 uS
Synch	Internal
Resolution	2.5253 nS

4.2 Pulse Amplifier Output

In Figure 1, the pulse amplifiers output is monitored using Ch. 2 of the TDS224 oscilloscope through a resistive take-off. The pulse amplifiers input is monitored using Ch. 1. Monitoring the pulse input to the DUT is useful to ensure the pulse amplifier is not loaded by the DUT resulting in a distorted pulse waveform. The pulse amplifier output response can also be compared to the VNA S21 magnitude and phase edge transition response. The AD8021 pulse amplifier exhibits asymmetry between its rise and fall times of about 450 nS and 150 nS respectively with the 150 nS fall time limited by the slew rate of the amplifier. Plots of the Oscilloscopes Ch. 1 and Ch. 2 rise and fall times are shown in Figures 6 and 7.

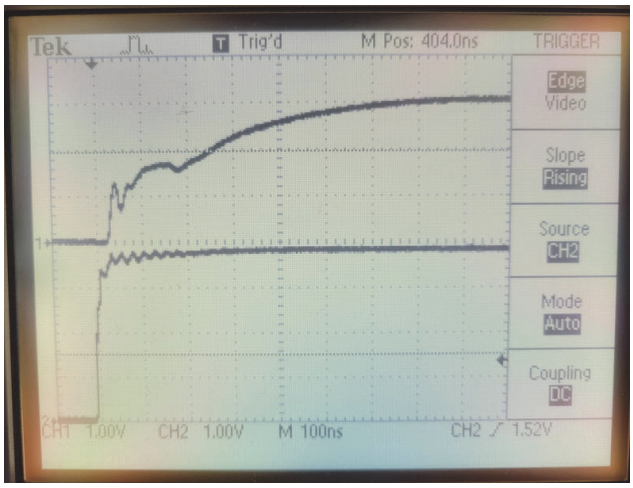

Figure 6 Pulse amplifier risetime, input (bottom trace) and output (top trace)

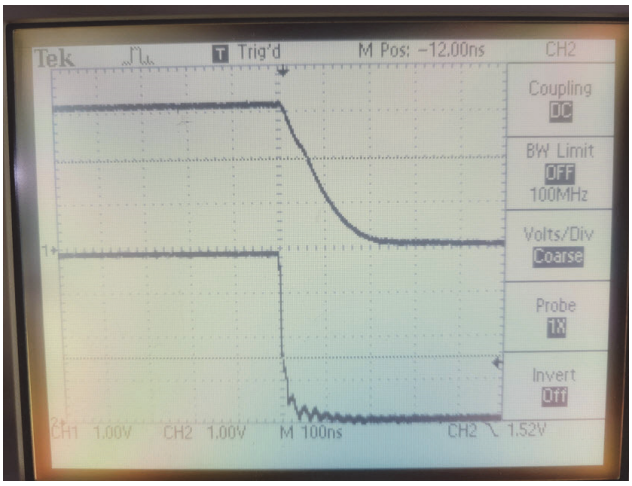

Figure 7 Pulse amplifier falltime, input (bottom trace) and output (top trace)

4.3 MS464XB VNA PulseView™ Measurements

If the switching speed of the varactor is limited by the 10%-90% rise/fall times of the pulse input to the DUT, the transmission magnitude and phase transition times will mirror the pulse rise/fall times. Using the MS464XB VNA PulseView pulse profile at continuous wave (CW) frequencies at 5, 10 and 15 GHz, the 10%-90% rise time can be measured from both S21 transmission magnitude and phase as shown in Figures 8, 9 and 10. Note that the relative trace noise is generally lower on the phase measurements which shows some of the value in using the complex S21 pulsed measurement. Since the DUT is a capacitor, this improved phase sensitivity would be somewhat expected. These risetimes are identical to DUT pulse input risetimes. For slight changes in either magnitude or phase, the measurement point scatter tends to increase or widen but risetimes can still be measured with transitions as small as 0.2 dB in magnitude and 0.5 deg in phase. The corresponding fall time plots are shown in Figures 11, 12 and 13 which show a 10-90% fall time of about 150 nS.

Only three CW frequencies are presented in this paper but any CW frequency within the range of the VNA could have been used. Rise and fall times for other CW frequencies beyond 15 GHz were measured and all exhibited identical 10%-90% rise and fall time durations, albeit at different absolute magnitude and phase values.

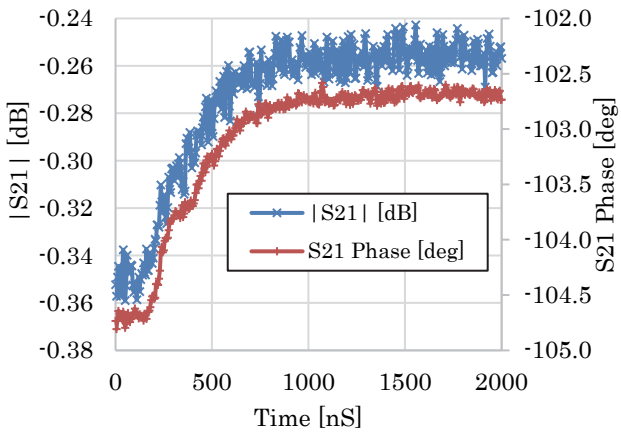

Figure 8 Risetime delta magnitude and phase at 5 GHz for 0.22pF varactor

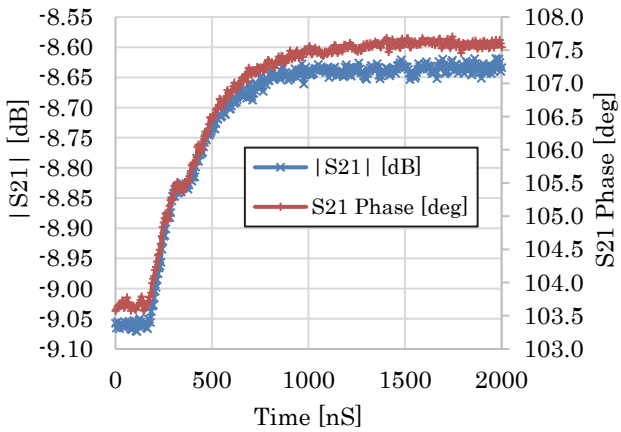

Figure 9 Risetime delta magnitude and phase at 10 GHz for 0.22pF varactor

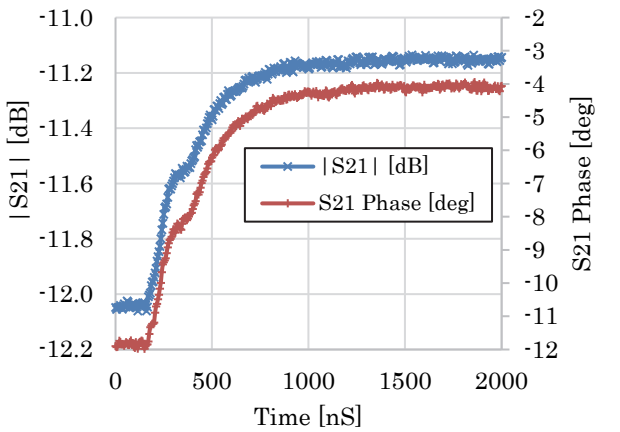

Figure 10 Risetime delta magnitude and phase at 15 GHz for 0.22pF varactor

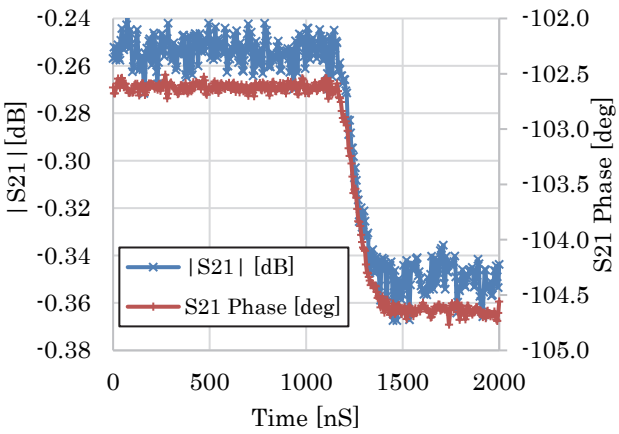

Figure 11 Falltime transmission magnitude and phase at 5 GHz for 0.22pF varactor

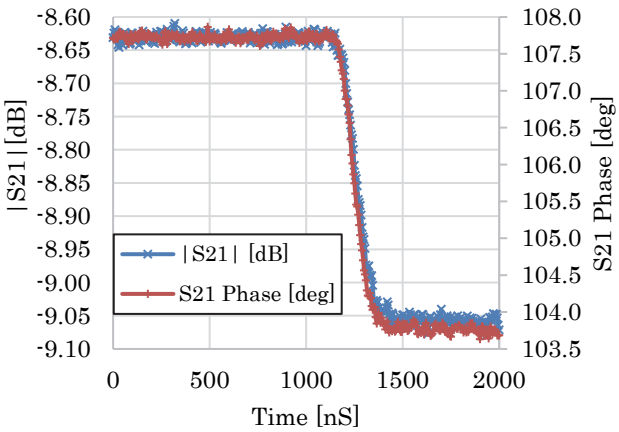

Figure 12 Falltime transmission magnitude and phase at 10 GHz for 0.22pF varactor

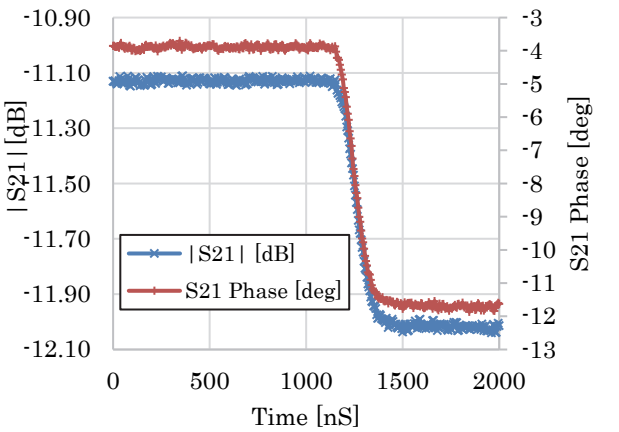

Figure 13 Falltime transmission magnitude and phase at 15 GHz for 0.22pF varactor

4.4 Varactor Current and Power Dissipation vs. Pulse Duty Cycle

All measurements in the previous sections were performed using a pulse duty cycle of 50%. With a duty cycle of 50%, the pulse amplifier positive current (Icc) is 37 mA. The quiescent current of the pulse amplifier with no input drive is 10 mA.

Figure 14 shows Pulse amplifiers supply current vs pulse duty cycle with Icc linearly proportional to the pulse duty cycle. The amplifier's negative current (Iee) remained relatively constant at 6 mA. Icc is used to calculate the varactor average power dissipation for a given duty cycle given by equation 1 and plotted in Figure 15.

$$P_v = \frac{DutyCycle\ [\%]}{100} * Vp * Icc \qquad (1)$$

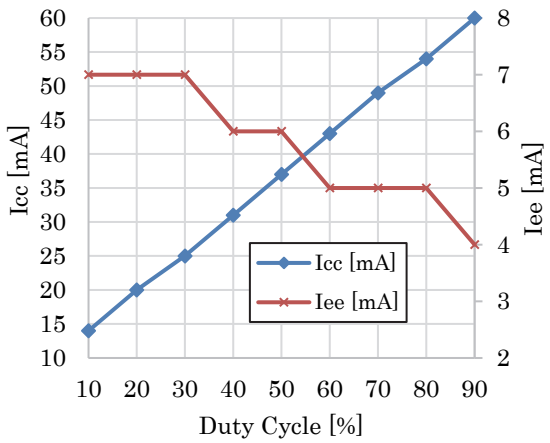

Figure 14 Pulse amplifier Icc and Iee vs. pulse duty cycle

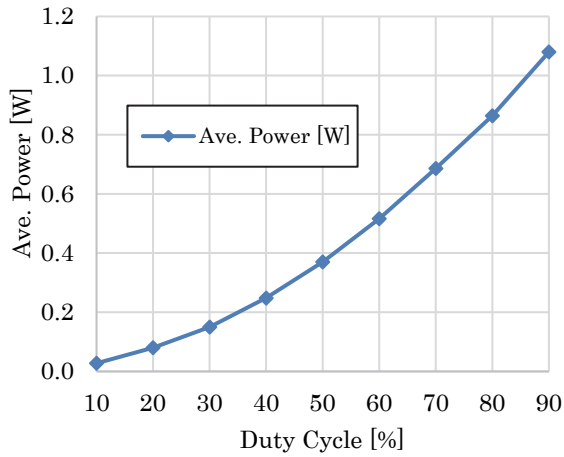

Figure 15 Varactor average power dissipation vs. pulse duty cycle

5 Conclusions

Characterizing the speed of switching devices is easily accomplished using an Anritsu MS464XB Vector Network Analyzer (VNA) with options 035 and 042. In this paper, switching speed of BST varactors were characterized using a digitized time interval sample of transmission magnitude and phase at specific frequencies. The change in either the transmission magnitude or phase with time can be used to determine device switching speed. The rise and fall times of either of these parameters is compared to the respective rise and fall times of the pulse input to the DUT.

For this work, the pulse amplifier limited how fast the varactor could be switched over its voltage bias range of 0-20 V. Due to the limited availability of high-speed op amps allowing a full +20 V output voltage, one compromise could be selecting a higher speed op-amp with a lower output voltage of +5 V for example. This compromise would allow a greater selection of high-speed op-amps to choose from. The amplifier's lower output voltage requirement translates to a high Gain Bandwidth Product (GBP) since the amplifier's gain would be 5 V/4 V or 1.25 maximizing its operational bandwidth.

References

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