

# Characterisation of Schottky Varactor Diodes for Pulse Compression Circuits

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**Abstract – The application of a non-linear lumped element circuit model for Schottky varactor diodes is presented in this paper. The nonlinear parameters of the GaAs varactor diode are extracted using small and large signal measurements. The modelled and measured results show strong agreement.**

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## I. INTRODUCTION

The need to transmit multigigabit data streams within optical networking equipment, such as routers and switches, is driving the need to increase the aggregate bandwidth through a copper medium. The dispersion and attenuation in the copper medium increases significantly with the increase in transmission frequency. The large increase in dispersion and attenuation which accompanies the increase of the transmission frequency is a bottle neck that limits the bandwidth in electro-optic backplane systems. Typical dispersion and attenuation on FR4 multilayer printed circuit board (PCB) is 0.9 dB/in and 1.2 ps/in respectively [1]. With the large improvement of the bandwidth which has extended to more than 10 Gbits/s for the OC192 standard, the communication channel designers now consider every single element in the communication channel. Signal distortion arising from attenuation and dispersion problems in the multilayer PCB in the electro-optic backplane can lead to significant inter-symbol interference (ISI). The ISI is increased by the multiple reflections and the low pass filter properties of the chip interconnects in the backplane card which causes the loss of the high frequency components of the digital bit stream.

To overcome this problem a digital bit stream is demultiplexed in the time domain to transmit the data at slower speeds and therefore reduce the distortion problems associated with the increase of the transmission frequency.

Different techniques are proposed for this purpose including equalization techniques [2]. An alternative solution using nonlinear wave transmission to compensate for the dispersion problem has been reported [3] using Non-Linear Transmission Line Technology (NLTL). The NLTL can compensate for dispersion by providing different propagation speeds for the harmonic contents of the digital bit stream. It can also regenerate the attenuated or lost harmonics due to the low pass filter properties of the digital interconnects.

The NLTL uses the non-linear CV characteristics of the shunt mounted Schottky diode to achieve nonlinear wave propagation properties. Typical C-V characteristics for the Schottky diode are shown in Figure 1.

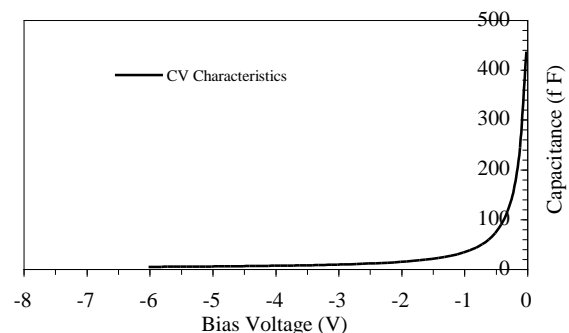


Figure 1 The Schottky diode CV characteristics.

The schematic diagram and circuit diagram of the NLTL are shown in Figure 2.

In this paper the Schottky diode equivalent circuit model which is extensively used to study Schottky diode mixer [4]-[5] properties is used to model the Schottky diode for NLTL applications. The full

nonlinear Schottky diode model is presented in this paper. Nonlinear characterization of the Schottky diode equivalent circuit parameters based on small and large signal measurements are also given. Analysis has been performed on two devices the Bookham  $6 \times 100 \mu\text{m}^2$  (device 1) and the OMMIC  $3 \times 40 \mu\text{m}$  (device 2) Schottky varactor diode.

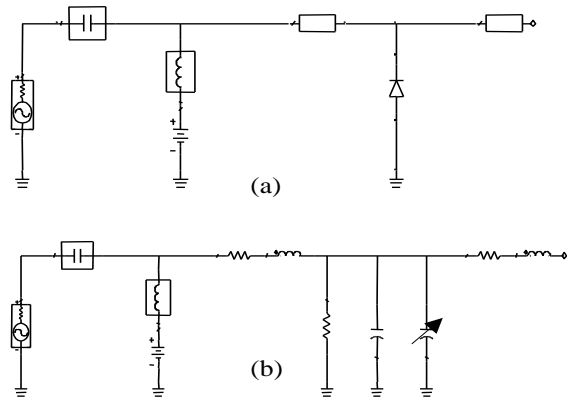


Figure 2 (a) Schematic diagram and (b) the equivalent circuit of the NLTL.

## II. SCHOTTKY DIODE MODEL

Basically the Schottky diode can be modelled by a nonlinear junction capacitance in parallel with a nonlinear junction conductance. The nonlinear capacitance models the Schottky diode under reverse bias conditions while the junction conductance models the diode under forward bias conditions. For accurate modelling, a series resistance and series inductance are considered in the Schottky diode equivalent circuit model. The Schottky diode equivalent circuit model is shown in Figure 3.

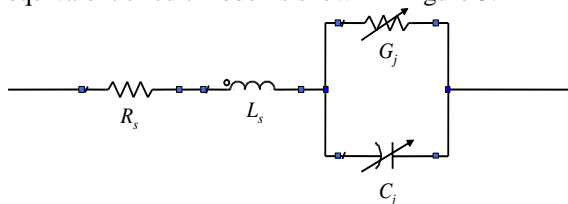


Figure 3 The equivalent circuit model of the Schottky varactor diode.

## III. SCHOTTKY DIODE PARAMETER EXTRACTION

The junction capacitance and the series resistance are the important parameters for the NLTL design. These two elements are extracted using small signal measurements under reverse bias conditions. The junction conductance is less important for the NLTL but it is extracted using DC measurements under forward bias conditions.

The Schottky diode model is verified using large signal measurements.

## IV. SMALL SIGNAL MEASUREMENTS

Small signal measurements were performed using the HP-8510B Vector Network Analyser (VNA) using the setup shown in Figure 4.

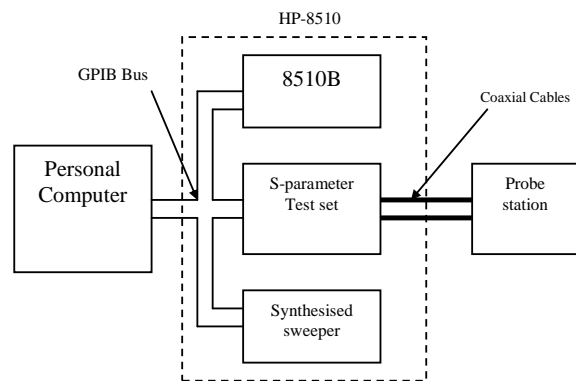


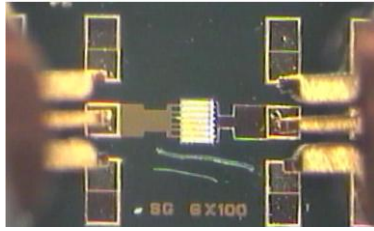
Figure 4 Small signal measurement setup

The system was calibrated using the Line Reflect Match (LRM) technique to eliminate the systematic errors from the S-parameter measurement system. The LRM calibration technique requires the use of three calibration standards to transfer the S-parameter measurement plane to the probe tips. The standards are:

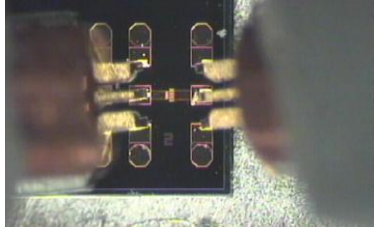
1. The reflect standard is either an open or short circuit. The open is preferred because the probe tips are left in air and no probe placement error occurs.
2. The match load standard is two separated  $50 \Omega$  loads.
3. Thru line standard which is a  $50 \Omega \times 30 \mu\text{m}$  length CPW line providing 1 ps electrical delay.

Port extensions of  $-0.5$  ps are added to each port to compensate for the delay caused by the thru line at each probe tip. The calibration standards are available on the Impedance Standard Substrate (ISS) with gold contacts and Ground Signal Ground (GSG) configuration.

Devices 1 and 2 were measured using the Cascade 12000<sup>TM</sup> probe station where Rigid GSG  $150 \mu\text{m}$  Cascade probes are used for probing the cathode and anode pads of each Schottky diode. Reverse DC bias was applied to the device under test using the bias tee on the VNA. A photograph showing probe heads contacting the measurement pads is shown in Figure 5.



Device 1



Device 2

Figure 5 Probe heads contacting the measurement pads for device 1 and device 2.

The measured reflection coefficient  $S_{11}$  of device 1 at different reverse bias points is shown in Figure 6.

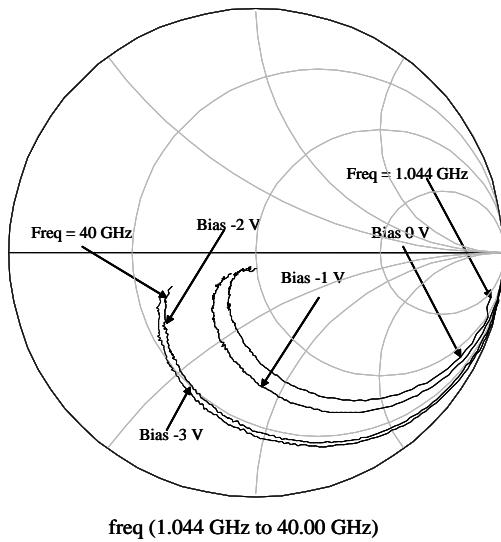


Figure 6 Measured reflection coefficient  $S_{11}$  for device 1 Schottky varactor diode at different bias points.

Figure 6 shows that the capacitance is the dominant parameter of device 1 as the measured reflection coefficient is in the lower half of the smith chart. It can also be noticed from the figure that the reflection coefficient is affected by the reverse bias voltage as it is varied from (0 to  $-2V$ ). Further increase in the reverse bias voltage has only a small effect on the measured reflection coefficient  $S_{11}$ .

This is because the depletion region under the Schottky contact experiences large non-linear characteristics as the bias is varied from (0 to  $-2V$ ) because of the hyper-abrupt doping profile [6], Figure 7. This profile experiences large non-linearities because of the non-uniform charge distribution under the Schottky contact which is approximated by a Gaussian distribution [6]. The hyper-abrupt doping

profile can be approximated by hyperbolic curve fitting as reported by [6]. The non-linearities of the diode can be modelled by

$$C_d(V) = \frac{212}{\left(1 - \frac{V}{0.6}\right)^\alpha} \quad (1)$$

where  $\alpha$  is the nonlinearity constant which depends on the doping profile of the Schottky diode. Larger nonlinear characteristics can be achieved if this constant is increased. Increasing the value of  $\alpha$  is limited to the fabrication process of the Schottky diode. The value of this constant for device 1 is ( $\alpha = 0.7$ )

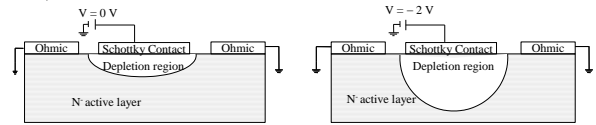


Figure 7 Cross section view of the Schottky diode shows the Schottky contact and the depletion region.

For reverse bias voltages larger than  $-2V$ , the depletion region is almost fully depleted. If the depletion layer is fully depleted then the diode parameters are almost constant, therefore the reflection coefficient  $S_{11}$  will be almost constant and does not change with bias.

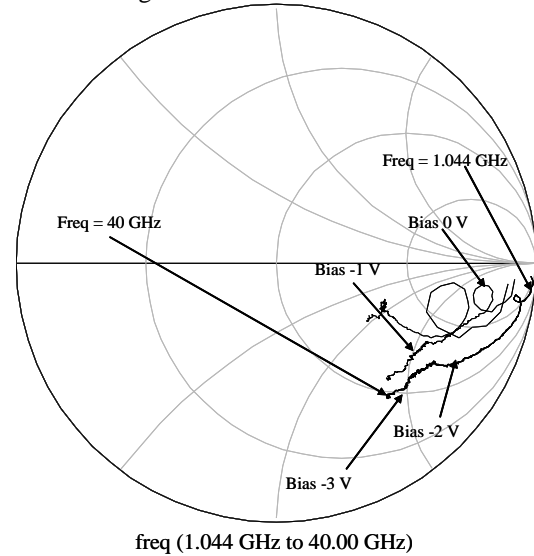


Figure 8 Measured reflection coefficient  $S_{11}$  for device 2 Schottky varactor diode at different bias points.

The measured reflection coefficient for device 2 is shown in Figure 8.

The measured reflection coefficient  $S_{11}$  of device 2 shows similar observations as for those of device 1 (i.e. the diode has capacitive properties and the diode parameters vary as the voltage is varied from 0 to  $-2V$ ). The reason for this is that the depletion region exhibits strong nonlinear characteristics for voltages ranging from 0 to  $-2V$ . For voltages more negative than  $-2V$  the depletion region is almost fully depleted, therefore the diode characteristics are

almost constant; hence the reflection coefficient is constant.

A comparison between Figure 6 and Figure 8 shows the reflection coefficient curves for device 1 are different from those for device 2. The reason for this difference is in the doping profile. Device 1 uses a hyper-abrupt doping profile [7] whereas device 2 uses a delta-doped profile [8].

The series resistance of the Schottky diode is extracted from the reflection coefficient ( $S_{11}$ ), where it is the real part of the reflection coefficient according to equation (1)

$$R_s = \text{real}(S_{11}) \quad (2)$$

The reflection coefficient is a function of the DC bias, and the series resistance is also a function of the DC bias. Because the Schottky diode resistance depends on frequency (skin effect which is basically in the metallization layers of the Schottky diode), the resistance is extracted at 5 GHz as a figure of merit. The series resistance of device 1 was  $5.71 \Omega$  while it was  $6.95 \Omega$  for device 2.

The junction capacitance and the series inductance are extracted based on an ABCD matrix technique. The extracted CV characteristic and series resistance for both diodes are given in Figure 9.

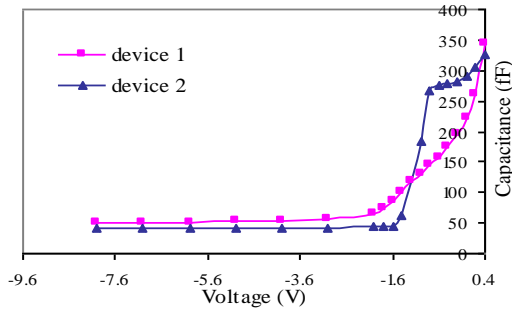


Figure 9 The extracted CV characteristics for both device 1 and device 2 Schottky varactor diodes.

Device 2 has larger nonlinearity compared with the device 1 since the capacitance of device 2 changes sharply over a smaller voltage range compared to device 1. The reason for this difference in nonlinearity is the difference in the doping profile where device 1 uses hyper-abrupt and device 2 uses a delta-doped profile.

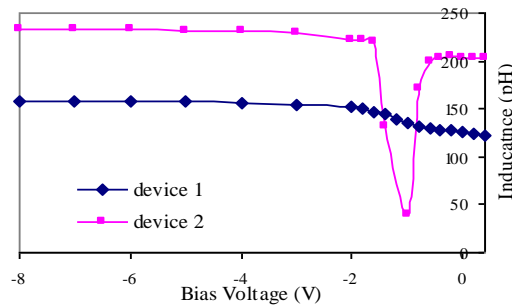


Figure 10 Extracted series inductance for device 1 and device 2 Schottky varactor diodes.

Figure 10 shows that device 2 has larger nonlinear characteristics between the reverse bias voltage range 0 V to  $-2$  V compared with device 1. The reason for that again refers to the delta-doping profile used in the device 2 foundry process.

## V. IV-CHARACTERISTICS.

The junction conductance of the Schottky diode is extracted from the IV measurements. The IV characteristics of the Schottky diode are given by equation 3 [9].

$$I_d = I_s \left( e^{\left( \frac{-qV_j}{nKT} \right)} - 1 \right) \quad (3)$$

where  $I_d$  is the Schottky diode current,  $V_j$  is the voltage across the junction conductance,  $I_s$  is the saturation current,  $K$  is the Boltzmann constant,  $T$  is the absolute temperature and  $q$  is the electron charge. The measured IV characteristics for both device 1 and device 2 Schottky varactor diodes are shown in Figure 11.

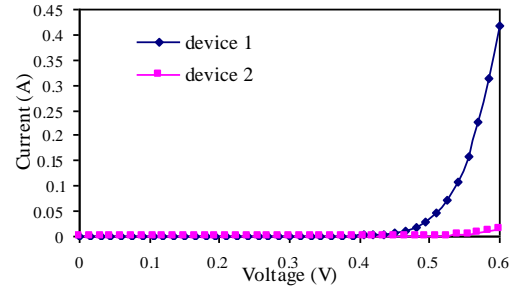


Figure 11 Measured IV characteristics for device 1 and device 2 Schottky varactor diodes.

Figure 11 shows that device 1 has much larger current compared to device 2 because device 1 has larger area compared to device 2.

The ideality factor ( $n$ ) and the saturation current are extracted based on the procedures outlined in [10]. The ideality factor ( $n$ ) for device 1 was 1.2 compared to 1.09 for device 2.

The saturation current for device 1 was 3 pA compared to 2.5 pA for device 2.

## VI. LARGE SIGNAL MEASUREMENTS.

The extracted Schottky diode model for both device 1 and device 2 was verified using large signal measurements. The large signal measurement system was calibrated to transfer the measurement reference plane to the probe tips for accurate measurements. A large signal with variable input power is injected through each Schottky varactor diode. The input signal frequency was 1 GHz and the diode was reverse biased at  $-1$  V. The power of the fundamental and the second harmonic were measured using the Microwave Transition Analyser

(MTA). The measured results are compared with the ADS<sup>TM</sup> harmonic balance (HB) simulation performed on the extracted model for device 1 and device 2.

The measured and simulated (using ADS<sup>TM</sup>) fundamental and second harmonic power of device 1 and device 2 are shown in Figure 12 and Figure 13 respectively.

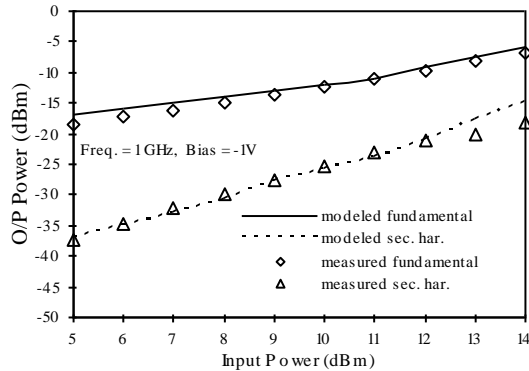


Figure 12 Measured and simulated fundamental and second harmonic powers for device 1 Schottky varactor diode.

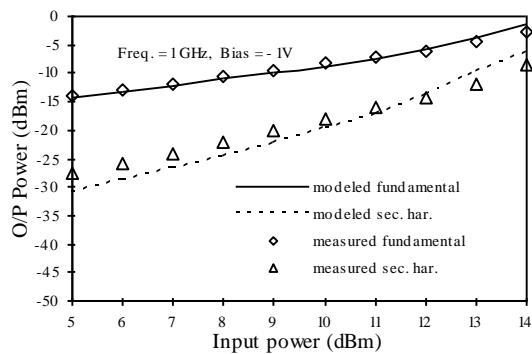


Figure 13 Measured and simulated fundamental and second harmonic powers for device 2 Schottky varactor diode.

Measurement shows good agreement with the simulated results for both device 1 and device 2 as shown in Figure 12 and Figure 13 respectively.

## VII. CONCLUSION

The non-linear equivalent circuit model for the Schottky varactor diode is extracted. This model is an important step in the design of the NLTL circuit which is used for pulse compression circuit applications.

Small signal measurements were bias dependent because the CV characteristics and the IV characteristics of the Schottky diode are bias dependent. The small signal measurements were bias dependent only up to  $-2$  V for both device 1 and device 2. This is because the depletion region is fully depleted for bias voltages larger than  $-2$  V, therefore equivalent circuit parameters become constant.

Device 2 shows stronger nonlinearities in the extracted parameters because of its delta doping profile compared to device 1 which uses a hyper-abrupt doping profile.

The extracted Schottky diode model for both diode types was verified to the actual Schottky diode device by large signal measurements. The measured and modelled results show good agreement indicating that the nonlinear circuit model for device 1 and device 2 was successfully extracted.

## VIII. ACKNOWLEDGMENT

This project has been supported financially by Solectron/C-MAC. The Schottky diodes were donated by Bookham and OMMIC.

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