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Frequency equivalent circuits for the on and off state of an optically triggered switch based on a PIN photodiode

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Abstract: In this work we have developed equivalent circuit models for the frequency response of an optically triggered switch based on a positive-intrinsic-negative photodiode (PIN-PD) for the On state (light applied to the PIN-PD) and the Off state (without applying light to the PIN-PD). From measurements it was found the frequency response in Off state behaves as a high-pass filter whereas in the On state as a low-pass filter; this means that depending on the input signal frequency there could be an approach or even an overlap between the output amplitude in the On and in the Off state. The developed models allow the calculation of the highest permissible frequency in the input signal to avoid distortion due to overlap of the On and Off state response, and the models take into account circuit parameters such as bias voltage, load resistance, resistance, and capacitance of PIN-PD, which in turn depend on the operating point and the desired linear range for the input's amplitude. Experimental measurements of the frequency response were made in both conditions (On and Off state) using three commercial photodiodes of bandwidth higher than 1 GHz. The measured frequency response as well as amplitude separation between the On and Off states to avoid the overlap is very well matched by the calculated results. Although the tests were performed for photodiodes with 1 GHz bandwidth, the technique can be applied for photodiodes with higher bandwidth.

Key words: Frequency response, photodiode, optical switch, optically triggered switch

1. Introduction

High-speed PIN photodiodes (PIN-PD) are essential components for analogue photonic applications such as software defined radios [1,2], antenna arrays [3], photonic analogue-to-digital converters [4–6], photonic oscillators [7], and photonic down-converters [8]. Optically triggered switching circuit is the principal configuration for the PIN-PD since they have the potential to improve many aspects of the system performance. Characteristics such as gain, noise figure, spurious free dynamic range, and frequency response can be defined by the switching circuit operation. In particular, frequency response is of the most important factors since it can define the bandwidth of the overall system and the output signal power for high frequencies [9]. The analogue input bandwidth of the PIN-based switching circuit is normally attributed to the response of extrinsic parasitic network and the intrinsic frequency response of the PIN-PD [10]. The intrinsic frequency response should offer the upper limitation of the bandwidth of the PIN-PD-based circuit, since the effect of a parasitic network can be reduced by elaborate design. Usually, the measured frequency response of a switching circuit must also

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include the effects of the packaging network, and the test fixtures. Hence, a realistic frequency response requires calibrations of the test fixtures and the packaging network [11,12].

A simple PIN-PD-based optically triggered switch is shown in Figure 1. The input signal is connected in series with the PIN-PD and a load resistor R_L. The dc voltage V_{bias} is applied to bias the photodiode, and the signal $V_{in}(t)$ is superimposed on V_{bias}. To operate the PIN-PD as an analogue switch the applied V_{bias} and the selected R_L must be able to operate the photodiode in the fourth quadrant of its I-V curve [13]. The chosen V_{bias} must be large enough to prevent the switched signal swings going to the forward conduction region. If a portion of the switched signal penetrates the forward region a nonlinear distortion will appear [14]. Different techniques to select an appropriated dc V_{bias} to prevent this nonlinear distortion have been previously reported [15,16]. On the other hand, in the switching circuit, the reverse biased PIN-PD acts as a fast normally off switch where the On state is established by light impinging on its photosensitive surface. Thus, in the absence of any light, the PIN-PD is in the Off state or high-impedance state. The Off state can be modeled by a large resistance ($\sim 10^6\,\Omega$) shunted by a small capacitance ($\sim$ 10 pF) whereas in On state the resistance becomes very small, of the order of a few ohms, and the capacitance becomes large (approximately microfarads) [16]. In the present study, the effect of the On and Off state in the frequency response was determined and a simplified expression was derived to calculate the highest permissible frequency in the RF input signal to avoid distortion due to the frequency response of the On and Off state. Theoretical results from modeling the frequency response in the On and Off states were experimentally verified with practical measurements obtained from a switching circuit implemented with a commercial PIN-PD.

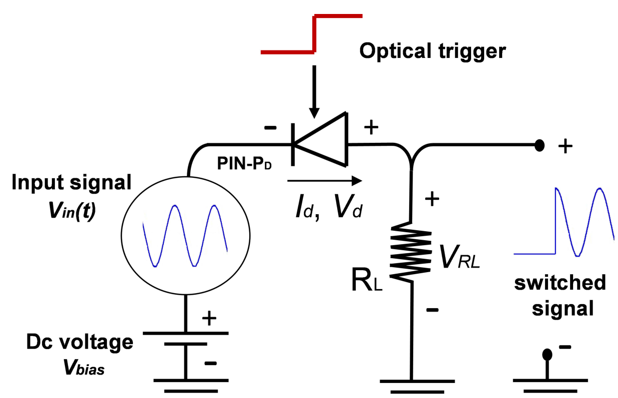

Figure 1. Optically triggered switch based on a PIN photodiode.

2. Operating point for the optically-triggered switching circuit

In the PIN-PD-based optically triggered switch in Figure 1, the dc bias voltage V_{bias} and load resistor R_L enable the photodiode to work in an operating point in which the electric current across it depends on the applied optical power P. Hence, the switching function is controlled by applying P in the PIN-PD. Figure 2 shows a measurement of the I-V curve in its fourth quadrant for a Si PIN-PD with a reverse saturation current $I_{sat} = 0.5$ nA, responsivity $R = 0.37$ A/W at a wavelength of 660 nm, for applied optical powers $P = 10$ mW and $P = 0$ mW. To guarantee a linear range for the peak-to-peak voltage of input signal (V_{ipp}), an operating point for the PIN-PD can be selected following the procedure explained in [13]. For example, for a linear range of $V_{ipp} = 300$ mV using an operating point at $V_d = 0.633$ V and $I_d = 2.076$ mA for a $P = 10$ mV, $k = 23.63$

is calculated from $I_d = -I_{sat}\left(e^{kV_d} - 1\right) + I_{ph}$, where $I_{ph} = PR$ is the photogenerated current, $I_{ph} = 3.652$ mA, as can be seen in Figure 2. The ideality factor $n = 1.636$ is calculated using the equation $n = q/(k_B T k)$, and the photodiode small-signal resistance $R_d = 26.84\ \Omega$, load resistance $R_L = 1\ \mathrm{k}\Omega$, and $V_{bias} = 1.4$ V were calculated using (1), (2), and (3), respectively

$$R_d = \frac{1}{kI_{sat}e^{kV_d}} \tag{1}$$

$$R_L = \frac{5kV_{ipp} - 1}{kI_{sat}e^{kV_d}} \tag{2}$$

$$V_{bias} = \frac{(5kV_{ipp} - 1)\left[-I_{sat}\left(e^{kV_d} - 1\right) + I_{ph}\right]}{kI_{sat}e^{kV_d}} - V_d \tag{3}$$

3. Measurements of the frequency response for the On and Off state

To measure the frequency response of the On and Off state of the switching circuit, we used the S-parameter network analyzer 8753ES. The experiment setup and test fixtures are shown in Figure 3. The Bias-T at the input was used to superimpose the sinusoidal voltage signal on V_{bias} and the Bias-T at the output was used to prevent the load resistor effect in the PIN-PD. Three photodiodes were used to test the setup of Figure 3; the relevant photodiodes characteristics are shown in the Table. To guarantee a peak-to-peak range of linear excursion of V_{ipp}= 500 mV for the input signal an operating point valid for the three photodiodes was established using the procedure explained in [13].

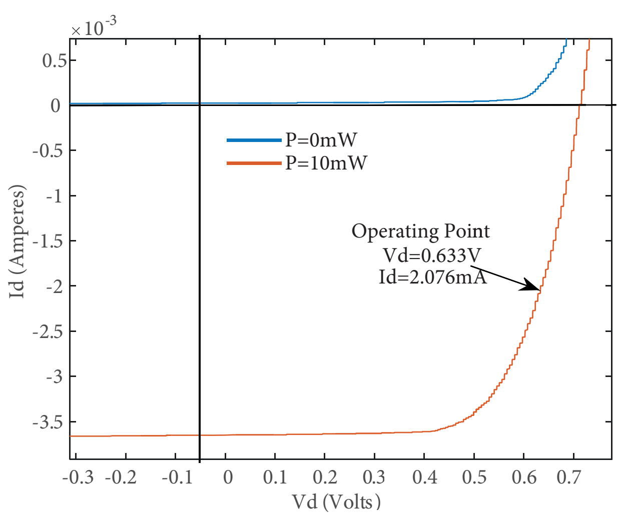

Figure 2. Measured I-V curve of a PIN-PD based optically-triggered switch showing a selected operation point.

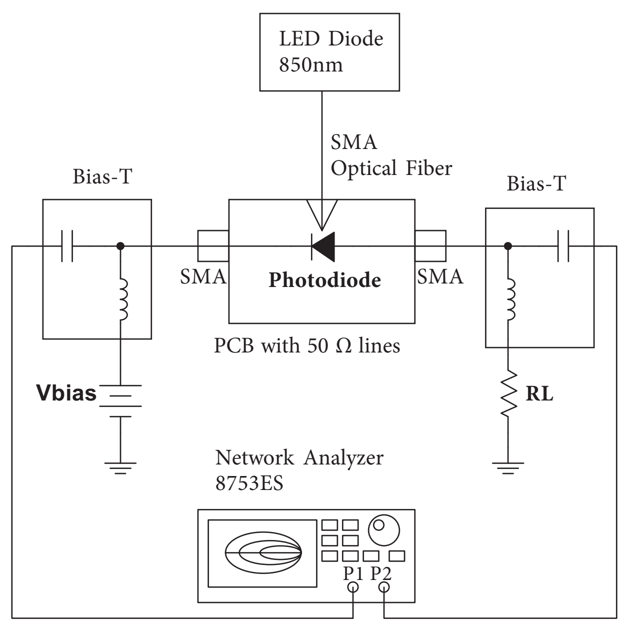

Figure 3. Setup and test fixtures to obtain the frequency response of the switching circuit.

Figure 4 shows the magnitude of the scattering parameter S21 as a function of frequency for the On state (with applied light) whereas Figure 5 shows the magnitude of S21 for the Off state (without applied light).

Table. Characteristics of the tested PIN-PDs.

Identifier	Material, device, and manufacturer	Model	Specification
PD1	InGaAs, PIN-PD, AC Photonics	PTD2A2211	Minimal fc > 1 GHz, Responsivity $R = 0.55$ A/W, Dark Current Is = 100 pA
PD2	Si, PIN-PD, Thorlabs	FDS025	Minimal fc > 1 GHz, Responsivity $R = 0.48$ A/W, Dark Current Is = 35 pA
PD3	InGaAs, PIN-PD, Thorlabs	FGA01	Minimal fc > 1 GHz, Responsivity $R = 1$ A/W, Dark Current Is = 50 pA

The frequency is shown in logarithmic scale for frequencies from 45 MHz to 4 GHz. From the On state plot, it is observed that the cutoff frequency of the photodiodes is slightly above 1 GHz, which is consistent with information given by the manufacturer. In addition, from the plot of the Off state it is observed that as the frequency increases the magnitude of the output of the circuit also increases.

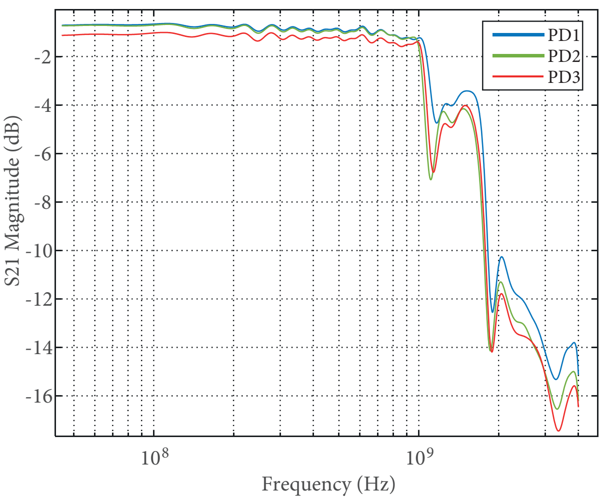

Figure 4. Frequency response in the On state for three tested PIN-PDs.

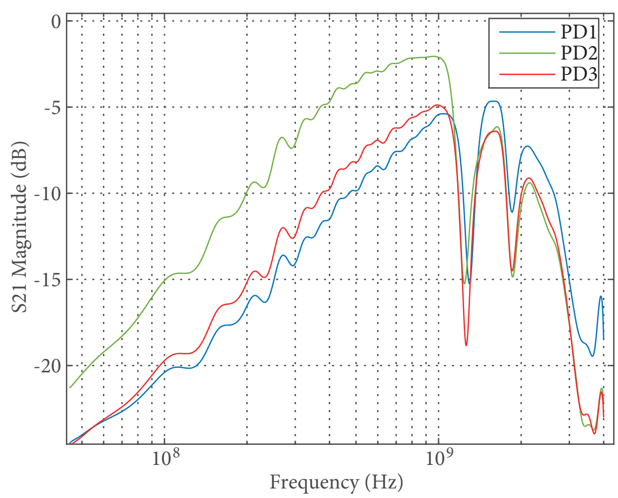

Figure 5. Frequency response in the Off state for three tested PIN-PDs.

4. Circuit modeling of the frequency response for the On and Off state

The equivalent circuit of the switching circuit in the On state is shown in Figure 6. It takes into accounts the junction capacitance C_{don} and the small signal resistance of the photodiode, R_{don}. In the On state, R_{don} depends on the operating point given by the bias voltage V_{bias} and the load resistor R_L as described in [13]. The capacitance can be obtained from the measurement of the frequency response; V_{db} represents the photodiode dc voltage. To calculate the frequency response of the circuit, all dc sources are equaled to zero, leaving only the input signal source V_{in}. The transfer function (TF) of the circuit in the On state is similar to a first order low-pass filter. Taking $a_{on} = 1/(C_{don}R_{don})$ and $b_{on} = (R_{don} + R_L)/(C_{don}R_{don}R_L)$ the TF is given in standard form by (4):

$$\frac{V_{RL}(s)}{V_{in}(s)} = \frac{a_{on}}{s + b_{on}} = \left(\frac{a_{on}}{b_{on}}\right)\left(\frac{b_{on}}{s + b_{on}}\right) \tag{4}$$

From (4) the cutoff frequency is obtained as the value where the amplitude of the output has an attenuation ratio of $1/\sqrt{2}$ and is given by (5):

$$\omega_c = \frac{R_{don} + R_L}{R_{don} R_L C_{don}} \tag{5}$$

On the other hand, the cutoff frequency of the switching circuit can be obtained from an actual measurement of the frequency response, as shown in Figure 4. Hence, we can solve (5) for the capacitance as $C_{don} = (R_{don} + R_L)/(R_{don} R_L \omega_c)$.

In addition, C_{don} can be calculated for a frequency less than the cutoff frequency using the factor $1/m$ instead of $1/\sqrt{2}$, as $C_{don} = \frac{R_{don}+R_L}{R_{don} R_L \omega}\sqrt{m^2-1}$. For example, for a frequency value f = 0.989 GHz, $R_{don} = 345$ Ω, and $R_L = 4$ kΩ, it is obtained a $m = 1.054$ and a $C_{don} = 0.16895$ pF.

In the case of the Off state, the equivalent circuit can be represented as a high-pass filter, as shown in Figure 7. Similar to the On state, to calculate the frequency response of the circuit, all dc sources are equaled to zero, leaving only the input signal source V_{in}. C_{doff} and R_{doff} represent the junction capacitance and small resistance in the Off state. The TF is given in standard form by taking $a_{off} = 1/(C_{doff} R_{doff})$ and $b_{off} = (R_{doff} + R_L)\Big/(C_{doff} R_{doff} R_L)$ as seen in (6).

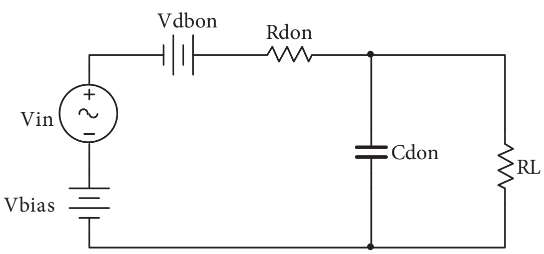

Figure 6. Equivalent circuit for the switch in the On state.

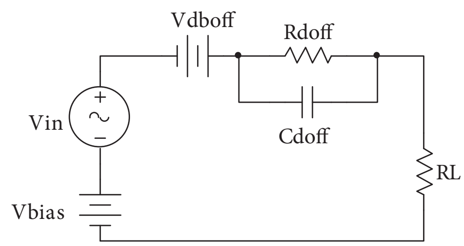

Figure 7. Equivalent circuit for the switch in the Off state.

$$\frac{V_{RL}(s)}{V_{in}(s)} = \frac{s + a_{off}}{s + b_{off}} \tag{6}$$

Using (6) the frequency value for specific amplitude at the output can be obtained as (7), where 1/m represents the amplitude attenuation for a specific frequency

$$\omega = \sqrt{\frac{\left(\frac{R_{doff}+R_L}{R_{doff} R_L C_{doff}}\right)^2 - m\left(\frac{1}{C_{doff} R_{doff}}\right)^2}{m^2 - 1}} \tag{7}$$

From the measurement of the frequency response in the Off state (Figure 5), we took the value of frequency that has the biggest amplitude at the output before reaching the cutoff frequency of the On state and we solved (7) for the capacitance. For example, for a frequency f = 0.855 GHz, $R_{off} = 183.79$ $k\Omega$ and $R_L = 4k\Omega$ we obtained $C_{doff} = 0.030185$ pF. From the previous analysis we can observed that the values for the small-signal resistance R_d and the junction capacitance C_d are different for the On and Off state circuit models.

5. Results from applying models and measurements comparison

Figure 8 shows a comparison between the measured and calculated frequency response of the photodiode PD1 for the On state and the Off state. It is observed that the calculated response agrees well with the measured response up to the cutoff frequency.

Ideally, the amplitude value in the Off state should be 0 V and should not increase when frequency increases but the measurements in Figures 5 and 8 show that the amplitude in the Off state increases as the frequency increases (high-pass behavior). In Figure 8 it is observed that the amplitude in the Off state is –27.8 dB at f = 45 MHz; this is less than 5% the amplitude of the On state at that same frequency. Figure 9 shows an example of a simulated response of the switching circuit taking into account the dc offsets; for Figure 9 we used a $V_{bias} = 1$ V, frequency f = 500 MHz, and peak-to-peak sinusoidal input signal $V_{ipp} = 500$ mV. The output signal in the On and the Off state (V_{RLon} and V_{RLoff}) is also shown in Figure 9. The offset of the voltage at the load resistor (V_{RL}) in the On state is $V_{bias} + V_d = 1$ V + 0.484 V = 1.484 V whereas in the Off state it is 0 V. In addition, the separation between V_{RLon} and V_{RLoff} is also shown. Similarly, Figure 10 shows another example of the simulated response, this time for a $V_{bias} = 0.45$ V, f = 900 MHz, $V_{ipp} = 700$ mV. The offset of the voltage at the load resistor (V_{RL}) in the On state is 0.934 V whereas in the Off state it is 0 V.

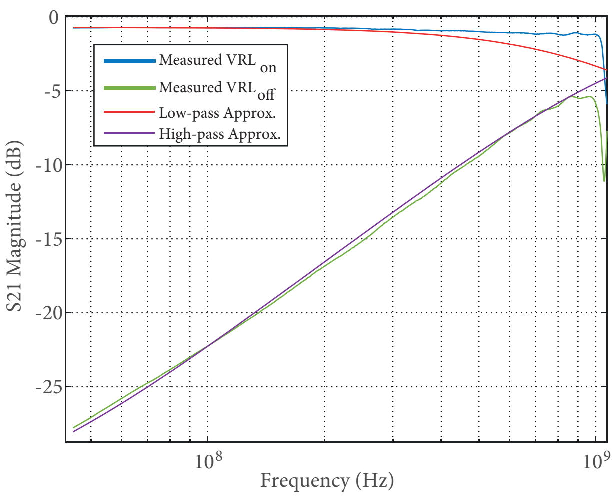

Figure 8. S21 magnitude vs. frequency, measurements, and approximations in the On and Off states.

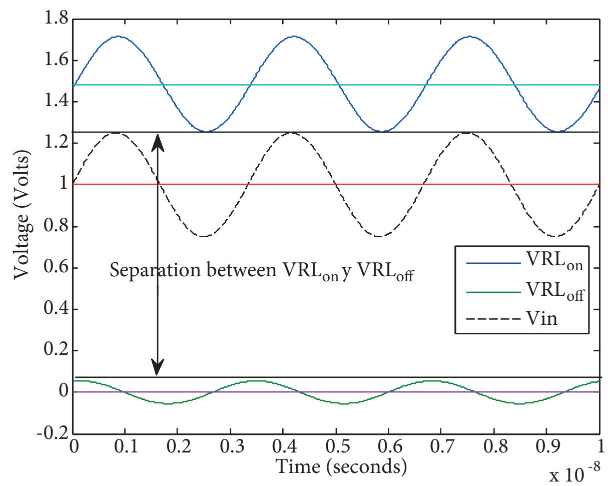

Figure 9. Simulated V_{RL} in the On and Off states and V_{in} for f = 500 MHz, $V_{bias} = 1$ V, and $V_d = 0.484$ V.

From Figures 9 and 10 it can be seen that separation is smaller in Figure 10 than in Figure 9. This is because V_{ipp} is greater than in Figure 9, because V_{bias} is smaller than in Figure 9, and because f is greater than in Figure 9. Increasing the frequency of the input signal V_{in} or decreasing the magnitude of V_{bias} reduces the separation between V_{RLon} and V_{RLoff}. Hence, depending on V_{bias} and the frequency of the input signal, V_{RLon} and V_{RLoff} can get close to each other and or even overlap, which could generate distortion in the switched signal.

Using the low-pass approximation (4) and high-pass approximation (6), and taking into account the dc offsets, the separation between the output in the On and Off states can be obtained as (8):

$$sepa = V_{bias} + V_d - V_{ip}\left(\frac{\sqrt{a_{on}^2}}{\sqrt{\omega^2 + b_{on}^2}} + \frac{\sqrt{\omega^2 + a_{off}^2}}{\sqrt{\omega^2 + b_{off}^2}}\right) \tag{8}$$

In (8), a_{on} and b_{on} refer to the circuit's parameters in the On state and the a_{off} and b_{off} to the circuit's parameters in the Off state; V_{ip} is the peak value of the input voltage. Figure 11 shows a comparison of the measured output voltage in the On and Off states and the approximation values calculated using (4), (6), and

(8); the units for the separation are Volts whereas the frequency response is in peak to peak Volts. From Figure 11 it is observed that the separation in V_{RL} due to the frequency response in the On state and the Off state is greater than 1 V even at the cutoff frequency, where it is close to the value of V_{bias} (1 V). In this case there will be no overlap distortion in V_{RL} when the circuit is switched from On to Off or vice versa by applying optical power in the PIN-PD. This shows us the importance of choosing an appropriate point of operation because if V_{bias} were a smaller value the separation between the On and Off signals would be smaller too.

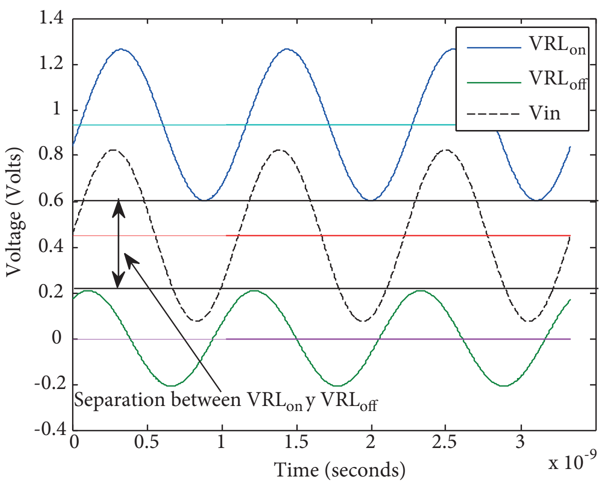

Figure 10. Simulated V_{RL} in the On and Off states and V_{in} for f = 900 MHz, V_{bias} = 0.45 V, and V_d = 0.484 V.

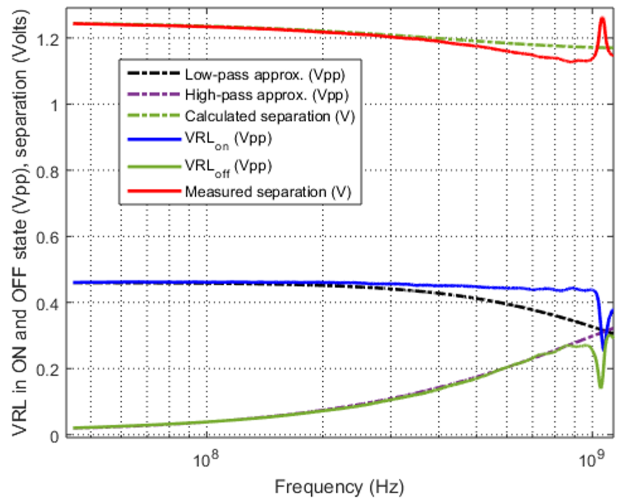

Figure 11. Comparison of the measured output voltage in the On and Off states and the approximations values calculated using (8).

6. Discussion and conclusions

In this work we have analyzed the frequency response in the On and Off state of an optically triggered switching circuit based on a PIN photodiode. Measurements of the frequency response were performed in the On state and Off for three commercial photodiodes. It was found they have the same behavior, that is in the Off state, as increasing the frequency of the input the output amplitude increases too, i.e. has a behavior as a high-pass filter whereas in the On state has the usual behavior of low-pass filter. Because of these behaviors the output amplitude in the On and Off state might get close to each other or even overlap for a certain frequency and this situation must be prevented since an ideal switching circuit must avoid the input signal pass to the output when it is in the Off state.

From the measurements, we made circuit models for the frequency response in the On state and in the Off state. These are first-order models and this allows us to easily relate the models to the photodiode capacitance, photodiode resistance, and load resistance. The models take into account the parameters of the switching circuit, V_{bias}, R_L, and R_d, which in turn depend on the operating point and the desired linear range for the input's amplitude (as described in [13]); also from the measurements, equivalent capacitance was obtained for circuit models.

The circuit models were compared with the actual measurements of frequency response using the photodiode that had the best response of the three tested photodiodes. It is shown that the models agree well with measurements until the cutoff frequency of the On state as seen in Figure 8. However, in order for the models to match more accurately the behavior of the response up to the cutoff frequency, higher order approximations would have to be used.

In addition, (8) was developed to calculate the separation between the output's amplitude in the On and Off state; (8) can be numerically solved for a given frequency value. The intention is the circuit designer can calculate the separation between the amplitude in the On state and the amplitude of the Off state; hence, the designer can decide on the maximum usable frequency according to a particular application.

The study explained in this paper complements the study done in [13], so the designer can choose an operating point given by V_{bias} and R_L complying with a desired linear input range and also that meets a proposed frequency response that avoids overlap of the output's amplitude in the On and Off states. Although the measurements and modeling were performed for photodiodes with 1 GHz bandwidth, the technique used can also be applied for photodiodes with higher bandwidth.

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