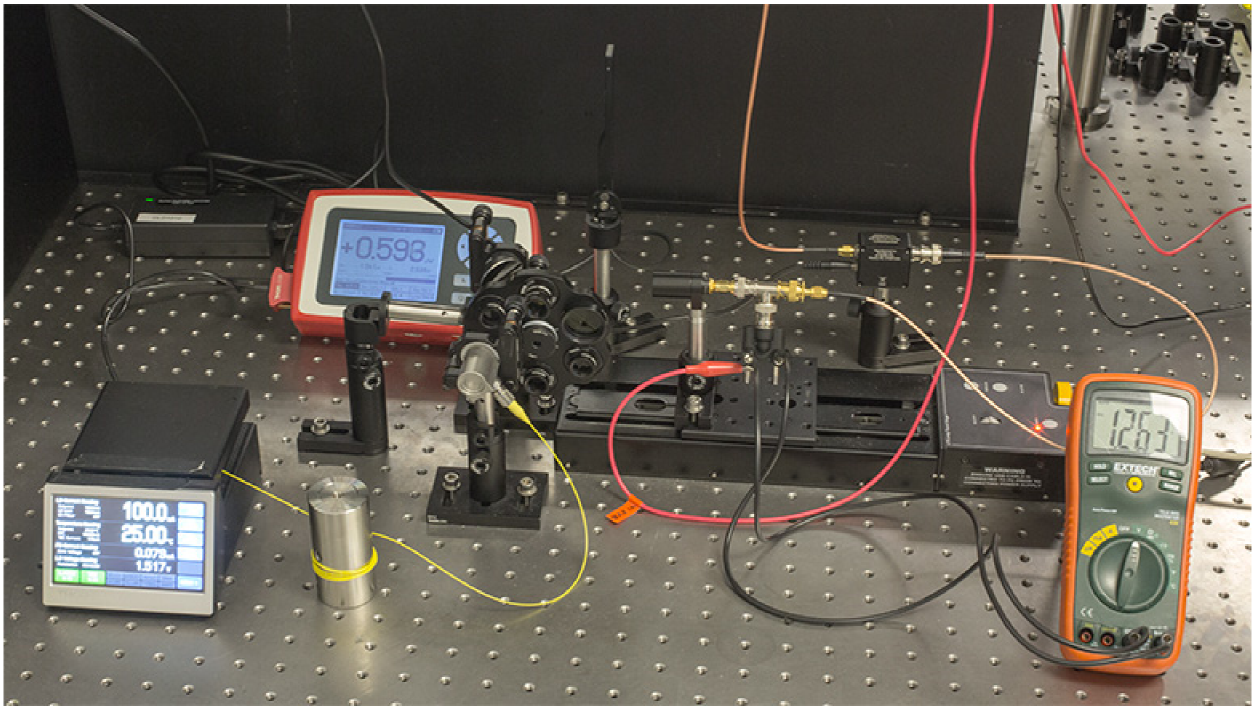
THORLABS

Lab Fact



Effects of Incident Optical Power on the Effective Reverse Bias Voltage of Photodiodes

This Lab Fact demonstrates how the effective reverse bias voltage on a photodiode can vary as a function of the incident CW optical power. This effect is important to consider if one is trying to maintain constant bandwidth or rise time performance of a photodiode, as both are functions of effective reverse bias.

Part 1. Theory

Figure 1, below, depicts a representative photodiode circuit, which consists of a voltage source (V_0), a bias module that includes an RC protection circuit comprised of a resistor (R_p) and a capacitor (C_p), a photodiode, as well as a terminating load resistor (R_L). The detection circuit would typically be used by measuring the voltage drop V_L across R_L with an oscilloscope or voltmeter. If no physical load resistor has been used in the circuit, the load resistor will be equivalent to the input impedance of the measurement device.

In this circuit, the voltage source supplies the initial voltage V_0. Considering the circuit as a whole, the initial voltage is equivalent to the sum of the voltage drops across the resistive components in the circuit ($V_P + V_L$) and the effective voltage applied to the photodiode, V_{eff}:

$$V_0 = V_P + V_L + V_{\text{eff}}. \qquad (1)$$

Rearranging terms, the effective bias voltage applied to the photodiode is the difference of the initial voltage and the sum of the aforementioned voltage drops:

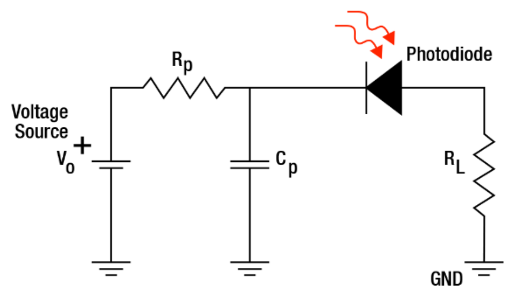


Figure 1: Representative Circuit of a Biased Photodiode

$$V_{\text{eff}} = V_0 - (V_L + V_{\text{P}}). \qquad (2)$$

This Lab Fact will only consider a continuous wave (CW) optical signal and constant initial voltage, so the capacitor can be ignored. The capacitor can be treated as a broken wire because current ceases to flow through the capacitor after it has fully charged.

The voltage drops across the resistive components in the circuit are dependent on the current in the circuit. In the representative circuit, the photodiode generates the photocurrent i_{PD}; Ohm's law ($V = iR$) can be used to rewrite Eq. 2:

$$V_{\text{eff}} = V_0 - i_{PD} * (R_P + R_L). \qquad (3)$$

Generated photocurrent is a function of the wavelength-dependent responsivity, $\Re(\lambda)$, of the photodiode and the optical power incident on the photodiode's active area, P:

$$i_{PD} = \Re(\lambda) * \text{P}. \qquad (4)$$

Responsivity is typically provided in units of Amps/Watts, allowing the incident optical power in Watts to be converted into the output electrical signal in Amps. Other components within the detector circuit and measurement device could cause the actual performance to differ from the ideal responsivity of the photodiode, so the generated photocurrent will instead be calculated from a direct measurement of the voltage drop across the load resistor:

$$i_{PD} = V_L/R_L. \tag{5}$$

Eq. 3 can then be rewritten as:

$$V_{\text{eff}} = V_0 - \frac{V_L}{P}\frac{P}{R_L}(R_P + R_L) \tag{6}$$

to provide an expression relating the effective bias voltage to both incident optical power and the measured voltage drop. Assuming the incident optical power is within the linear range of the photodiode, the generated photocurrent will vary linearly with changes to the incident optical power, and slope can be defined as:

$$m = \frac{\Delta V_L}{\Delta P}. \tag{7}$$

Substituting Eq. 7 into Eq. 6 yields:

$$V_{\text{eff}} = V_0 - m\left[\frac{P}{R_L}(R_P + R_L)\right] \tag{8}$$

which is an expression for the expected change in effective bias voltage versus incident optical power.

Part 2. Experiment

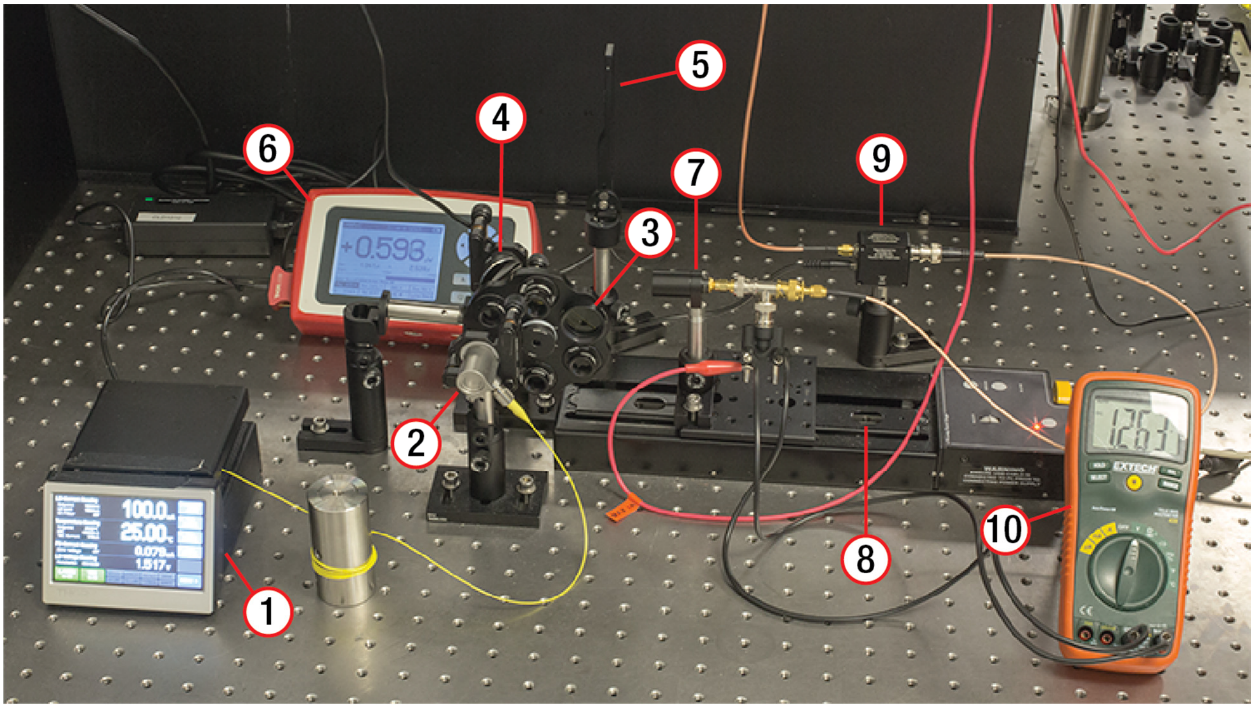


Figure 2: Experimental Setup with Labels
(Not Pictured: Instek GPS-4303 Voltage Source and Agilent DSO-X 3104A Oscilloscope)

1. CLD1010LP Laser Mount and Driver with TEC (LP915-SF40 Fiber-Coupled Laser Diode Mounted Internally)
2. RC04FC-P01 Reflective Collimator
3. FW1AND Filter Wheel (Filters Listed in Table Below)
4. MPD254508-90-P01 Off-Axis Parabolic Mirror
5. S130VC Slim Power Sensor
6. PM100D Power Meter
7. Device Under Test (SM05PD1A, SM05PD5A, or SM05PD6A)
8. LTS150 Translation Stage
9. PBM42 Bias Module
10. Extech 430 Multimeter

The optical signal was supplied by an LP915-SF40 fiber-coupled laser diode in a CLD1010LP laser mount and driver with TEC. The photodiode devices under test (DUT) were SM05PD1A, SM05PD5A, and SM05PD6A. These photodiodes were chosen as representative photodiodes for Si, InGaAs, and Ge, respectively. The bias voltage was applied to the photodiode DUT using a PBM42 bias module, which has a 1 kΩ resistor as part of an RC protection circuit. The voltage source used was an Instek GPS-4303 benchtop power supply. The oscilloscope used was an Agilent DSO-X 3104A. The multimeter used was an Extech 430.

The TEC of the CLD1010LP was set at 25 °C. For tests with the SM05PD1A, the laser diode was driven at 80 mA, which provided an output power of 21.9 mW. For tests with the SM05PD5A and SM05PD6A, the laser diode was driven at 100 mA, which provided an output power of 30.2 mW. The light from the laser diode pigtail was collimated using an RC04FC-P01 reflective collimator and sent through various combinations of ND filters mounted in an FW1AND filter wheel. This method of changing the incident optical power was chosen over changing the drive current on the CLD1010LP because the latter would require lowering the drive current near the lasing threshold of the laser for lower power measurements.

Two sets of ND filters were used: one set for SM05PD1A and one set for SM05PD5A/SM05PD6A. Due to a higher maximum bias voltage than the other photodiodes, the SM05PD1A had a higher saturation point and larger linear operating range that required a broader range of optical powers to test.

The ND filters were individually selected with 3 criteria. First, the power throughput from the ND filter with the lowest optical density (OD) was within the photodiode's linear operating region, prior to saturation. Second, the power using the highest OD ND filter resulted in a detectable signal that was within the linear region and above the noise floor of the oscilloscope. And third, an attempt was made to evenly space the power levels sampled between the minimum and maximum. Because of the wavelength dependency of ND filters, the OD and percent transmission of each filter were characterized experimentally. See Table 1 below for specific ND filters used and the incident power levels.

SM05PD1A		**SM05PD5A and SM05PD6A**	
Filter	**Power (mW)**	**Filter**	**Power (mW)**
NE513A	1.416	**NE520A**	1.50
NE510A	4.13	**NE513A**	1.96
NE506A	6.24	**NE10A**	3.45
NE505A	7.67	**NE504A + NE505A**	4.48
NE504A	9.23	**NE510A**	5.71
NE502A	11.98	**NE506A + NE501A**	6.38

Table 1: List of Filter Combinations and their Resulting Power Incident on the DUTs

The MPD254508-90-P01 off-axis parabolic mirror (OAP) was placed after the ND filter wheel to focus the laser beam onto the photodiode active area. The photodiode was mounted on an LTS150 translation stage, in order to move each photodiode to a point along the optical axis where the beam's focused spot size was approximately 50% of the photodiode's active area. A spot size of Ø1.5 mm was used for the SM05PD1A and SM05PD6A and a spot size of Ø1 mm was used for the SM05PD5A. The spot sizes were calibrated using the LTS150 translation stage and a beam profiler. An S130VC slim power sensor connected to a PM100D power meter was placed between the OAP and the photodiode on a 90° flip mount to record the incident optical power for each measurement.

Channel 1 on the oscilloscope measured the voltage from the positive lead on the voltage source to the table ground in order to provide the initial voltage V_0 (Point 1 to GND in Figure 3). Channel 2 measured the voltage from the input of the photodiode to the table ground, represented by $V_{\text{eff}} - V_L$ (Point 2 to GND in Figure 3). The multimeter directly measured the effective bias V_{eff} across the photodiode (Point 2 to Point 3 in Figure 3). Channel 4 directly measured the voltage across the 50 Ω terminating load resistor, FT500, referred to as V_L (Point 3 to GND in Figure 3). Note that the effective voltage across the photodiode itself was not measured directly on the oscilloscope, as the grounds on the oscilloscope's channels were not isolated.

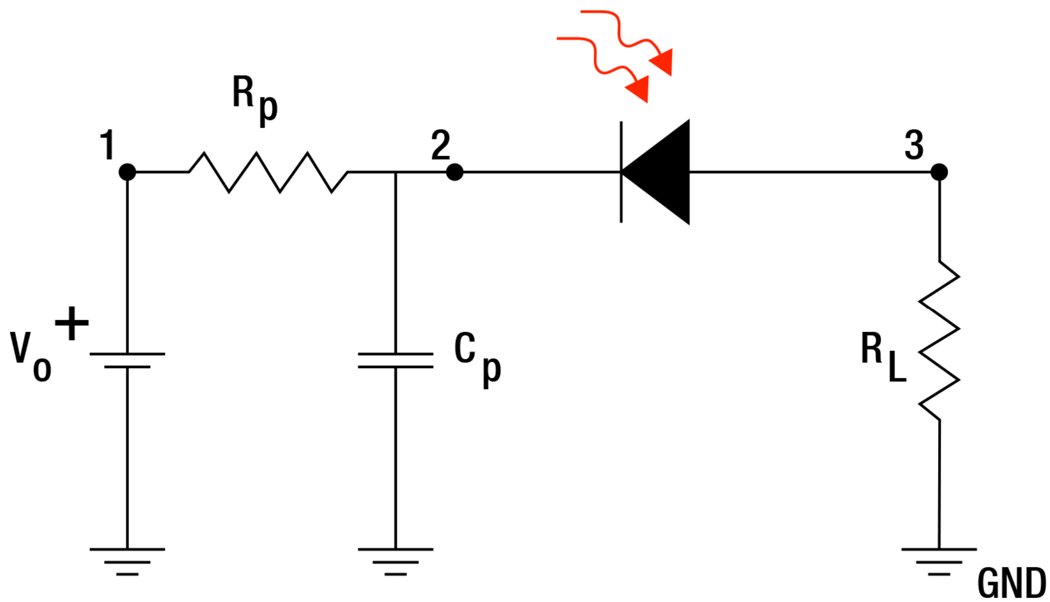


Figure 3: Representative Circuit with Measurement Points Noted

Before turning on the laser, "dark" measurements were taken across the 3 oscilloscope channels and the multimeter to account for any system noise by turning off the voltage source and blocking the photodiode. These values were subtracted from the measurements taken afterwards with the optical power incident on the photodiode. After unblocking the photodiode and turning on the voltage source, the optical power was then incrementally ramped up by cycling through ND filters with decreasing OD, while recording the voltages across the oscilloscope's 3 channels and the multimeter.

Part 3. Results

As mentioned in Part 1, the voltage data from Channel 4 (V_L) was plotted against the incident optical power P. We then applied a linear fit, where the slope of the fit was equivalent to m in Eq. 7.

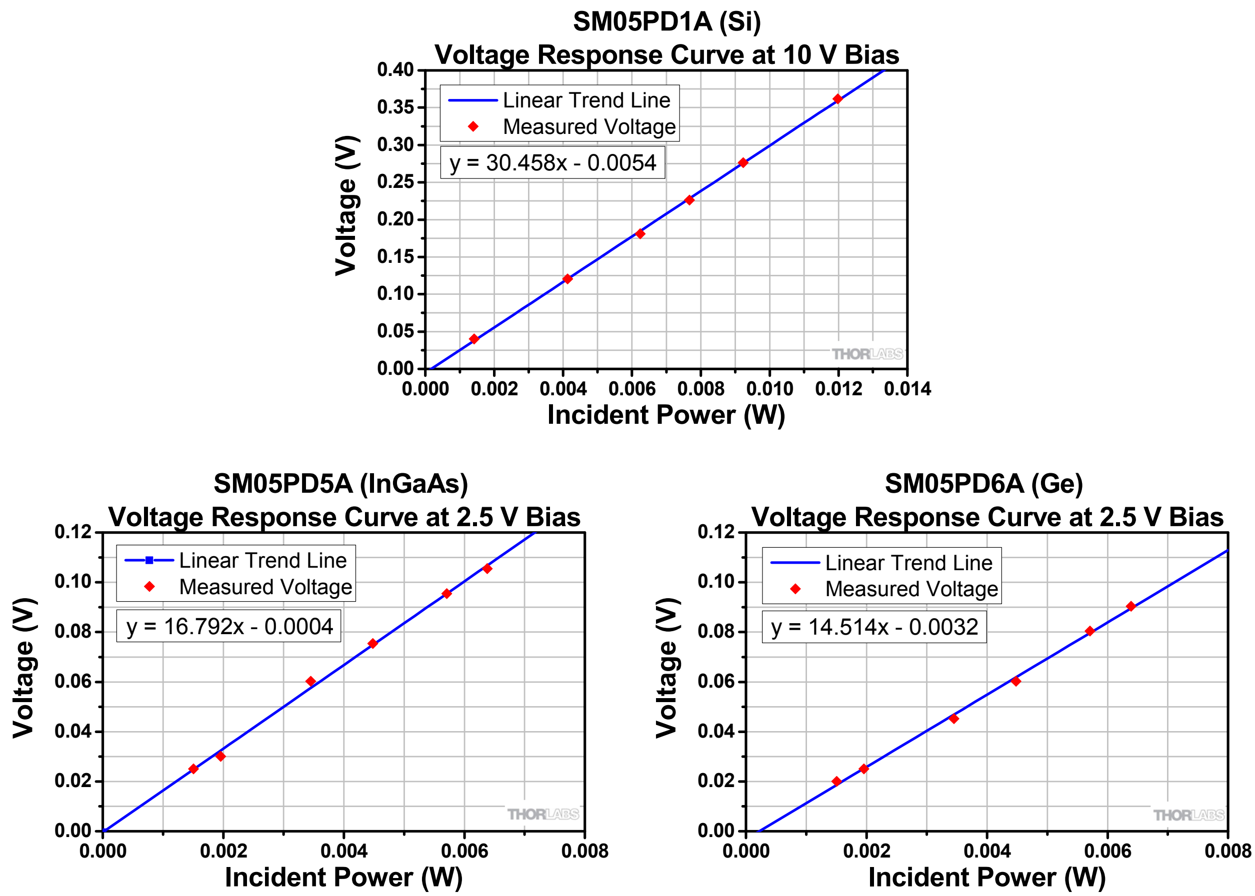


Figure 4: Voltage Across Load Resistor vs Incident Power on DUT for All Materials with Calculated Trend Line

Once the slope, m, was calculated for each photodiode, the expected values for V_{eff} were calculated using Eq. 8, which is rewritten below for convenience:

$$V_{\text{eff}} = V_0 - m\left[\frac{P}{R_L}\,(R_P + R_L)\right]. \quad (8)$$

Based on our setup, V_0 was the initial voltage, which was the difference between the reading on Channel 1 of the oscilloscope and the system noise; R_L and R_P were known values of 50 Ω and 1 kΩ, respectively; and P was the measured optical power. Figure 5 below shows the V_{eff} values measured directly on the multimeter plotted with the expected V_{eff} values calculated from Eq. 8.

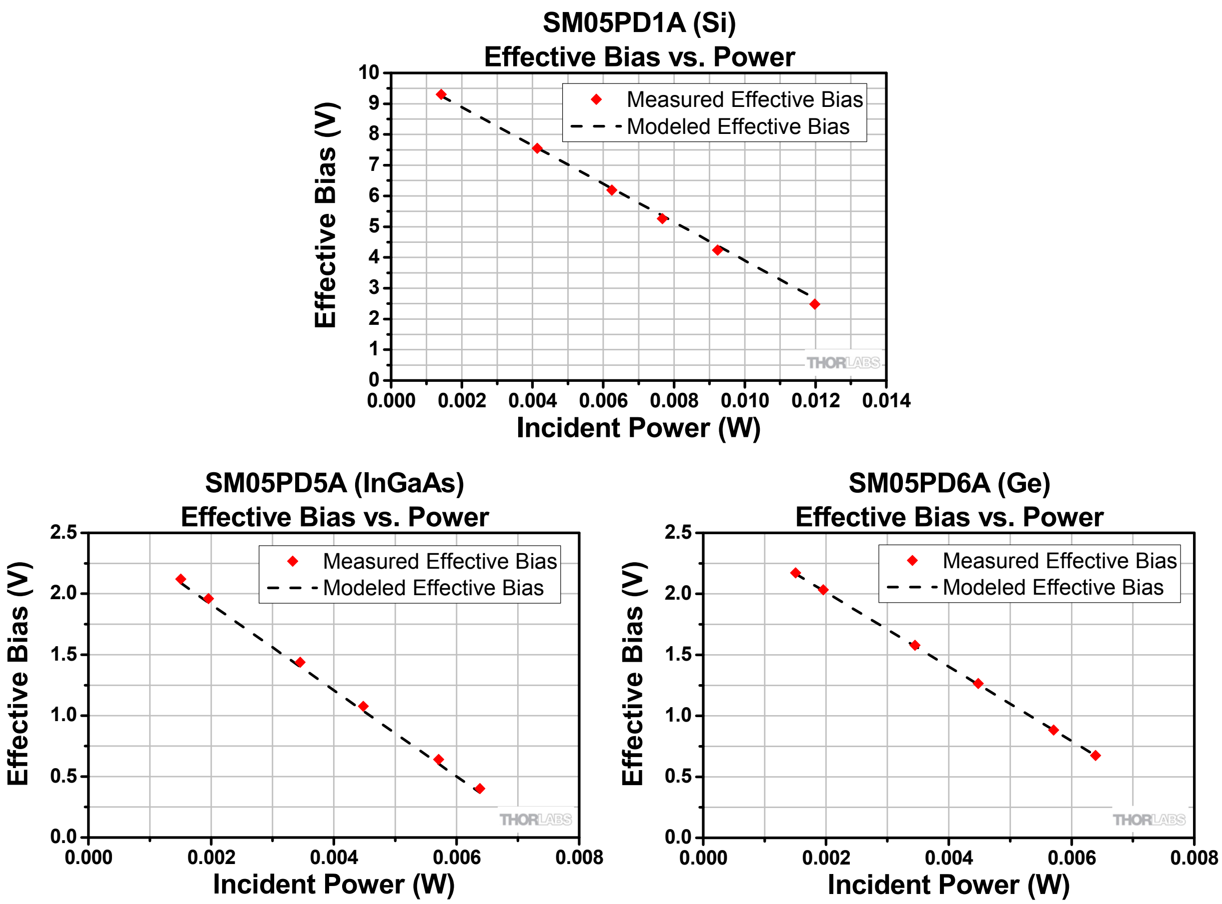


Figure 5: Measured Effective Bias Compared to Modeled Effective Bias vs. Incident Power on DUT for All Materials

The graphs show that with a fixed initial voltage from the voltage source, the effective bias voltage decreased as the incident power upon the photodiode increased. This is because as the power increased, the generated photocurrent also increased linearly, and thus produced larger voltage drops across the resistive components within the circuit. By Eq. 2, V_{eff} must decrease when V_L and V_P decrease.

This effect is significant because the voltage set at the voltage source is not necessarily the bias voltage applied to the photodiode. One must account for resistive components within the circuit to calculate the effective bias voltage applied across the photodiode.

Part 4. Limitations

The voltage drop across the resistor in the bias module, V_P, as well as the photocurrent, i_{PD}, generated by the photodiode were not measured directly. Instead, both were calculated using the measured contributions from the other circuit components. In addition, the tests for effective bias voltage vs power were conducted under CW conditions. No information was gathered for the model with the use of a modulated laser.