Characterization of the Avalanche Photo Diode Detector Used for Optical Communications Experiments With the Japanese ETS-VI

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The avalanche photo diode (APD) was used as the front-end light collector on the receiving telescope in a series of optical communications experiments. These experiments were conducted between October 1995 and May 1996 in two phases at Table Mountain, California, and utilized the Japanese Engineering Test Satellite (ETS-VI). Following the Phase 1 experiments, extensive laboratory testing of the APD module was carried out and the results documented here. Essentially, it is found that the APD provides a linear response profile between input light power and output voltage level over the expected operational range of from 2 to 20 nW. In addition, it was found that the APD used in the Phase 1 experiments yields a 1.75-MHz, 3-dB bandwidth. It was also found that a better gain distribution could be obtained by cascading the APD with a linear power amplifier. This extended the APD bandwidth to 3.75 MHz for the Phase 2 experiments. This improved gain distribution also results in improved optical receiver performance as characterized by the bit-error rate.

I. Introduction

From October 1995 through May 1996, a series of optical communications experiments was performed utilizing the Japanese Engineering Test Satellite (ETS-VI). The ground portion of these experiments employed the 0.61- and 1.22-m telescopes located at Table Mountain, California. A bit-error rate tester (BERT) provided the data stream that was used to modulate the transmit laser located in the 0.61-m telescope. The 1.22-m telescope acted as the Earth-based optical receiver. The light gathered at this telescope was focused on an avalanche photo diode (APD). The signal produced by the APD was amplified and fed into the receive BERT.

This article describes the results of a series of tests that was performed with the APD module following the completion of the Phase 1 satellite experiments. Two APD configurations are considered in this article. The first configuration consists of the APD module that was used during the Phase 1 experiment. The second configuration is a combination of the APD and a new amplifier stage that was used in the Phase 2 experiment.

II. Testbed Equipment Configuration

Three testbed configurations were used in this experiment. Diagrams of the different configurations are presented in Figs. 1 through 3. The setups were quite similar and so, in order to make it easier to note the differences, the components that were replaced remain in the diagram but are crossed out. Key elements common to all three configurations include the power meter probe 2 and the monitor APD. The power meter probe 2 was used for real-time monitoring of the light level reaching the APD under evaluation. The monitor APD was used to establish the bandwidth of the laser modulator.

Figure 1 shows the configuration used to calibrate the ratio of light levels between probes 1 and 2 of the light power meter. The configuration used to determine the bandwidth of the received signal is presented in Fig. 2. Figure 3 is a diagram of the configuration used to test the amplitude response of the received signal for varying light levels. Finally, Figure 4 shows the configuration used for bit-error rate (BER) testing. Details about the equipment used in the laboratory testing can be found in Table 1.

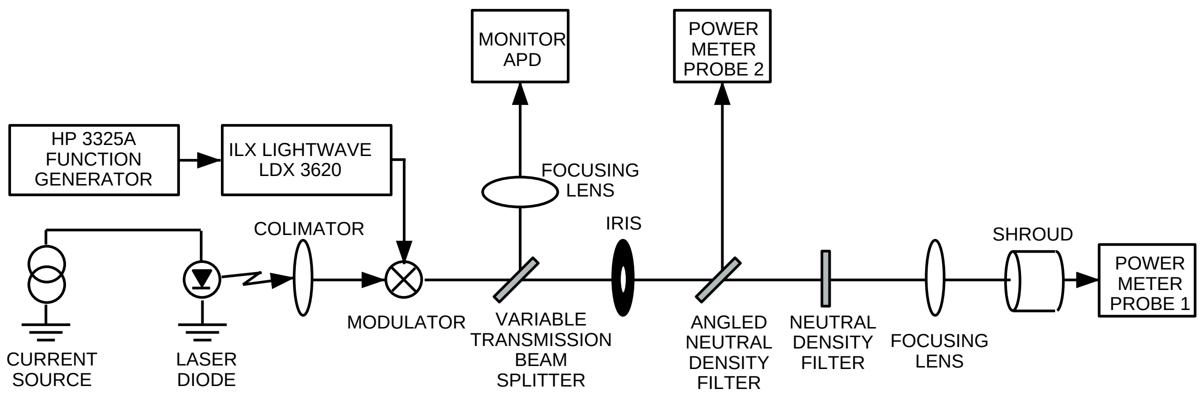

Fig. 1. The power meter probe and modulator frequency response calibration configuration.

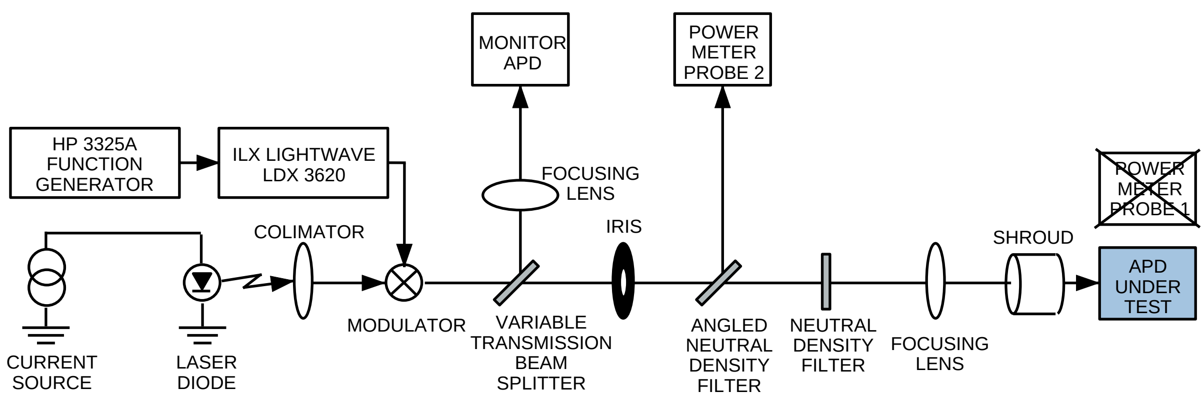

Fig 2. The APD frequency response configuration.

III. Testbed Calibration

Before any experiments were performed, it was necessary to calibrate the test setup being used. In this regard, there were two primary areas of interest. First, it was important to determine if any bandwidth limitations existed in the transmitted signal. Second, it was necessary to calibrate the laser light power readings so that a relatively precise estimate of the laser light collected by the APD could be provided.

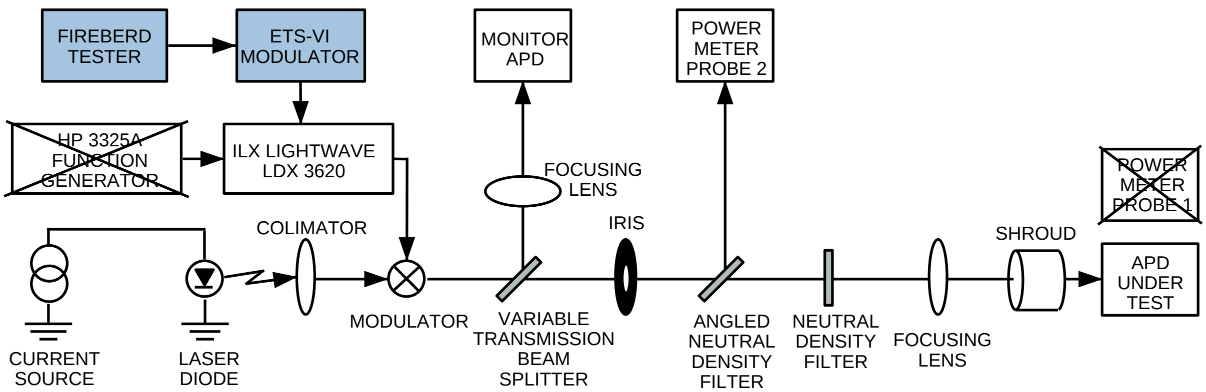

Fig. 3. The APD amplitude response configuration.

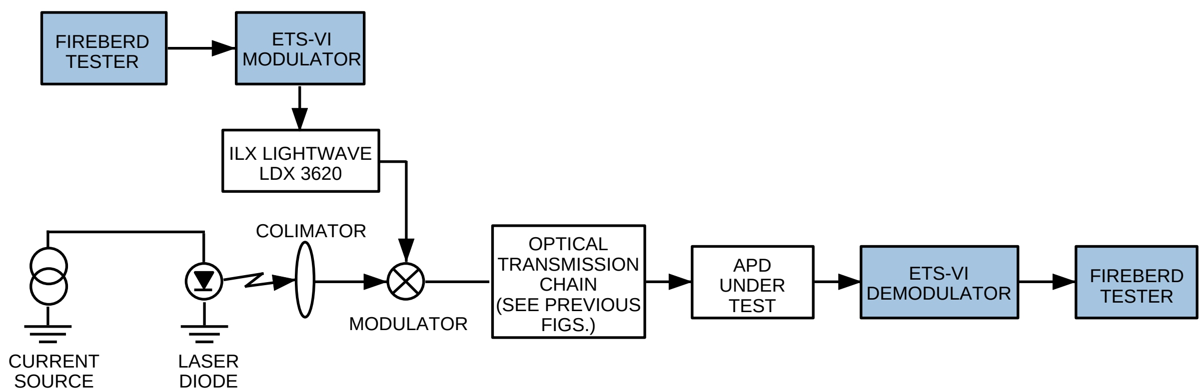

Fig. 4. The APD bit-error rate test configuration.

A. Light Power Meter Calibration

In order to obtain the most accurate light power meter readings, the responsitivity of the light power meter probes must be set prior to operation. For probe 1, the factory-provided responsitivity calibration factor is -1.593×10^{-1}, and for probe 2 it is -1.556×10^{-1}.

Using the test setup of Fig. 1, several readings of the light levels at probes 1 and 2 were taken. The room was darkened during the measurements to ensure that stray light did not cause false readings. Figure 5 shows a plot of the resulting measurements. The response appears to be largely linear, with a slope of approximately 2.518×10^{-3} μW/nW over the measurement region. This information is used when experimental measurements are taken. By multiplying the light power impinging on probe 2 by the slope, the power reaching the APD under test can be determined.

B. Transmitter Characterization With the Monitor APD

The final phase of the calibration was to characterize the modulation/transmitter portion of the test setup. The modulator was the same one used during field experimentation, a Conoptics Model 10. For this test, the variable transmission beam splitter was adjusted to maximize the light impinging on the monitor APD. The output voltage of the monitor APD was terminated with 50 Ω's and observed on an oscilloscope. Then, the frequency was changed, and the resultant peak-to-peak voltage was noted. The results of this test, provided in Fig. 6, show the 3-dB roll-off occurring at approximately 17 MHz. Since it is possible that the measurement equipment could be limiting the bandwidth of the signal, this value serves only as a lower limit for the bandwidth of the signal being transmitted. This bandwidth is adequate to determine the bandwidth of the receive APD.

Table 1. Test configuration equipment details.

Item (block label)	Manufacturer	Model no.	Serial no.	Notes
Current source	ILX Lightwave	LDX 3620	36201207	High bandwidth setting
Laser diode	Spectra Diode Labs	SDL2300	N/A	810 nm, 200 mW
Colimator	Melles Griot	4X	N/A	—
Function generator	Hewlett Packard	3325A	1748A04830	Delivers a sine wave from 0 to 1
Fireberd test set	Telecommunications Techniques Corp.	Fireberd MC6000	17402	Diphase card installed
Uplink modulator	JPL Satellite Communications Group	N/A	N/A	Bias set to 150 V
Modulator	Conoptics	10	765	10-MHz bandwidth
Monitor APD	N/A	ET200	N/A	—
Angled neutral density filter	N/A	N/A	N/A	3.0
Light power meter	United Detector Technologies (UDT)	S380	17874	–Measures watts at 633 nm –Accuracy: from 10 pW–10 mW is ±5% of reading –See probe 1 and probe 2 settings for further information
Light power meter probe 1	UDT	268R	16249	–Calibration 20169 –Responsitivity set to -1.593×10^{-1}
Light power meter probe 2	UDT	268R	16249	–Calibration 20169 –Responsitivity set to -1.556×10^{-1}
Neutral density filter	N/A	N/A	N/A	#2 0D2.0 1.0 bmm
APD under test	EG&G Optoelectronics Canada	C30872E	1366	Bias voltage set to -270 VDC

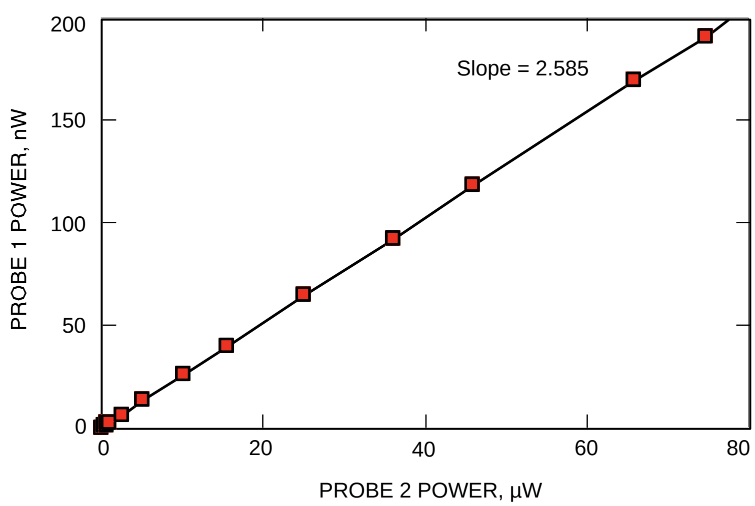

Fig. 5. Relative light power at probe 1 (nW) and probe 2 (μW).

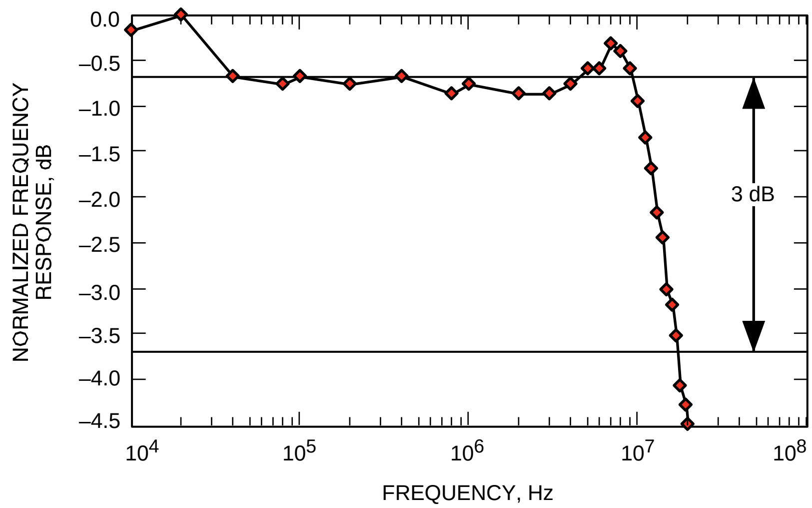

Fig. 6. The frequency response of the modulator section in the testbed.

IV. APD Module Characterization

The purpose of this section is to provide a characterization of the APD module that was used in the field during the Phase 1 experiments at Table Mountain. No attempt has been made to optimize either magnitude or frequency response. After the laboratory tests were completed, the feedback resistance for the APD amplifier was determined by direct measurement to be 2.51 MΩ.[1]

A. Frequency Response

Figure 2 shows the test setup used to determine the frequency response of the APD. Initially, a 10-kHz sine wave was output from the modulator. The variable transmission beam splitter was adjusted until the power level at probe 2 measured 10.1 μW, corresponding to an APD light level of about 26.21 nW. The peak-to-peak voltage at this frequency was noted. Then, the output voltage was measured for an increasing series of frequencies. The normalized results of this test (along with two other tests performed at differing power levels) are provided in Fig. 7. Note that as the signal magnitude decreased, the difficulty in measuring the signal amplitude increased due to a substantial drop in the signal-to-noise ratio (SNR). All curves in Fig. 7 show a 3-dB roll-off point to be at about 1.75 MHz, based on an initial normalized power level of -1.5 dB.

B. Amplitude Response

Figure 3 shows the test setup used to determine the amplitude response of the APD. For this test, a P_n sequence of length $2^9 - 1$ (511) bits was input to the transmitter at a data rate of 1,024,000 bps. This resulted in a laser signal modulated with a P_n sequence exhibiting square-wave characteristics. This is representative of the ETS-VI signal format. The light level to the APD was varied with the variable transmission beam splitter, and the light power at probe 2 was noted along with the peak-to-peak voltage output from the APD. To determine the actual light power at the APD, the probe 2 level was multiplied by 2.518×10^{-3}, as described in Section III.A. The results of this test are shown in Fig. 8. From this figure, it is apparent that there is a linear relationship between input light power and output voltage level.

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[1] The feedback resistance, along with the current sourced by the APD, determines the amount of gain the operational amplifier provides, according to the equation $A_V = -i_D R_F$, where R_F is the feedback resistance and i_D is the diode current.

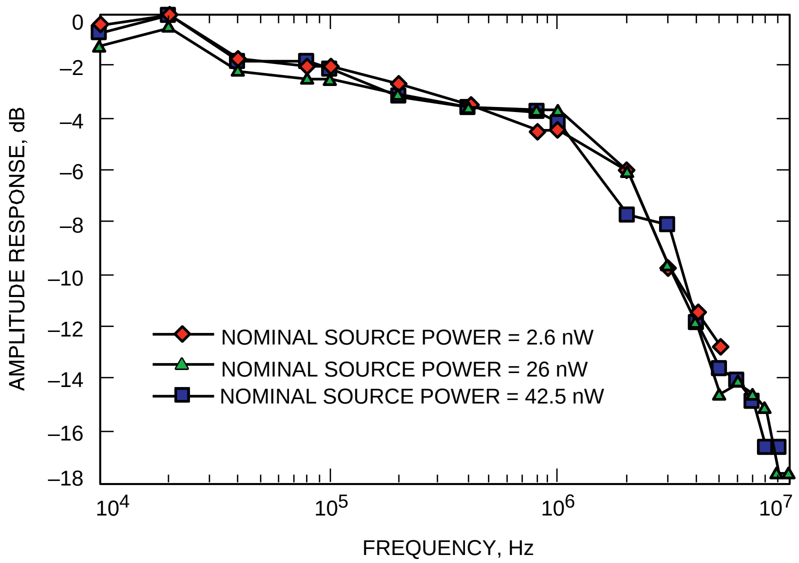

Fig. 7. The APD frequency response (gain set to maximum).

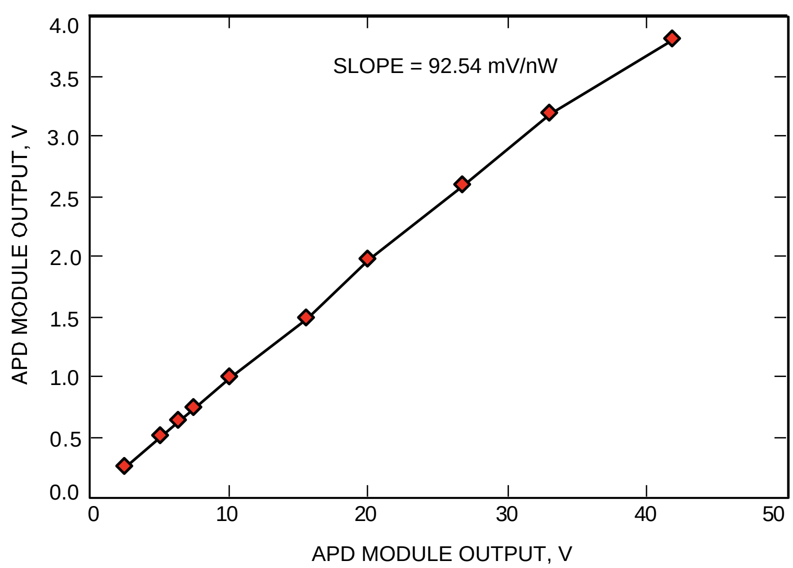

Fig. 8. The APD amplitude response.

V. APD With Amplifier Module Characterization

The frequency response results of the APD module set at high gain showed band limiting beginning at about 1.25 MHz. In an effort to extend the bandwidth of the receiver, the gain of the APD module was reduced by a factor of five, and an amplifier module was added to the telemetry chain after the APD module. The resultant frequency response is depicted in Fig. 9. The 3-dB roll-off point is at about 3.75 MHz. This represents an improvement in bandwidth of approximately 3.3 dB.

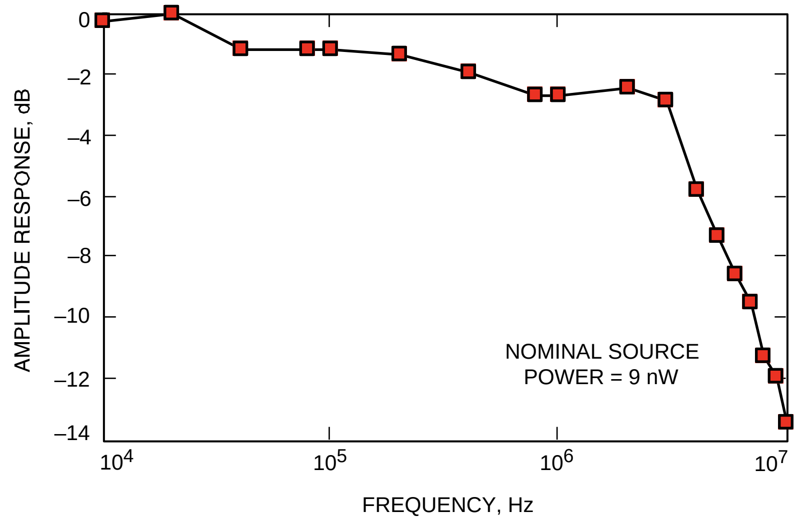

Fig. 9. The APD with amplitude frequency response (ADP gain reduced).

VI. BER Characterization

As a final test, BER characterizations were performed on the APD module and on the APD module–amplifier combination. Figure 10 summarizes the results of this test. Clearly, there is a substantial performance improvement from utilizing the APD–amplifier combination. The BER was quite sensitive to background noise. Any light not generated by the laser affects the results. Simply moving around the darkened laboratory could cause an increase in bit errors. Additionally, if the laboratory lights were on, the communications link could not be maintained. This was the case even though a shroud was used at the APD.

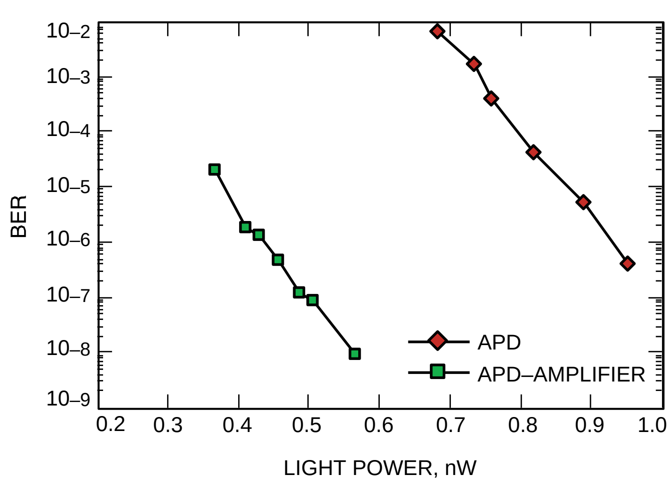

Fig. 10. The ADP BER characterization.

VII. Conclusions

The APD configuration used at the receiver band limited the received signal to about 1.75 MHz. This phenomenon likely is caused by the high-gain setting on the APD circuitry and the low light levels. Furthermore, the band limiting is likely to cause intersymbol interference and so, if possible, the bandwidth of the receiver should be increased. To this end, the gain of the APD was reduced and an amplifier module was added to the telemetry chain. This resulted in the extension of the 3-dB bandwidth to about 3.75 MHz. The input light power level-to-output voltage curve is quite linear and highly repeatable. The BER response of the APD is quite good. However, a substantial improvement ($>$3 dB) was realized with the addition of an amplifier. The combined APD–amplifier circuit was able to achieve a BER of 10^{-6} at light power levels of 0.45 nW.