Project

The objective of this project is to select a research paper and use simulations to demonstrate the improvements it introduces over the current state-of-the-art. The project may be completed individually or by a pair of students.

The first example involves simulating an optical receiver and integrating a new detector from a journal paper, then comparing its performance with the existing detector.

The second example focuses on an RF receiver, where the error correction coding is replaced with a new scheme from a journal paper to demonstrate the performance improvement.

Required Steps:

1. Obtain approval for the selected paper from the Teaching Assistant (TA).
2. Submit the final project report.
3. Deliver a brief presentation in class.
4. Review and discuss the simulation outcomes with the TA.

Project

Submission Requirements

Please include a folder (ZIP) and one PDF file containing the following :

1. A concise PowerPoint presentation, consisting of up to 10 slides.

2. A project summary document, with a maximum of 5 pages.

3. Formulate three calculation-based questions derived from the paper.

3. Your MATLAB or Python code.

4. The research paper upon which the work is based.

Project

List of journals (The last 5 years)

1. IEEE Transactions on Aerospace and Electronic Systems
2. IEEE Transactions on Antennas and Propagation
3. International Journal of Satellite Communications and Networking
4. IEEE/OPTICA Journal of Lightwave Technology
5. IEEE Transactions on communication
6. IEEE Transactions on wireless communication
7. Optics Express
8. Nature Photonics
9. IEEE Journal on Selected Areas in Communications

In special cases, approval for papers from other journals may be granted; however, prior written approval is required.

Project

Evaluation Criteria for the Project:

1. **Understanding of the Paper (40%)**
   - Clear comprehension of key concepts, methods, and context.
   - Critical analysis and understanding of the paper's strengths and weaknesses.
   - Formulate three calculation-based questions derived from the paper.

2. **Quality of the Simulation (50%)**
   - Correct and functional code, reflecting the paper’s methodology.
   - Effective implementation and creativity in handling complex aspects.
   - Accurate and realistic simulation results.
   - Proper analysis of simulation results, linked to the paper's objectives.
   - Comparison with state-of-the-art methods and insightful conclusions.

3. **Communication and Presentation (10%)**
   - Clear, well-structured project report and presentation.
   - Effective oral presentation

Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

1. **Gather Background Knowledge & Choose Your Research Topic**
    - Study the course book, along with additional books, research papers, and reputable online sources, to build a strong foundational understanding of APD-based optical receivers.
    - Explore different aspects of the topic and select a research focus that aligns with your interests and course objectives.
2. **Research Focus: Improving Optical Receiver Performance with APDs**
    - In this example, we investigate how the performance of an optical receiver for satellites can be improved using a new avalanche photodiode (APD).
3. **Formulate Key Research Objectives**
    - Develop a mathematical model to analyze the Bit Error Rate (BER) performance of APD-based satellite optical receivers.
    - Search for research papers on Google Scholar that discuss advancements in next-generation APD technology.
    - Identify a datasheet for an APD with performance characteristics similar to those described in the selected research paper.
    - Implement Python or MATLAB code to calculate and compare the Noise and BER for the receiver configuration using both the paper's APD and the datasheet APD.
    - Ensure fair comparison, summarize findings, write conclusion, and maintain objectivity.

Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

An avalanche photodiode (APD) is a highly sensitive semiconductor photodetector that operates with an internal gain mechanism. When a photon strikes the APD, it generates an electron-hole pair, which is then accelerated by a high reverse bias voltage. This causes an avalanche multiplication effect, where secondary charge carriers are created, leading to a significant amplification of the photocurrent. APDs are used in applications requiring high sensitivity and fast response times, such as LIDAR, fiber-optic communication, and low-light detection. However, they require a stable high-voltage power supply and generate more noise compared to regular photodiodes.

Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

1. Developing mathematical model

The **Bit Error Rate (BER)** is a critical parameter in evaluating the performance of an **Avalanche Photodiode (APD)** optical receiver. It quantifies the probability of errors in received data due to noise. The following sections provide a detailed explanation of how to calculate the BER by considering various noise sources.

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1. Fundamentals of BER Calculation

The **BER** is typically defined in terms of the **Q-factor**, which relates to the **Signal-to-Noise Ratio (SNR)**. The BER can be expressed as:

$$BER = 0.5 \times \mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)$$

Where:

- **erfc** is the complementary error function,
- **Q** is the **Q-factor**, representing the SNR.

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2. The Q-Factor for an APD Receiver

The **Q-factor** for an APD receiver is calculated as:

$$Q = \frac{I_1 - I_0}{\sigma_1^{\square} + \sigma_0^{\square}}$$

Where:

- I_1 is the photocurrent corresponding to bit "1",
- I_0 is the photocurrent corresponding to bit "0",
- σ_1 is the standard deviation (noise) for bit "1",
- σ_0 is the standard deviation (noise) for bit "0".

---

3. APD Noise Sources

The noise sources in an **APD-based optical receiver** include the following:

3.1 Shot Noise

Shot noise arises from the discrete nature of light and is amplified by the APD's gain factor. The shot noise is given by:

$$\sigma_{\text{shot}}^2 = 2qI_pM^2F(M)B$$

Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

Where:

- q is the elementary charge (1.6×10^{-19} C),
- I_p is the primary photocurrent,
- M is the APD gain factor,
- $F(M)$ is the excess noise factor, which is typically modeled as:

$$F(M) = kM + (1-k)\left(2 - \frac{1}{M}\right)$$

  Here, k is the ionization ratio, which is material-dependent,

- B is the receiver bandwidth.

3.2 Thermal Noise (Johnson Noise)

Thermal noise, caused by the random motion of electrons, is given by:

$$\sigma_{\text{thermal}}^2 = \frac{4k_B T B}{R_L}$$

Where:

- k_B is the Boltzmann constant (1.38×10^{-23} J/K),
- T is the temperature in Kelvin,
- B is the bandwidth,
- R_L is the load resistance.

3.3 Dark Current Noise

Dark current noise is generated by the APD even in the absence of light. It is given by:

$$\sigma_{\text{dark}}^2 = 2qI_d M^2 F(M) B$$

Where I_d is the dark current before multiplication.

3.4 Background Radiation Noise

Ambient light also contributes noise to the receiver. The background radiation noise is expressed as:

$$\sigma_{\text{background}}^2 = 2qI_b M^2 F(M) B$$

Where I_b is the photocurrent generated by background radiation.

Guidelines for Preparing a Project:
An Example of an APD-Based Optical Receiver

4. **Total Noise Calculation**

The total noise for the "1" and "0" bits can be expressed as:

$$\sigma_1^2 = \sigma_{\text{shot1}}^2 + \sigma_{\text{thermal}}^2 + \sigma_{\text{dark}}^2 + \sigma_{\text{background}}^2$$

$$\sigma_0^2 = \sigma_{\text{shot0}}^2 + \sigma_{\text{thermal}}^2 + \sigma_{\text{dark}}^2 + \sigma_{\text{background}}^2$$

Where the shot noise will differ for bits "1" and "0" due to different photocurrent levels.

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5. **Photocurrent Calculation**

The photocurrent levels for bits "1" and "0" can be calculated as:

$$I_1 = M \times R \times P_1$$

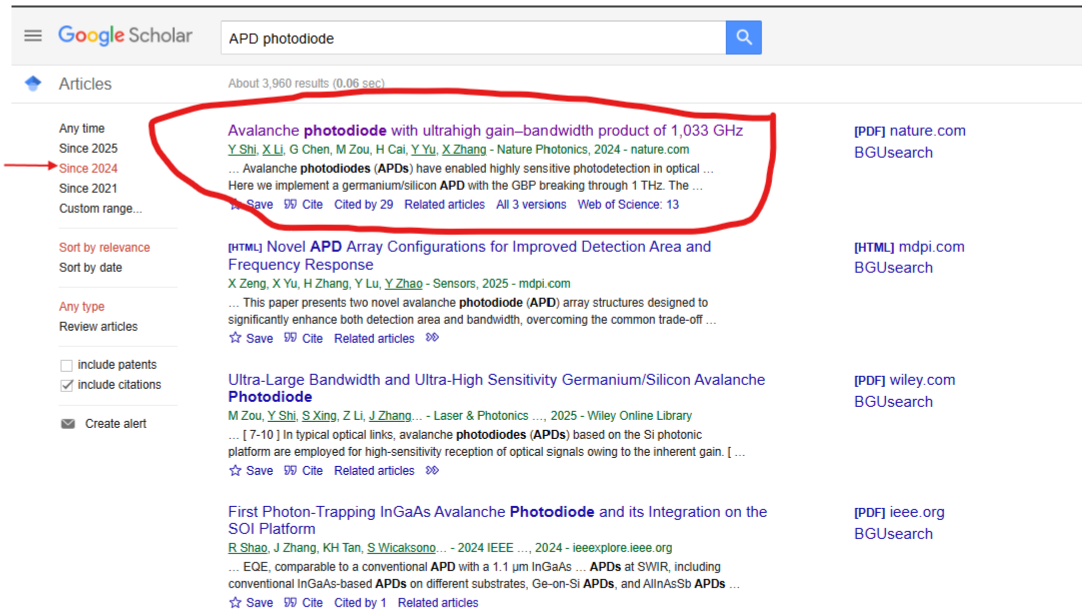
$$I_0 = M \times R \times P_0$$

Where:

- R is the responsivity of the photodiode (in A/W),
- P_1 and P_0 are the optical power levels for bits "1" and "0", respectively.

How to Begin the Project: An Example

2. Searching in google scholar the subject APD photodiode looking for papers starting 2024



Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

nature photonics

Article

https://doi.org/10.1038/s41566-024-01421-2

Avalanche photodiode with ultrahigh gain–bandwidth product of 1,033 GHz

Received: 4 April 2023

Accepted: 18 March 2024

Published online: 9 April 2024

Check for updates

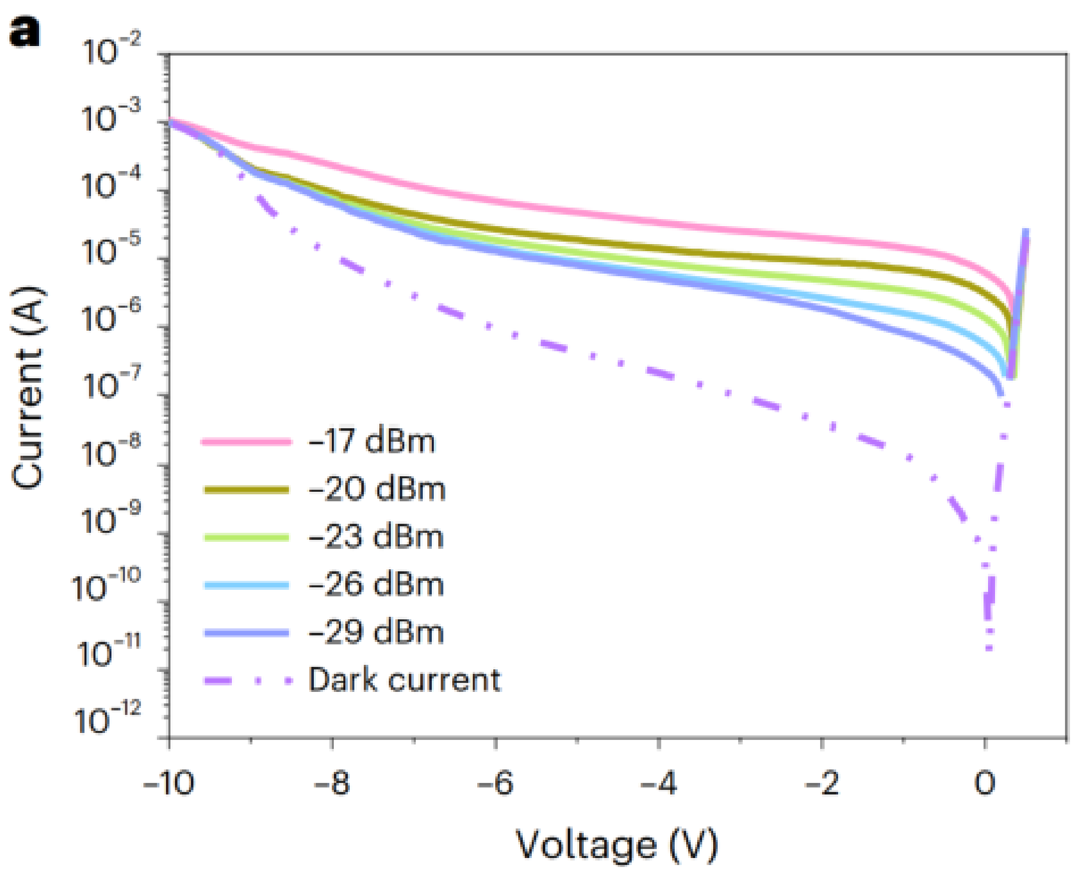
Yang Shi[1], Xiang Li[2], Guanyu Chen[1,3], Mingjie Zou[1], Hongjun Cai[1], Yu Yu[1,4] & Xinliang Zhang[1,4]

Avalanche photodiodes (APDs) have enabled highly sensitive photodetection in optical communication, sensing and quantum applications. Great efforts have been focused on improving their gain–bandwidth product (GBP). However, further advance has encountered enormous barriers due to incomplete consideration of the avalanche process. Here we implement a germanium/silicon APD with the GBP breaking through 1 THz. The performance is achieved by introducing two cooperative strategies: precisely shaping the electric field distribution and elaborately engineering the resonant effect in the avalanche process. Experimentally, the presented APD has a primary responsivity of 0.87 A W^{-1} at unity gain, a large bandwidth of 53 GHz in the gain range of 9–19.5 and an ultrahigh GBP of 1,033 GHz under −8.6 V and at 1,550 nm. For demonstration, data reception of 112 Gb s^{-1} on–off keying and 200 Gb s^{-1} four-level pulse amplitude modulation signals per wavelength are achieved with clear eye diagrams and high sensitivity, as well as 800 G reception via four channels. This work provides a potential successor for high-speed optoelectronic devices in next-generation optical interconnects.

Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

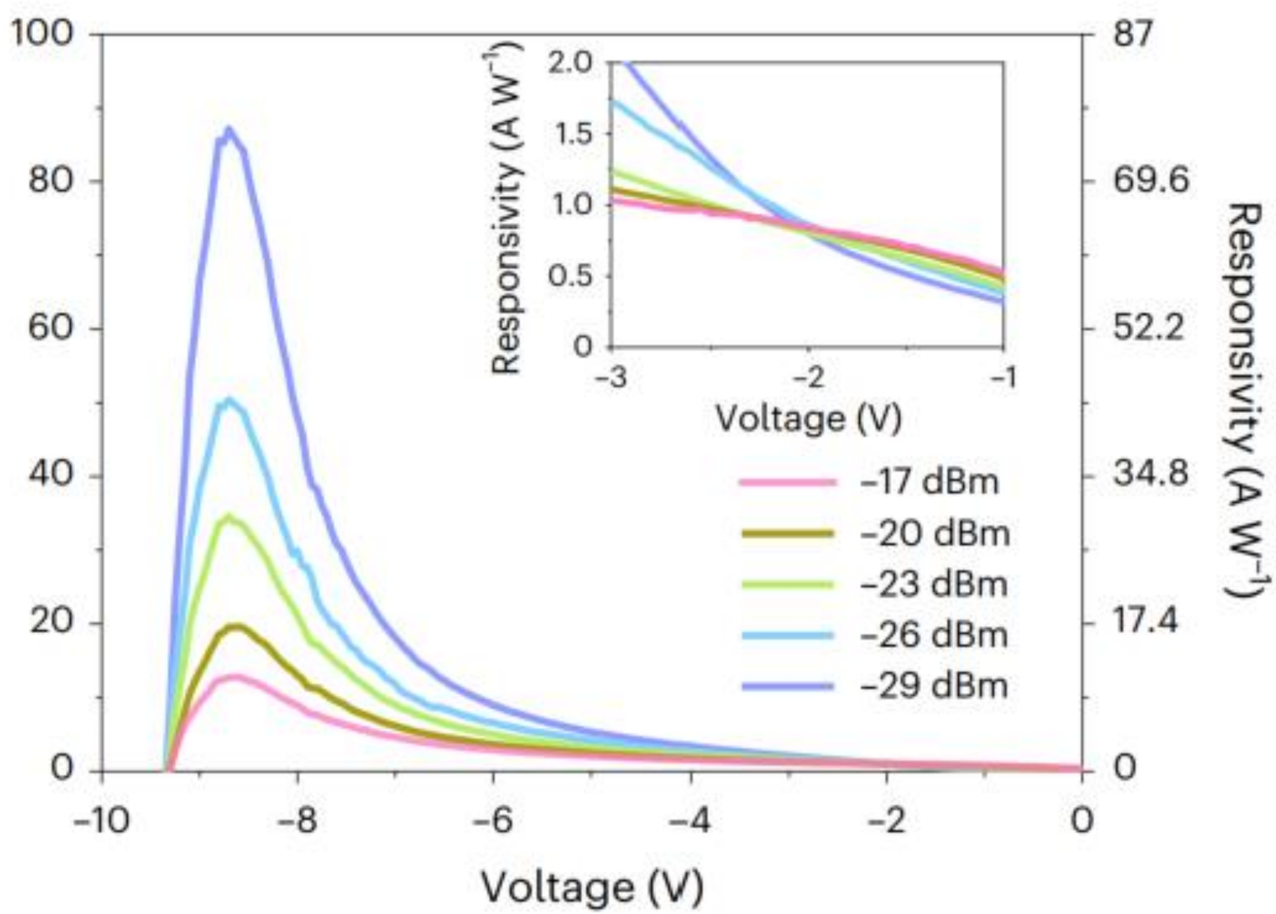
Dark current



Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

Gain



Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

3. Searching online for the datasheet of a high-speed APD

HAMAMATSU
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InGaAs APD

G8931 series

High-speed response

The G8931 series are InGaAs APDs used for distance measurement, optical communication, and low-light-level detection. The G8931-04 provides high-speed response at 2.5 Gbps, which is necessary for SONET, G/GE-PON, and other optical trunk lines. The G8931-20 features a large ϕ0.2 mm photosensitive area.

Features

- High-speed response: 2.5 Gbps (G8931-04)
- Low dark current
- Low capacitance
- High sensitivity

Applications

- Distance measurement
- Optical communications
- Low-light-level detection

Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

3. Searching online for the datasheet of a high-speed APD

GPD

OPTOELECTRONICS CORP.

IAV80
IAV200
IAV350

InGaAs Avalanche Photodiodes (APD)

InGaAs Avalanche Photodiodes

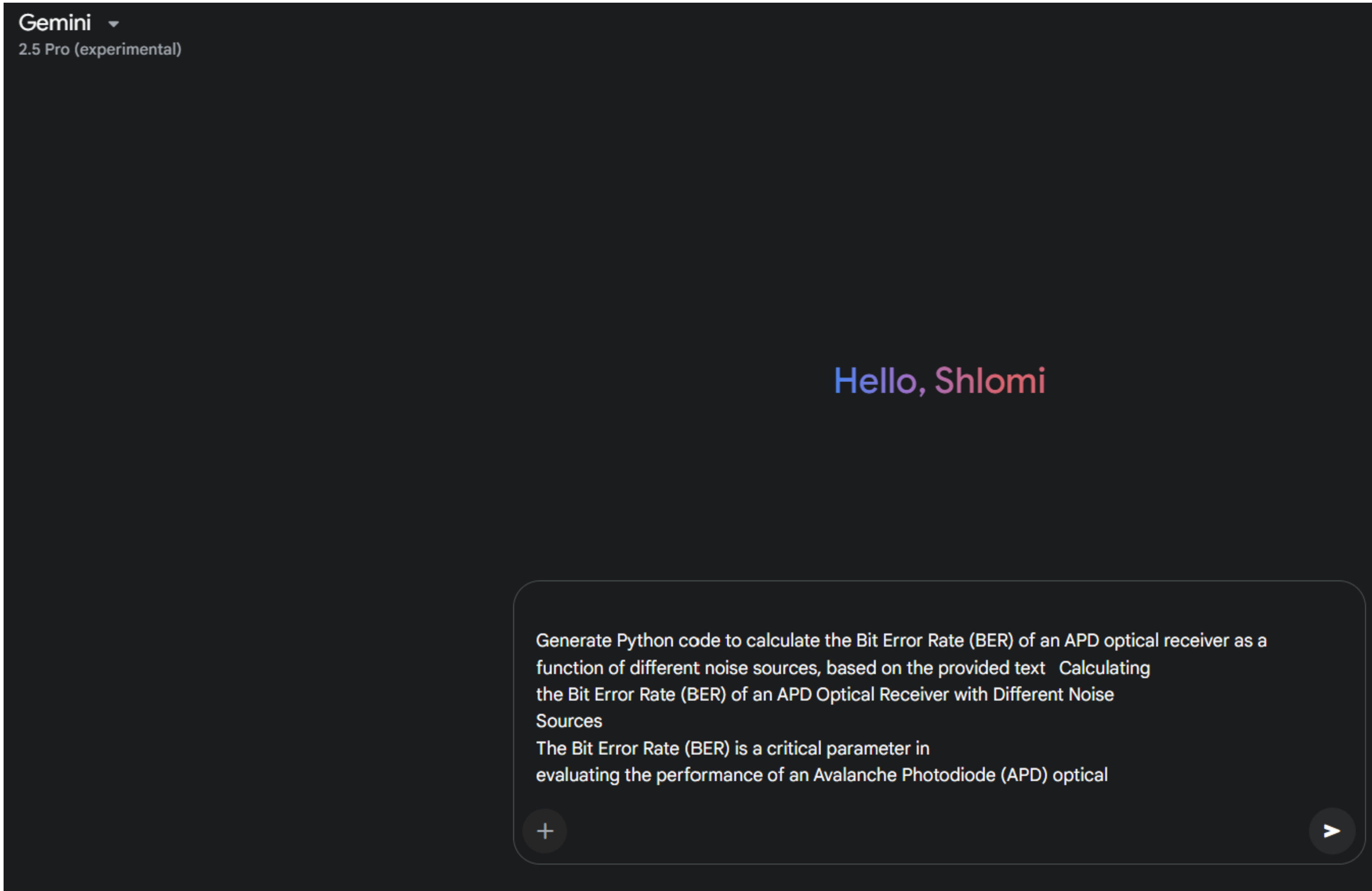
Electrical Characteristics @ 23 °C ± 2 °C

Performance Specification	IAV80	IAV200	IAV350	Units
Active Diameter	80	200	350	µm
Wavelength Range	1.0 - 1.63	1.0 - 1.63	1000 to 1630	µm
Responsivity @ M=1 @ 1.55 µm	0.85 min|0.90 typ |0.95 max	0.85 min|0.94 typ|1.05 max	0.85 min|0.90 typ|0.95 max	A/W
Dark Current @ M = 10	4 typ|15 max	8 typ|25 max	30 typ|250 max	nA
Operating Voltage, V_R @ M = 10	43 min|55 typ|70 max	43 min|55 typ|70 max	37 min|52 typ|68 max	V
Breakdown Voltage, V_{BR} (I_D=10 µA)	40 min|65 typ|80 max	50 min|63 typ|75 max	45 min|60 typ|75 max	V
Capacitance @ M = 10	0.35 min|0.38 typ|0.45 max	1.8 typ|2.2 max	3.2 typ|4.0 max	pF
V_{BR} temperature coefficient	0.06 typ	0.075 typ|0.08 max	0.075 typ	V/°C
Bandwidth @ M = 5	2 min|2.5 typ|3 max	0.5 min|1.5 typ|2 max	0.6 typ	GHz
Bandwidth @ M = 10	1 min|1.5 typ|2 max	1 min|1.5 typ|2 max	0.6 typ	GHz
Bandwidth @ M = 20	1.5 min|2.2 typ|2.5 max	0.5 min|1 typ|1.5 max	0.6 typ	GHz
Excess Noise Factor, F @ M = 10	3.2 typ|3.7 max	3.2 typ|3.7 max	3.2 typ|3.7 max	
Excess Noise Factor, F @ M = 20	5.5 typ|6 max	5.5 typ|6 max	5.5 typ|6 max	
Noise Equivalent Power, @ M = 10	10 typ|40 max	32 typ|100 max	80 typ|100 max	$fW/Hz^{½}$
Package	TO-46 window cap	TO-46 window cap	TO-46 window cap	

Guidelines for Preparing a Project:

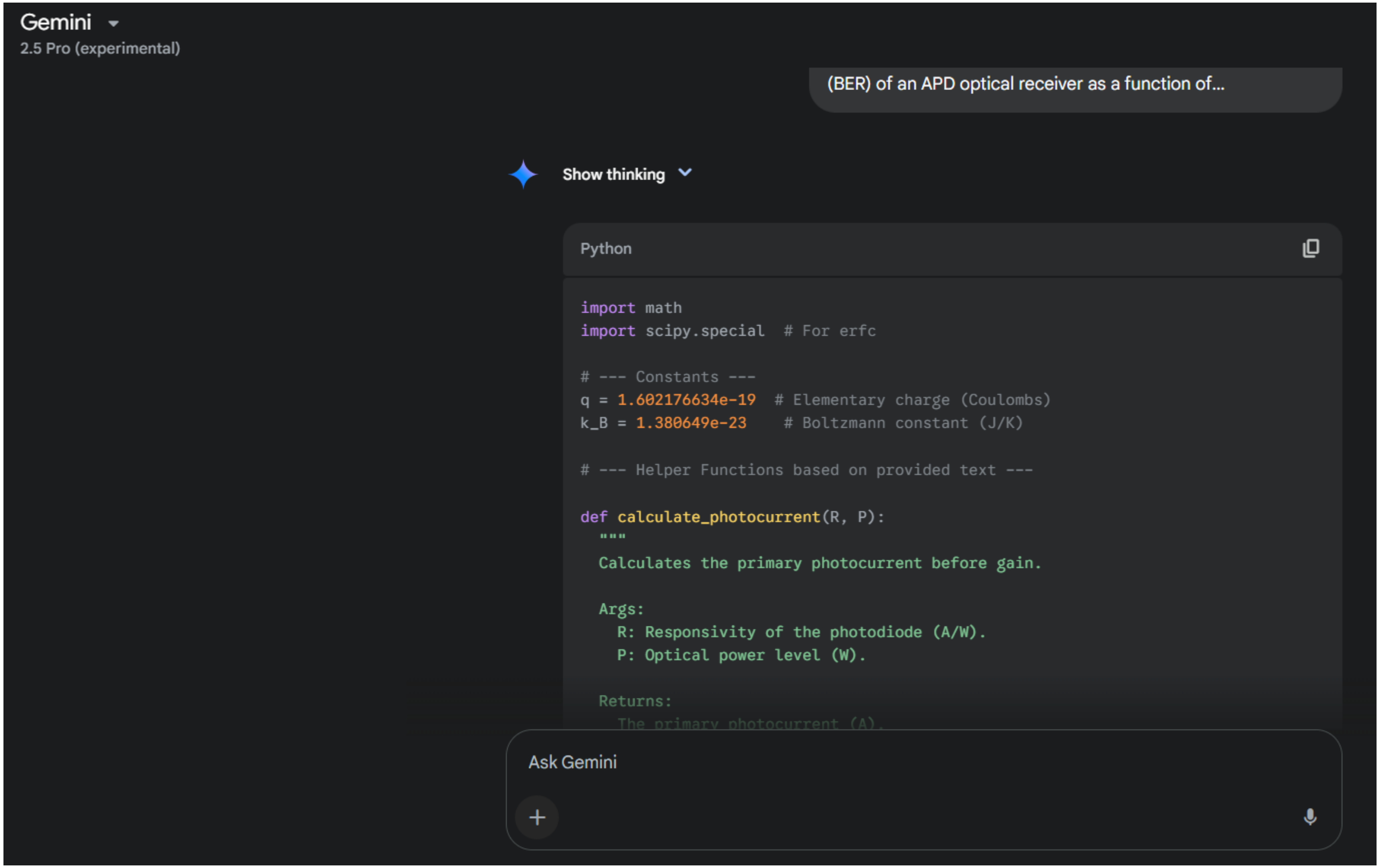
An Example of an APD-Based Optical Receiver

4. Generate Python code to calculate the Bit Error Rate (BER)



Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver



Guidelines for Preparing a Project:

An Example of an APD-Based Optical Receiver

```
# --- Example Usage ---
if __name__ == "__main__":
    # Define example parameters (adjust these values based on your specific system)
    params = {
        'P1': 1e-6,         # Optical power for bit "1" (e.g., 1 uW)
        'P0': 1e-8,         # Optical power for bit "0" (e.g., 10 nW, extinction rati
        'R': 0.8,           # Responsivity (e.g., 0.8 A/W)
        'M': 10,            # APD Gain Factor (e.g., 10)
        'k': 0.02,          # Ionization ratio for InGaAs APD (typical 0.02 - 0.5)
                            # Note: Text uses k, some literature uses k_eff or alpha,
        'B': 1e9,           # Receiver Bandwidth (e.g., 1 GHz)
        'T': 298.15,        # Temperature (e.g., 25 C = 298.15 K)
        'R_L': 1000,        # Load Resistance (e.g., 1 kOhm)
        'I_d': 5e-9,        # Dark current (before gain) (e.g., 5 nA)
        'I_bg': 1e-9        # Background photocurrent (before gain) (e.g., 1 nA)
    }

    print(f"Calculating BER with parameters:")
    for key, value in params.items():
        print(f"  {key}: {value}")
    print("-" * 30)

    try:
        results = calculate_apd_ber(**params)
```

Guidelines for Writing the Project Discussion and Conclusion Section

1. Introduction

- State the purpose and key performance parameters (e.g., APD comparison).

2. System Performance Analysis

Use numerical data and graphs for fair comparison.

- **Responsivity & Gain:** Compare signal conversion efficiency.
- **Noise Performance:** Evaluate excess noise factor and SNR.
- **Bandwidth & Response Time:** Highlight speed and efficiency.
- Calculate the BER of both systems vs different signal power

3. Data Representation

- Use graphs and tables to illustrate trends.
- Ensure fair comparison under identical conditions.

4. Conclusion

- Summarize key findings and advantages.
- Discuss applications and future research directions.

Final Tips

- Keep it clear and concise.
- Support claims with data.

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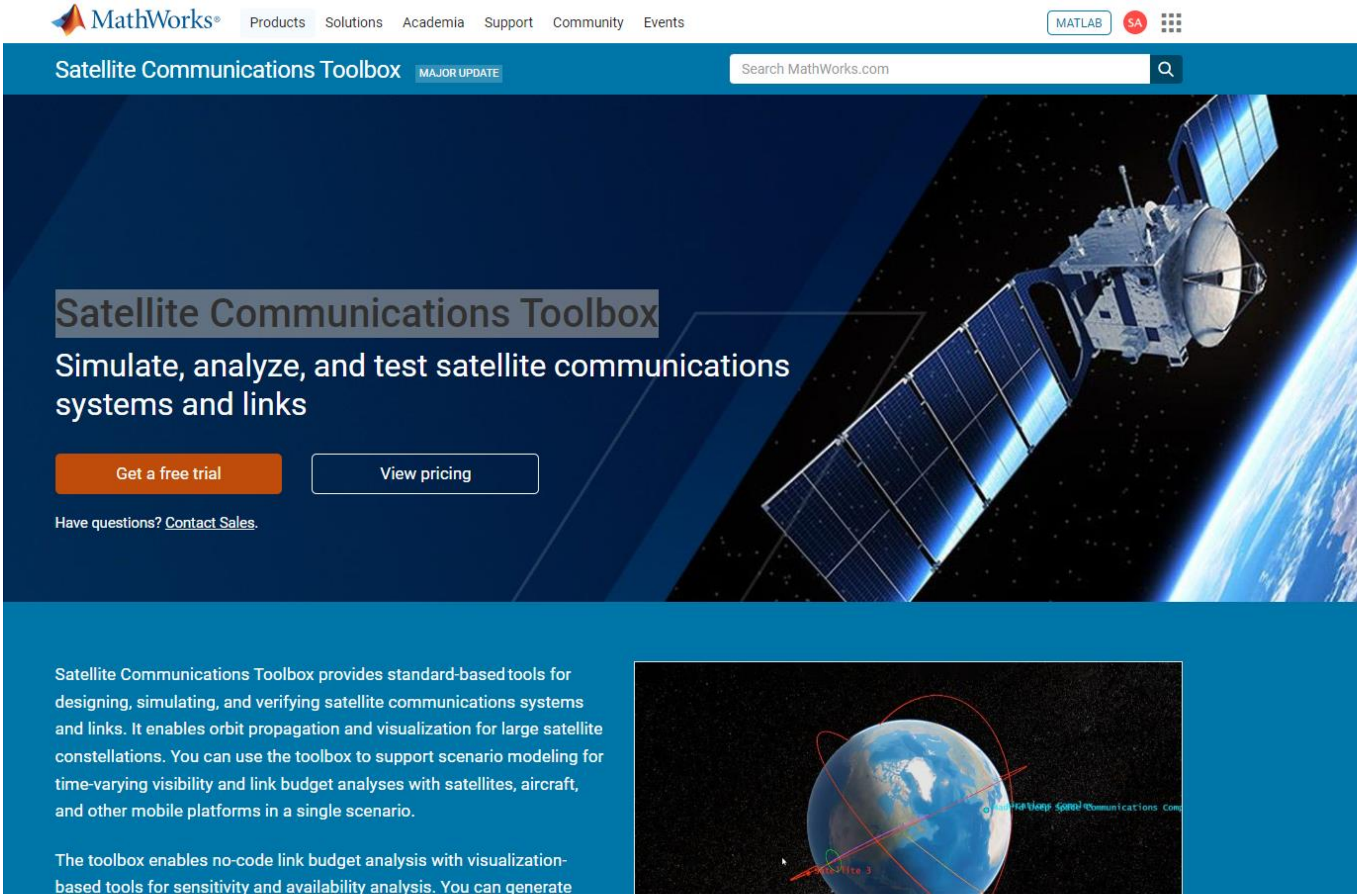
MATLAB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Satellite Communications Toolbox provides standard-based tools for designing, simulating, and verifying satellite communications systems and links. It enables orbit propagation and visualization for large satellite constellations. You can use the toolbox to support scenario modeling for time-varying visibility and link budget analyses with satellites, aircraft, and other mobile platforms in a single scenario.
The toolbox enables no-code link budget analysis with visualization-based tools for sensitivity and availability analysis. You can generate