Photodetector Basics And Application In DQPSK Receivers

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Abstract

Photodiodes are fundamental optoelectronic devices widely used for the detection and conversion of optical signals into electrical currents. This paper presents a comprehensive overview of the physical principles governing photodiode operation, introducing its main features. Building on these fundamentals, the paper explores the practical implementation of photodiodes in a Differential Quadrature Phase Shift Keying (DQPSK) optical receiver.

I. Semiconductor Photodiodes

A. Main idea

Photodiodes are reverse-biased PIN junctions featuring an active area that can be either front or side illuminated, with the latter being more common in optical applications. Upon illumination, incident light generates electron-hole pairs thanks to the photoelectric effect. If generated within the depletion region, these carriers produce a photocurrent proportional to the incident optical power. On the other hand, if generated in the neutral regions, they are simply screened by the population of free carriers and do not contribute to the current.

B. Stationary operation

Under stationary illumination, the device operates in reverse bias, maximizing the width of the depletion region W_d, and therefore the probability of carrier pair generation within it. The built-in electric field sweeps the photo-generated electrons and holes toward the n-type and p-type contacts, respectively, giving rise to a net photocurrent IP . The response is linear with incident power over several decades, making PIN photodiodes well suited for analog optical links.

II. Main Parameters

A. Photon Detection Efficiency: η_D

It is the parameter which express the probability of a photon to generate a free electron-hole pair in the depletion layer. We can describe it as the product of the probabilities of not being reflected at the surface and of being absorbed by the depletion layer

$$\eta_D = (1 - R_f)(1 - e^{\frac{-\Gamma W_d}{L_a}}) \tag{1}$$

where R_f is the reflectivity coefficient of the substrate, Γ is the optical confinement factor, L_a is the absorption length and W_d is the physical length of the depletion layer.

B. Radiant Sensitivity: S_D

It's the parameter which expresses the quantity of current generated by the optical power. Since with the energy of one photon we have some probability to generate a current of one electron-hole pair, it can be easily computed as

$$S_D = \frac{\eta_D \cdot q}{hc/\lambda} = \eta_D \cdot \frac{\lambda[\mu m]}{1.24} \tag{2}$$

In real world this S_D is not perfectly linear with λ: there is a band in which it's linear, outside of which it drops towards zero.

C. Dark-Current

A reverse biased diode will never have zero current, except for a nihil bias voltage. So there will be a so called *Dark Current* circulating in our component even with no light. This current is responsible for a shot noise component of the device. The physical origin of this current can be traced back to the phenomena of carrier generation within the depletion region.

D. Current expression

Based on the previous parameters, we can easily compute the photocurrent generated by the device as

$$I_P = S_D * P_{opt} \tag{3}$$

It goes accordingly that to be properly sensed, I_P must be higher than I_{dark}, so we need $P_{opt} > \frac{I_{dark}}{S_D}$.

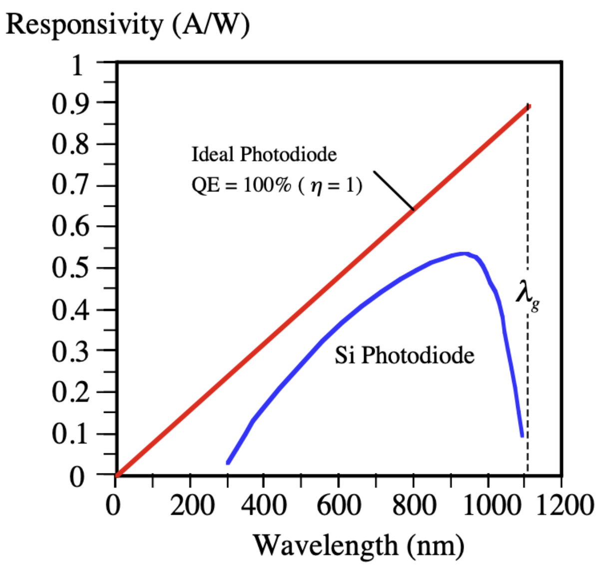

Fig. 1. Radiant sensitivity S_D vs wavelength λ in an ideal and a real Si-Photodiode

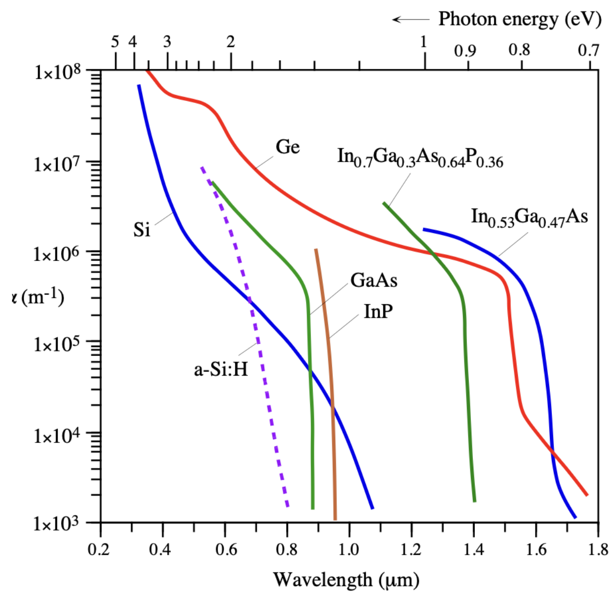

Fig. 2. Absorption coefficient Γ vs wavelength λ for various semiconductors

III. Dynamic Response

The frequency response of a photodiode is limited by two concurrent mechanisms:

A. Transit-time limit.

Carriers photo-generated within the depletion layer must drift to the contacts under the action of the electric field. The associated 3-dB bandwidth is approximately:

$$f_{\text{tr}} \approx \frac{0.45\, v_s}{W_d} \tag{4}$$

where v_s is the carrier saturation velocity ($\approx 10^7$ cm/s in silicon). A wider depletion region improves η_D but degrades f_{tr}, creating a fundamental trade-off. This approximation was done considering the current at the contacts passing abruptly from a constant value to zero, creating a rectangular response. In the frequency domain this becomes a sinc, which is put equal to the -3dB bandwith

$$\left|\frac{\sin(\pi f_{tr}\tau)}{\pi f_{tr}\tau}\right| = \frac{1}{\sqrt{2}}$$

We solve analitically finding

$$\pi f_{tr}\tau \approx 1.39$$

B. RC limit.

The junction capacitance $C_j = \varepsilon_r\varepsilon_0 A/W_d$ (where A is the device active area) forms a low-pass RC filter with the load resistance R_L:

$$f_{\text{RC}} = \frac{1}{2\pi R_L C_j} \tag{5}$$

C. Bandwidth estimation

The overall 3-dB bandwidth is obtained by combining both limits:

$$\frac{1}{f_{\text{3dB}}^2} \approx \frac{1}{f_{\text{tr}}^2} + \frac{1}{f_{\text{RC}}^2} \tag{6}$$

IV. Equivalent circuit

A. Small-Signal Model

The small-signal equivalent circuit of a PIN photodiode consists of a current source I_P in parallel with the junction capacitance C_j, the shunt resistance R_{sh} (modelling the finite reverse-biased leakage), and a series resistance R_s accounting for contact and bulk resistances. The model is shown schematically in Fig. 3.

B. Noise Model

Two primary noise contributions must be accounted for in the equivalent circuit. The *shot noise* current has a power spectral density:

$$S_{i,\text{shot}} = 2q(I_P + I_{\text{dark}}) \tag{7}$$

The *thermal noise* (Johnson-Nyquist) from the shunt resistance R_{sh} contributes:

$$S_{i,\text{th}} = \frac{4k_BT}{R_{sh}} \tag{8}$$

In high-speed receivers, the transimpedance amplifier (TIA) input noise also plays a significant role and is usually the dominant term at low optical powers. The current produced will then be processed by the TIA and converted into voltage through ADC in the following steps.

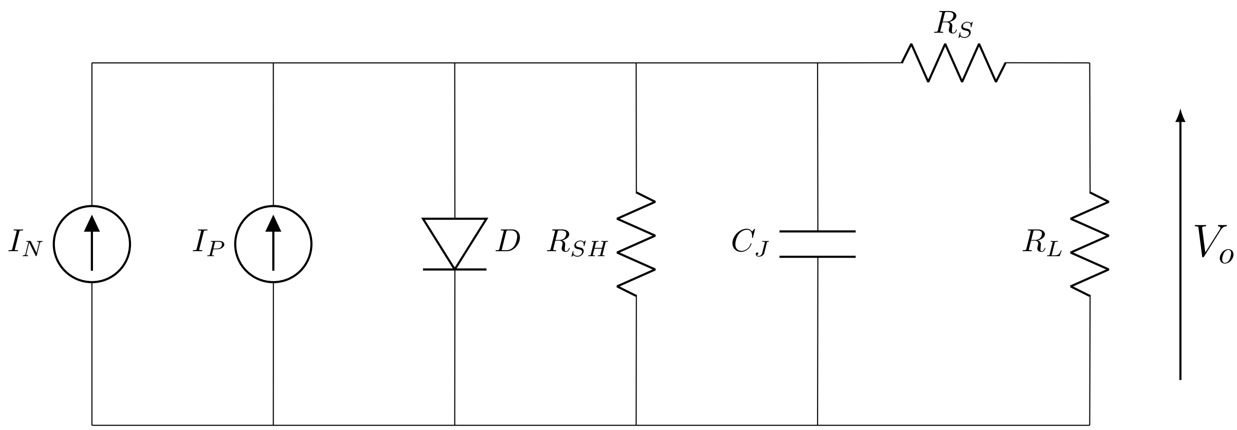

Fig. 3. Small-signal equivalent circuit of a PIN photodiode.

V. DQPSK receiver application

A. DQPSK Modulation Format

Differential Quadrature Phase Shift Keying (DQPSK) encodes two bits per symbol by differentially encoding the phase of the optical carrier in four possible states $(0, \pi/2, \pi, 3\pi/2)$. Compared to QPSK, DQPSK doubles the spectral efficiency and relaxes the required optical signal-to-noise ratio (OSNR) by approximately 3 dB. These properties make it attractive for dense WDM systems operating at 40 Gbaud (symbols/second), which means reaching up to 80Gbps thanks to the two bits transported by each symbol.

B. Receiver Architecture

A DQPSK receiver demodulates the received signal thanks to two parallel Umbalanced Mach-Zehnder filters, each providing a one-symbol delay and a differential phase shift of $\pm\pi/4$, respectively. The structure is illustrated in Fig. 4.

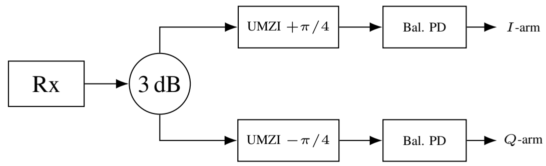

Fig. 4. Block diagram of a DQPSK optical receiver.

C. Balanced Photodetection

Each filter drives a pair of photodiodes connected in a balanced configuration. The two output ports of the Mach-Zehnder carry complementary signals; their photocurrents are:

$$I_{\pm} = \frac{S_D P_{\text{in}}}{2} \left(1 \pm \cos(\Delta\theta - \phi_{\text{ref}})\right) \tag{9}$$

where $\Delta\theta$ is the differential phase between adjacent symbols and $\phi_{\text{ref}} = \pm\pi/4$. The balanced detector computes $I_+ - I_-$, thus obtaining:

$$I_{\text{diff}} = S_D P_{\text{in}} \cos(\Delta\theta - \phi_{\text{ref}}) \tag{10}$$

This subtraction doubles the signal swing while suppressing common-mode noise (in particular intensity noise and dc dark current), improving the receiver sensitivity by up to 3 dB relative to single-ended detection [3].

D. System Requirements

Usually, the photodiodes employed in a 40 Gbaud DQPSK receiver must satisfy stringent specifications. The required 3-dB bandwidth must exceed 30 GHz (roughly $0.75 \times B$), with a junction capacitance below 100 fF to limit the RC contribution. The radiant sensitivity S_D should be maximised at the transmission wavelength (typically 1530–1565 nm), calling for InGaAs absorbers on InP substrates, which provide a responsivity of 0.8–1.0 A/W in that range [4]. Dark current must be kept below a few nanoamperes to avoid excessive shot noise that would degrade the OSNR.

E. Performance Metrics

The primary value of the evaluated DQPSK receiver is the required Optical Signal-to-Noise Ratio (OSNR), typically defined within a standard 0.1 nm reference bandwidth, to achieve a target Bit Error Rate (BER). Under ideal shot-noise-limited operation with balanced configuration, the theoretical E_b/N_0 required to reach a baseline BER of 10^{-3} is approximately 7.5 dB. Where E_b is the Energy per bit and N_0 is the noise spectral density, this enables removing the dependance on the transmission velocity and extension of the bandwidth, normalizing to the single bit.

$$SNR = \frac{S}{N} = \frac{E_b \cdot R_b}{N_0 \cdot B}$$

From which we obtain:

$$\frac{E_b}{N_0} = SNR \cdot \frac{B}{R_b}$$

Where R_b is the Bit-Rate and B/R_b represents the spectral efficiency of the system.

In practical implementations, hardware non-idealities introduce a significant OSNR penalty. Specifically, at low input optical powers, the photodiode dark current and thermal noise injected by the subsequent transimpedance amplifier (TIA) dominate, severely degrading the SNR. Furthermore, the finite extinction ratio of the Mach-Zehnder Interferometers causes signal leakage, inducing phase crosstalk between the in-phase (I) and quadrature (Q) tributary channels. Consequently, minimizing the dark current ($<$ a few nA) and optimizing the TIA noise spectral density are strict design constraints to approach the fundamental shot-noise limit and preserve receiver sensitivity.

VI. Conclusion

In conclusion, PIN photodiodes represent critical components in modern high-speed optical communication systems. Their physical design inherently involves a fundamental trade-off between photon detection efficiency and dynamic bandwidth, primarily governed by the depletion region width which dictates both transit-time and RC limits. The implementation of balanced photodetector pairs within a 40 Gbaud DQPSK receiver architecture proves highly effective in maximizing performance. This balanced configuration significantly improves receiver sensitivity, allowing the system to approach the shot-noise limit. Finally, the continuous co-integration of these detectors onto silicon photonic platforms will be essential for developing the compact, low-loss, and high-efficiency receivers required by future needs.

References

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