4. Optical Receivers

The job of the optical receiver is to convert the optical signal back into an electrical signal and to recover the transmitted data. The main component of a receiver is the photodetector, which handles the job of converting from the optical to electronic domains (and is in a sense the opposite of a laser). For practical optical communications systems, the photodetector must have certain properties - high sensitivity, fast response, low noise, low cost, and high reliability.

4.1. Photoconductive detectors

The simplest photodetector is the photoconductive detector, which can be an undoped semiconductor as shown in the figure, or a $pn$-junction, as described in the next section. A photoconductive detector works under an applied external voltage. Very little current flows through the device in the dark state, as the resistance of the semiconductor is very high in the absence of carriers. Thermally-generated carriers contribute to a small dark current, $I_d$, which, for a good detector, is typically less than 10 nA. Incident light generates electron-hole pairs which then drift due to the applied field. However, the frequency of the light must satisfy the condition

$$h\omega \geq E_g,$$

where $E_g$ is the bandgap energy. The resistance of the device is directly related to the incident optical power, and for a constant applied voltage, can be measured as a photocurrent.

4.1.1. Responsivity and quantum efficiency

The photocurrent can be written in terms of the responsivity and incident power

$$I_p = RP_{in}.$$

The responsivity has units of A/W (which is the inverse of a laser diode). Note that the textbook uses the symbol $\rho$ for responsivity in order to avoid confusion with the notation “R” for circuit resistors; we’ll typically denote a resistor by $R_L$, which is a load resistor.

The detector quantum efficiency is defined

$$\eta = \frac{\text{electron generation rate}}{\text{photon incidence rate}} = \frac{I_p}{q} = \frac{h\nu}{q} R.$$
In terms of the quantum efficiency then, the responsivity can be written

\[ R = \frac{\eta q}{h \nu} \sim \frac{\eta \lambda_f}{1.24}, \]

where \( \lambda_f \) is expressed in \( \mu \text{m} \). The quantum efficiency can be calculated based on the optical absorption coefficient \( \alpha \) of the semiconductor medium. The transmitted optical power

\[ P_{tr} = P_{in} e^{-\alpha W}, \]

where \( W \) is the width of the absorbing layer. Power absorbed by the detector is then

\[ P_{abs} = P_{in} - P_{tr} = P_{in} \left( 1 - e^{-\alpha W} \right). \]

Since each absorbed photon creates an electron-hole pair, the quantum efficiency is then

\[ \eta = \frac{P_{abs}}{P_{in}} = 1 - e^{-\alpha W}. \]

Therefore, when \( \alpha = 0 \) (as would occur if the photon energy is below the bandgap), the quantum efficiency is zero and the detector won’t work. The figure shows values of \( \alpha \) versus wavelength for a variety of intrinsic semiconductors.

### 4.1.2. Bandwidth

Another important photodetector property is the bandwidth, or the frequency response to a time-varying optical intensity. The detector rise time is defined

\[ T_r = \ln 9 \left( \tau_{tr} + \tau_{RC} \right), \]

which is the time for the detected photocurrent to rise from 10% to 90% in response to a steep rising edge. The rise time is an important figure for digital systems. Here, \( \tau_{tr} \) is the carrier transit
time from the point of generation to the contact and $\tau_{RC}$ is the time constant of the RC equivalent circuit. The carrier transit time is equal to the separation between contacts divided by the carrier velocity (which increases with applied field, up to the saturation velocity $\sim 10^8$ m/sec). The detector bandwidth is defined
\[ \Delta f = \frac{1}{2\pi (\tau_{tr} + \tau_{RC})}, \]
which is more appropriate for analog systems. Recall that bandwidth and rise-time are related by $t_r = 0.35/\Delta f$.

4.1.3. Metal-semiconductor-metal photodiodes

MSM photodetectors use closely spaced electrodes to minimize the distance between electron hole generation and collection. Bandwidth up to 300 GHz have been obtained with MSM structures.

![Interdigitated electrodes]

Separ. $\sim 1$ μm