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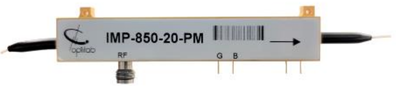
Application Notes - Modulators

High-performance, user friendly, at an excellent value

Optilab offers a wide variety of modulators such as phase, intensity, BPSK, QPSK, DP-QPSK, and much more. Our large inventory of modulators makes it easy to find a suitable device for your project. The modulators we offer come with operational wavelengths from 850–1550nm and 3dB bandwidths ranging from 5–50GHz. These high-performance modulators have a low insertion loss, high extinction ratio, can operate with high optical power, and offer excellent stability. Additionally, we offer modulators with PM outputs and low drive voltages to suit a wider variety of applications.



Introduction to Modulators

Modulator Type

The basic construction of a modulator starts with a wafer made of lithium niobate. Embedded in the wafer is a waveguide used to direct the light through the modulator. At least two electrodes are placed on the top surface of the wafer near the waveguide. These electrodes are used to modulate the signal by utilizing the Pockels effect. Simply put, the Pockels effect is when an electric field applied to a crystal causes the refractive index to change. By changing the refractive index of the crystal, the light traveling through the waveguide changes phase which is used to modulate the signal.

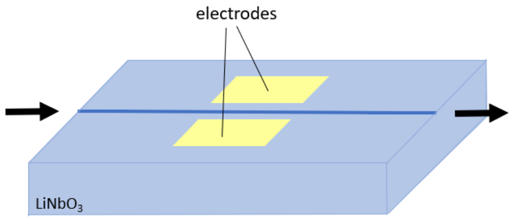


Figure 1. Phase modulator

Phase Modulator

A phase modulator consists of a single waveguide seated in lithium niobate with two electrodes placed on either side of the waveguide (Figure 1). This is the simplest type of modulator, making its applications limited.

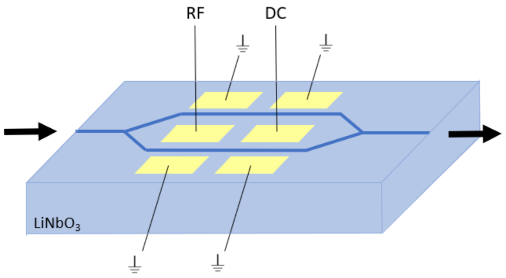


Figure 2. Mach Zehnder intensity modulator

Intensity Modulator

An intensity modulator uses the architecture of a Mach Zehnder interferometer (MZI) by splitting the waveguide into two paths and recombining them (Figure 2). The electrodes are placed around the two waveguide paths to modulate the phase in the light while split. When the paths recombine, the light path undergoes either constructive or deconstructive interference depending on the phase, thereby modulating the light intensity.

Intensity Modulator Transfer Function

The transfer function of an intensity modulator can simply be thought of as a sine wave where the X axis is the voltage applied to the modulator and the Y axis is the optical power measured at the output (Figure 3). The operating point is typically set at the midpoint of this sine wave. When the operating point is to the left of a peak (as the wave is ascending), this point is referred to as the quadrature plus point (Q+). When on the right side of a peak (as the wave is descending), this point is referred to as the quadrature minus point (Q-). However, certain types of modulators will require the operating point to be either at the maximum (peak) or at the minimum (null).

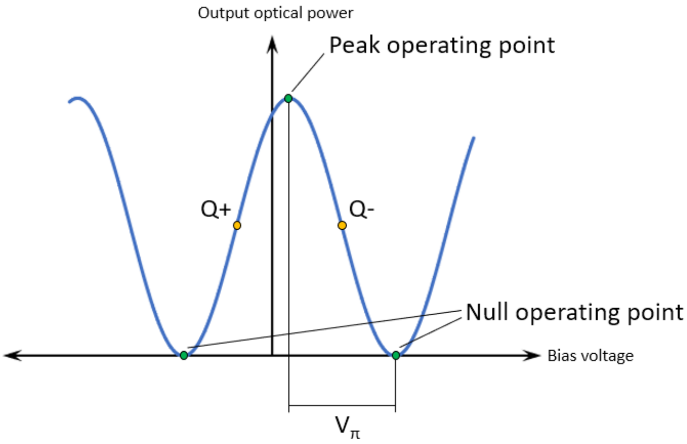


Figure 3. Intensity modulator transfer function

The equation for this transfer function is:

$$T(t) = \frac{P_{out}}{P_{in}} = \frac{\alpha}{2}[1 + \eta\cos(\frac{\pi}{V_\pi}V(t) + \phi(t))]$$

Where V_π is the half wave voltage, V(t) is the overall voltage applied to the modulator, and ϕ(t) is the phase of the transfer function. This phase will change slowly with time, which is known as the drift phenomena associated with MZI modulators.

In this expression, α is related to the insertion loss and η is related to the extinction ratio. Insertion loss corresponds to the maximum transmission, where:

$$T_{max} = \frac{1+\eta}{2}\alpha \approx \alpha$$

$$T_{min} = \frac{1-\eta}{2}\alpha$$

$$\text{Extinction Ratio} = \frac{T_{max}}{T_{min}} = \frac{1+\eta}{1-\eta}$$

Usually, η is very close to 1. The closer to 1, the higher the extinction ratio. In the following analysis, we consider an ideal modulator which has zero insertion loss and an infinitely large extinction ratio. This means $\alpha = \eta = 1$.

In the actual operation of an MZI modulator, a DC voltage and a modulation signal are applied to the bias port and RF port respectively. Therefore, the overall V(t) is:

$$V(t) = V_b + V_m\sin(\omega t)$$

Where V_b is the bias voltage and V_m is the modulation amplitude. The transfer function may be expanded into a series expansion using Bessel functions. When the modulator is biased at the quadrature plus (Q+) point, the even terms cancel out and we are left with:

$$T(t) = \frac{1}{2} + \sum_{n=1}^{\infty} J_{2n-1}(\beta)\sin[(2n-1)\omega t]$$

$$T(t) = \frac{1}{2} + J_1(\beta)\sin(\omega t) + J_3(\beta)\sin(3\omega t) + J_5(\beta)\sin(5\omega t) + \cdots$$

This equation tells us the transmission signal consists of the fundamental frequency signal (input modulation) and all the high order odd number harmonic signals (3f, 5f, etc.) when the modulator is biased at Q+. The value of the ordinary Bessel function $J_n(\beta)$ determines the modulation amplitude of the transmitted signal. For a modulation signal at frequency $\omega = 2\pi f$ and peak to peak voltage $V_{pp} = 2V_m$. The modulation index β can be defined as:

$$\beta = \frac{\pi V_{pp}}{2V_\pi}$$

Important Parameters

Insertion Loss

The insertion loss is a modulators capacity to transmit light when the operating point is set to the peak of the transfer function. It can be found by using the following function:

$$\alpha = 10\log\frac{P_{in}}{P_{out}}$$

Where P_{out} is the optical power measured at the output of the modulator, P_{in} is the optical power at the input, and α is the insertion loss given in dB. Loss is due to a number of factors, such as crystal impurities, manufacturing imperfections, reflections at the inlet and the injection side of the modulator, and recovery between the optical mode of the fiber and the waveguide mode.

Extinction Ratio

The extinction ratio is the ratio of transmitted optical power in the off state (deconstructive interference) to the on state (constructive interference). The equation to find the ER (extinction ratio) is:

$$ER = 10\log\frac{P_{max}}{P_{min}}$$

Where P_{min} is the optical power measured at the output while in the off state and P_{max} is the optical power at the output while in the on state.

Half-wave Voltage (V_π)

With an intensity modulator, the half-wave voltage is the voltage necessary to range from minimum transmission to maximum transmission. In a phase modulator, this voltage corresponds to a phase shift of π. Typically, the operating point is set to half of this value. Having a larger V_π means having a larger 1dB compression point. For analog modulation, the typical linear operating range is less than a quarter of V_π, making this type of modulation energy efficient.

Wavelength

Each modulator is designed to work at an optimal wavelength specified on its datasheet. If the input wavelength is not close to the optimal wavelength, then the modulator may not operate as expected.

Using a wavelength outside of the given range on a modulator's datasheet may increase the insertion loss or decrease the extinction ratio, which may not be acceptable depending on the modulator's application.

Bandwidth

The bandwidth of a modulator simply defines the usable frequency range. This depends on the design and structure of the electrodes. This value is typically given at the 3dB drop in electronics or at the 6dB drop in electro-optics.

RF Port and Bias Port

Intensity modulators will typically have two ports on them, one port is for the bias voltage and the other is for the RF voltage. The bias voltage port is used to set the operating point for the modulator, while the RF port is used to apply the modulating voltage to the electrodes, therefore modulating the signal. The RF port is typically closer to the optical input side than the bias port.

Intermediate Knowledge

Crystal Orientation: X-cut and Z-cut

Intensity modulators are produced in either an X-cut or Z-cut configuration. An X-cut modulator has a symmetrical design, where the waveguides are positioned between the electrodes. In a Z-cut modulator, the waveguides are offset so that they're underneath the electrodes (Figure 4). The X-cut design has a low frequency chirp where the Z-cut design has a high frequency chirp. However, Z-cut modulators are more efficient (lower half-wave voltage) in comparison. Phase modulators are only made in the Z-cut configuration, since they do not benefit from the symmetry of the X-cut configuration.

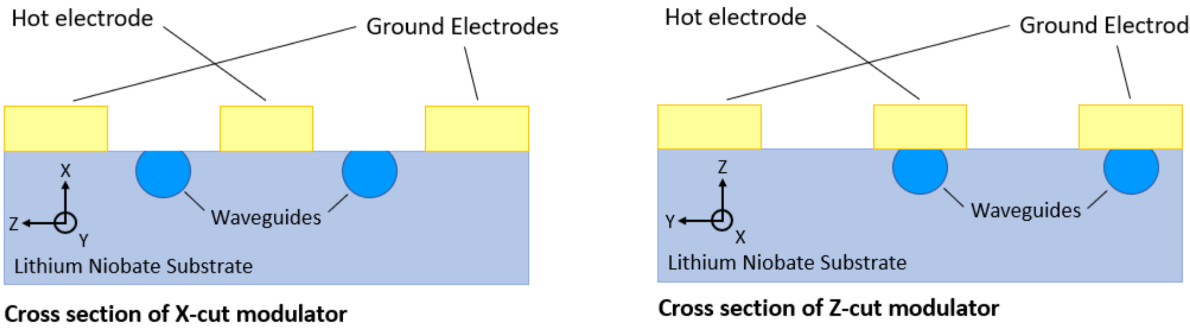


Figure 4. (Left) cross section of an X-cut modulator and (right) cross section of a Z-cut modulator

Waveguide Fabrication Methods

Since the mid-70's of the last century, the most common integrated optical waveguide-based devices in lithium niobate crystals have been realized by exploiting Ti in-diffusion due to its lower cost in massive production. For this reason, this technique is one of the most widespread and studied of all the lithium niobate technology.

Proton Exchange (PE) is another classical technique for waveguide fabrication in lithium niobate. Compared with Ti in-diffusion, it can generate higher extraordinary refractive index changes (Δn_e close to

0.1) but is not suited for ordinary light confinement. Often PE is complemented with a subsequent annealing in a controlled atmosphere, leading to the so-called Annealed Proton Exchange (APE). This process permits a high polarization rejection and a better resistance to the optical damage, for applications using a shorter wavelength than those exploited in the telecommunications. The annealing, in fact, helps in recovering the nonlinear coefficients that are compromised by standard PE processing. A comparison between the two methods is listed as in Table 1.

	Ti in-diffusion	APE
Cost	Simple and lower cost	Longer process, higher cost
Process temperature	1060 °C max, more resistant to higher temperature processes later but may introduce wafer warping	350 °C max, lower temperature process, less likely to warp
Propagation loss	~ 0.3 dB/cm typical	~ 0.5 dB/cm typical
Crystal orientation	Waveguide can be formed on both X and Z cut crystal	X cut only
Polarization	Both TE & TM, need to build in a separate polarizer	TE only, > 60 dB PER
Operation Wavelength	O & C band typical, not good for 1um or shorter	Visible to NIR
Optical Power Handling Capability	Photorefractive damage undermines performance when operated under high power density	10x Higher than Ti in-diffusion
Waveguide profile	Out-diffusion leading to unwanted guided modes	Better control of mode field profile
Surface Roughness	~Twice the thickness as the originally deposited titanium layer	Immeasurable change in surface roughness

Table 1. Comparison between Ti in-diffusion and APE waveguide fabrication methods

Polarization Maintaining Fiber

All optical fibers experience some degree of birefringence due to mechanical stress, (such as bending of the fiber), ambient temperature, or imperfections within the fiber. This birefringence causes the polarization of the propagating light to change in an uncontrollable way. Therefore, polarization maintaining fibers are made to prevent this issue. Our company uses PANDA fibers which have two stress rods built into the fiber that apply mechanical stress to the core (Figure 5), thereby inducing a high birefringence. This method allows the polarization state of the light to be maintained throughout the fiber, even if it is bent. However, in order for this to work properly, the polarization of the input light must align with the slow axis, otherwise little to no light will be transmitted through the fiber. By convention, the slow axis of the fiber is aligned to the connector key, as seen in Figure 6.

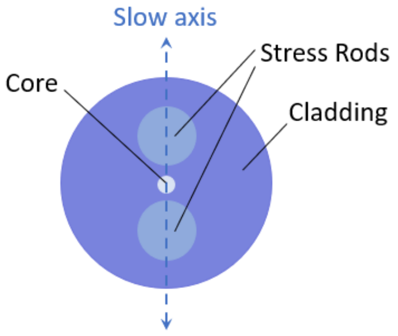


Figure 5. PANDA fiber cross section

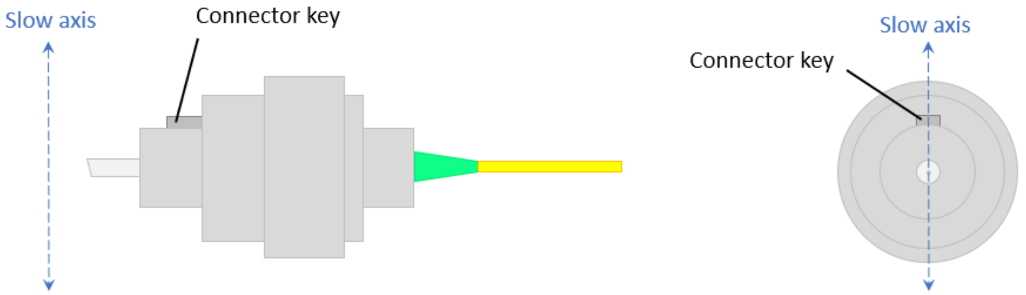


Figure 6. (Left) Side view of fiber connector and (Right) front view of fiber connector

Modulation Schemes

There are many different methods a modulator uses to encode information onto a signal, where the information is encoded in a series of 1's and 0's. The method of encoding either a 1 or 0 in the signal is what sets these methods apart from each other. Additionally, the construction of a modulator determines how information is encoded onto the signal.

Binary Phase Shift Keying (BPSK)

BPSK is one of the simplest types of modulation schemes with two symbols. A phase of 0 represents binary 1 and a phase of π represents binary 0. Because the phase of these symbols are as far as possible from each other, this method is useful when modulating a weak signal.

Differential Phase Shift Keying (DPSK)

DPSK is similar to BPSK in that two symbols are used, however the binary number recovered depends on the change in phase rather than the phase itself. When the data bit is low (0), the phase is not reversed and it stays the same. When the bit is high (1), the phase is reversed.

Quadrature Phase Shift Keying (QPSK)

A modulator built to operate in QPSK is essentially two Mach-Zehnder interferometers combined. This allows the modulator to transmit two bits per symbol rather than one. A symbol in BPSK or DPSK represents either a 1 or a 0, whereas with QPSK, a symbol can represent 00, 01, 10, or 11 depending on the phase of the symbol.

Differential quadrature phase shift keying (DQPSK) expands on this design by encoding the symbol information as the change in phase, similar to DPSK.

Dual Polarization Quadrature Phase Shift Keying (DP-QPSK)

This modulator is two QPSK modulators combined, where each QPSK modulator corresponds to either the X or Y polarized signal. Light enters as a single polarization state and goes through each QPSK modulator. The signal leaving one of the two QPSK modulators is rotated 90° so that it is orthogonal to the other signal. These two signals are combined to create a signal with both X and Y polarizations. With 16 possible symbols, the bit rate is essentially quadrupled compared to a single QPSK modulator.

Internal Monitoring Photodiode

Some intensity modulators have a photodiode (PD) built in to monitor the optical output power. One method to implement a monitor PD is to construct a "tap" near the end of the waveguide, after light has passed through the MZI structure. The tap splits power from the waveguide and redirects it to the PD. Another method of integrating a monitor PD is by placing it near the end of the waveguide so that it detects light which leaks from the waveguide. Here at Optilab, our IMC series modulators utilize a tap PD and our IML and IMP series modulators utilize a leakage PD.

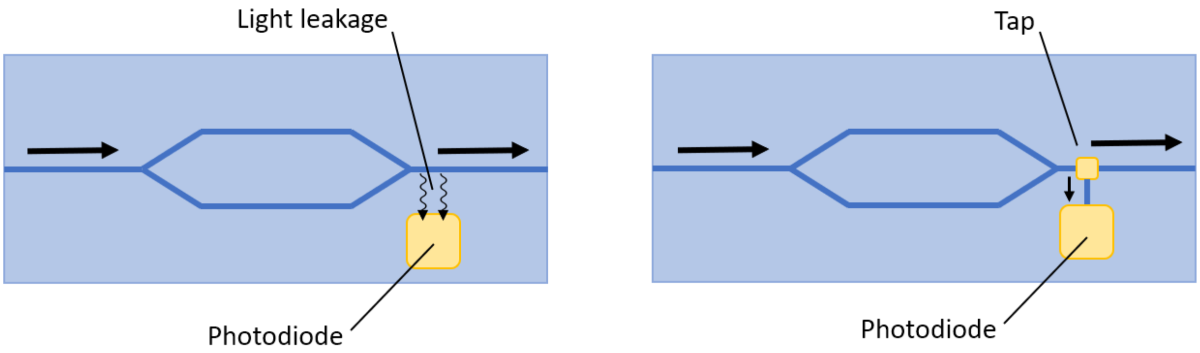


Figure 7. Intensity modulators using a leakage PD (left) and a tap PD (right)

The current generated by a tap PD is directly proportional to and in phase with the modulation output power, making optical power monitoring very straightforward. However, introducing such a tap would increase the overall insertion loss of the modulator, making it undesirable in some applications. A leakage detection mode PD configuration is more cost-effective and does not introduce extra loss; however, it is more complicated to relate the PD current to the modulation output power. When there is constructive interference in the waveguide, light propagates in a waveguide mode and the PD detects near minimal power. When there is deconstructive interference, light converts to a radiation mode and leaks outside of the waveguide, and the PD detects near maximum power. This means the PD current caused by the radiation mode is out of phase with the modulation output power. In a real device the PD current even slightly deviates from the exact out of phase situation. As shown in Figure 8, there is a slight voltage offset, V_{OS}, between the minima of the PD signal curve and the maxima of the modulation output power. The amount of offset can be defined as the monitor PD bias shift:

$$\text{PD Bias shift (\%)} = \frac{V_{OS}}{V_{\pi}} * 100\%$$

PD bias shift varies with the temperature and the wavelength. When $P_{O\,MAX}$ is behind $I_{PD\,MIN}$, such as it is in Figure 8, PD bias shift is positive. When $P_{O\,MAX}$ is in front of $I_{PD\,MIN}$, PD bias shift is negative.

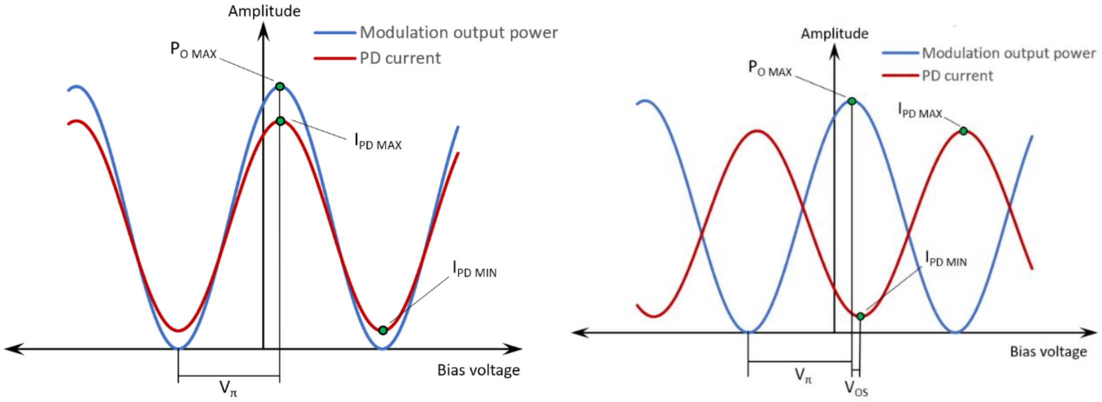


Figure 8. Monitor PD in tap detection mode (left) and leakage detection mode (right)

The extinction ratio of the PD can be calculated using the maximum and minimum of the PD current:

$$\mathrm{ER}_{\mathrm{PD}}(\mathrm{dB}) = 10\log\frac{\mathrm{I}_{\mathrm{PD\ MAX}}}{\mathrm{I}_{\mathrm{PD\ MIN}}}$$

Typically, $\mathrm{ER}_{\mathrm{PD}}$ of PD in leakage detection mode is much smaller than the modulator ER. For example, $\mathrm{ER}_{\mathrm{PD}}$ could be 6 to 10 dB for a modulator with an ER range from about 20 – 30 dB.

The responsivity of the monitor PD is quantified as:

$$\text{PD responsivity (A/W)} = \frac{\mathrm{I}_{\mathrm{PD\ MAX}}}{\mathrm{P}_{\mathrm{O\ MAX}}}$$

Per the definition above, we can see that the PD responsivity is referenced to the modulator output power, not the input power.