Application Note 2

Practical Uses and Applications of Electro-Optic Modulators

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Electro-optic amplitude and phase modulators allow you to control the amplitude, phase, and polarization state of an optical beam electrically. For instance, in communications systems, these modulators impress information onto an optical frequency carrier. Unlike direct modulation of the laser itself, external modulators do not cause any degrading effects on laser linewidth and stability. In measurement systems, amplitude modulators can be used as actuators to hold the intensity in a laser beam constant, or as optical choppers to produce a pulse stream from a CW laser beam. Phase modulators are used to stabilize the frequency of a laser beam, or to mode-lock a laser.

There are basically two types of modulators: bulk and integrated-optic. Bulk modulators are made out of discrete pieces of nonlinear optical crystals and are typically used on a lab bench or an optical table. They feature very low insertion losses, and high power-handling capability. Integrated-optic modulators, because they use waveguide technology to lower the required drive voltages, are wavelength specific. Unlike bulk modulators, these modulators are fiber pigtailed and compact.

After a brief discussion on the electro-optic effect, Part I of this application note will describe the use and application of bulk modulators. Part II of this application note will discuss integrated-optic modulators.

The Electro-Optic Effect

The linear electro-optic effect is the change in the index of refraction that is proportional to the magnitude of an externally applied electric field.[1] The effect of an applied electric field on the index of refraction, seen by an optical beam polarized in an arbitrary direction in a crystal, is described by a third-rank tensor.[2] Ignoring the vector nature of the physical quantities, the effect of an external electric field on the index of refraction of a crystal has the form

$$\Delta n = n_0^3 r \frac{E}{2}$$

where Δn is the change in the index of refraction, n_0 is the unperturbed index of refraction, r is the appropriate element in the electro-optic tensor, and E is the applied electric field. This effect is small even in the few crystals with large electro-optic coefficients. For example, an electric field of 10^6 V/m applied to a crystal of lithium niobate will produce a fractional index change of roughly 0.01%. It is rare to see fractional index changes greater than 1%.

Part I: Bulk Modulators

New Focus manufactures electro-optic amplitude and phase modulators using lithium niobate, $LiNbO_3$, and lithium tantalate, $LiTaO_3$—two crystals with high electro-optic coefficients and good optical and electrical properties. These crystals are grown in large, low scatter-loss boules, and have a wide transparency window. They are also nonhygroscopic so they can be left on an optical table for indefinite periods without being in a sealed enclosure.

Phase Modulation

The phase modulator is the simplest electro-optic modulator. Here, an electric field is applied along one of the crystal's principal axes.[3] Light polarized along any other principal axis experiences an index of refraction change, hence an optical path length change, that is proportional to the applied electric field. The phase of the optical field exiting from the crystal therefore depends on the applied electric field. The most common bulk phase modulator is the transverse modulator, as shown in Fig. 1, which consists of an electro-optic crystal between parallel electrodes. These modulators develop large electric fields between the electrodes while simultaneously providing a long interaction length, l, in which to accumulate phase shift. The optical phase shift, $\Delta\phi$, obtained from applying a voltage, V, between the electrodes is given by

$$\Delta\phi = \frac{\pi n_0^3 r V}{\lambda} \cdot \frac{l}{d}$$

where λ is the free-space wavelength, and d is the electrode separation. A commonly used figure of merit for electro-optic modulators is the **half-wave voltage**, V_π. It is defined as the voltage required to produce an electro-optic phase shift of 180°. Substituting into the preceding equation yields

$$V_\pi = \frac{\lambda}{n_0^3 r} \cdot \frac{d}{l}$$

for a transverse phase modulator.

It is important to note that the properties of a phase-modulated optical beam do not differ in any way from those of any other phase-modulated carrier wave.[4] Most importantly, phase modulation cannot be separated from **frequency modulation**. The instantaneous frequency of a periodic signal is defined as the time derivative of the overall phase of the signal. Therefore, for a phase-modulated signal

$$2\pi f(t) \equiv \frac{d\Phi(t)}{dt} = \omega + \frac{d\phi(t)}{dt}$$

where $f(t)$ is the instantaneous frequency, $\phi(t)$ is the signal's global phase, and ω is the optical frequency. Given a phase modulation $\phi(t)=m\sin\Omega t$ where m is the phase-modulation index, sinusoidal phase modulation results in sinusoidal frequency modulation at a fixed frequency Ω, but with a 90° phase lag and a peak-to-peak excursion of $2m\Omega$.

The phase-modulated field amplitude can be represented as a set of Fourier components in which power exists only at the discrete optical frequencies $\omega \pm k\Omega$

$$E_{pm} \equiv E_o e^{i[\omega t + m\sin\Omega t]}$$

$$\equiv E_o \left\{ \sum_{k=0}^{\infty} J_k(m) e^{ik\Omega t} + \sum_{k=0}^{\infty} (-1)^k J_k(m) e^{-ik\Omega t} \right\} e^{i\omega t}$$

where k is an integer, m is the phase-modulation index (modulation depth) and $J_k(m)$ is the ordinary Bessel function of order k.

In the case of small modulation index, $m<<1$, then only the $k=0$ and $k=1$ terms are significant and the expansion reduces to

$$E_{pm} \approx E_o\left[1 + im\sin\Omega t\right]e^{i\omega t}.$$

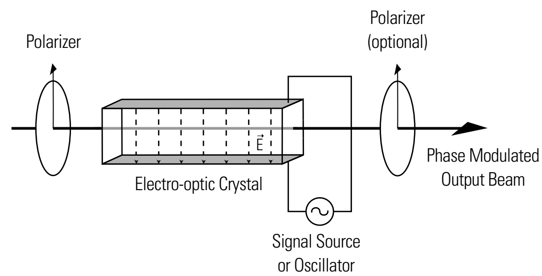

Fig. 1: A transverse electro-optic phase modulator. In the case shown, the input beam is polarized in the direction of the electric field within the crystal. The signal is applied as a voltage across electrodes on the top and bottom of the electro-optic crystal.

Here, most of the optical power resides in the Fourier component, called the "carrier," at frequency ω, with a small amount of optical power residing in the two first-order sidebands at frequencies $\omega \pm \Omega$. This frequency-modulating property makes phase modulators useful in laser mode-locking.[5]

Amplitude Modulation

To understand the operation of an electro-optic amplitude modulator, let's first consider an **electro-optic waveplate**. Suppose an optical beam, polarized at 45° to the crystal's principal axes, travels parallel to the third axis of an electro-optic crystal. With no applied field, the crystal is generally an arbitrarily retarding, multiple-order waveplate.[6] When an external electric field is applied, the electro-optic effect changes the indices of refraction along the two crystal directions to a different degree, thereby changing the retardation of the effective waveplate.

The geometry of a simple amplitude modulator, as shown in Fig. 2, consists of a polarizer, an electro-optic crystal cut for zero retardation, and an analyzer. The input polarizer guarantees that the optical beam is polarized at 45° to the crystal's principal axes. The crystal acts as a variable waveplate, changing the exit polarization from linearly polarized (0° rotated from the input) to circularly polarized, to linearly polarized (90° rotated), to circular, etc., as the applied voltage is increased. The analyzer transmits only the component of the exit polarization that has been rotated, thereby producing a total transmission of 0, 0.5, 1, and 0.5

respectively. The relationship between the transmission and applied field is not linear but rather has a $\sin^2$ dependence. To obtain **linear amplitude modulation**, these modulators are often biased at 50% transmission and only operated with small applied voltages. Two ways to bias the modulators are by one, adding a DC voltage through a bias tee, or two, adding a quarter-wave plate before the analyzer. The voltage required to bias the modulator at 50% transmission without a quarter-wave plate is the quarter-wave voltage of the modulator. It has a similar form to the quarter-wave voltage of the transverse phase modulator.

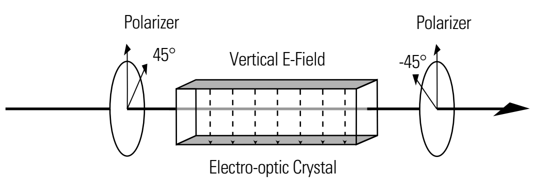

Fig. 2: An amplitude modulator in its simplest form consists of an electro-optic crystal between two crossed polarizers. The signal is applied as a voltage across electrodes on the top and bottom of the electro-optic crystal.

This simple geometry is not practical with most electro-optic crystals, due to the temperature dependence of these crystals' birefringence. This dependence introduces a temperature-dependent waveplate into the modulator. Consequently, the transmission of an uncompensated modulator using birefringent nonlinear media (such as $LiNbO_3$, or $LiTaO_3$) will exhibit substantial **thermal drift**. This temperature sensitivity can be overcome by either stabilizing the temperature of a single-crystal modulator, or by using two identical crystals. The second scheme employs two equal-length crystals placed optically in series with their principal axes rotated 90° with respect to each other, as seen in Fig. 3. The optical beam's polarization components therefore travel equal path lengths in each of the two index regions, which leads to a structure with zero birefringence, independent of temperature. Thermal drift limits the usefulness of a phase modulator, which is typically made out of a single crystal.

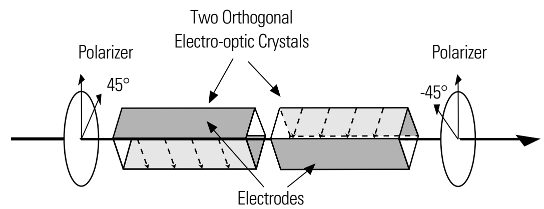

Fig. 3: Thermal bias drift can be passively compensated using two crystals oriented orthogonally with respect to each other. In the case shown above, the crystals are mounted at 45°. Thus, the input polarization is vertical. The applied field is reversed in the second crystal. In this manner, the thermal birefringence is compensated but the desired birefringence is doubled.

Practical Limitations

There are several practical limits on the performance of these devices. Mainly, the **optical power handling capability** of $LiNbO_3$ and $LiTaO_3$ is limited by an effect known as photorefractive damage. Although this effect is sometimes useful (as in holographic data storage) and does not permanently damage the crystals, it can degrade the performance of a modulator. A modulator with a photorefractively damaged crystal will distort an optical beam passing through it.[7] The best way to avoid photorefractive damage is to keep the optical intensity below the specified limit for the modulator. Since the photorefractive effect is highly wavelength dependent, modulators can handle correspondingly higher powers at longer wavelengths. New Focus also uses $LiNbO_3$ that has been doped with magnesium-oxide (Mg-O). This new material exhibits far superior power-handling capability.

Another limitation results from the fact that all materials with nonzero electro-optic coefficients are also **piezoelectric**. This means that the same electrical signal that produces phase modulation also generates vibrations. Strains induced by these vibrations alter the indices of refraction via the elasto-optic effect. These vibrations can cause unwanted amplitude modulation or beam displacements at the modulation frequency. The piezoelectric constants of $LiTaO_3$ and $LiNbO_3$ are fairly weak, and typically do not affect the performance of the crystals as long as the mechanical resonance frequencies (typically between 1 and 10 MHz) are avoided. New Focus will not ship single-frequency modulators tuned near a piezoelectric resonance.

A third limitation when using a phase modulator is **residual amplitude modulation**. An ideal phase modulator should not modulate the intensity of an optical beam. Amplitude modulation will be induced by sources of back-reflection placed after the phase modulator. Back-reflections result in weak étalons which will alter the harmonic content of the modulated optical beam by introducing a measurable amplitude modulation component onto the beam. Unwanted amplitude modulation can be minimized by properly aligning the input polarization state to the principal axis of the modulator, which is vertical in the case of New Focus modulators. You can further reduce residual amplitude modulation by using a collimated optical beam positioned down the center of the modulator. To enable quick and easy alignment of its modulators, New Focus offers the Model 4902 tilt aligner.

Broadband Modulators

New Focus offers modulators designed to modulate either the amplitude or phase of linearly polarized light over a wide bandwidth, from DC to roughly 100 MHz, with a relatively low drive voltage. The electrical input impedance of these devices in this frequency range is dominated by the capacitance of the electro-optic crystal. This capacitance ranges from 10 pF for the Model 4104 amplitude modulator to 30 pF for the Models 4002 and 4004 phase modulators. Signal generators and frequency synthesizers typically have 50-**Ω** output impedances, and are not optimized for driving capacitive loads. However, since 30 pF is a fairly small capacitance, most signal generators are adequate drivers at low frequencies (<10 MHz) and small signal levels. High-voltage amplifiers optimized to drive capacitive loads can also be used to effectively drive modulators. New Focus offers the Model 3211 high-voltage amplifier, capable of delivering a 200-V_{pk} signal into a 100-pF load at a frequency of 1 MHz.

At high frequencies, the impedance mismatch between the cable carrying the modulation signal and the modulator causes a fraction of the RF signal to be reflected back toward the source.[8] A directional coupler inserted between the source and the modulator, as shown in Fig. 4, can be used to redirect the reflected

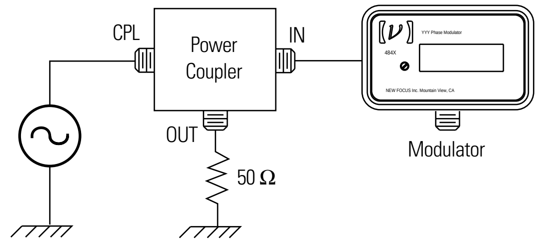

Fig. 4: When using a broadband modulator, use the directional coupler to protect the RF source from back-reflections from the modulation.

power to a matched terminator and thereby protect the signal source. Terminating the line driving the modulator with a 50-**Ω** load in parallel with the modulator input is an easy way to improve the system's impedance match. At drive frequencies greater than 100 MHz for phase modulators and 200 MHz for amplitude modulators, the RC pole created by this termination will reduce the response to the drive signal by 20 dB per decade. Since the modulators dissipate a minimal amount of power, it is important that all terminators chosen are rated to handle the maximum power output of the signal source or power amplifier. For example, to sinusoidally modulate the phase of an optical beam with a peak phase excursion, m, of 0.5 radian in a 50-**Ω** system requires an electrical power

$$P = \frac{m^2 V_\pi^{\ 2}}{2\pi^2 R} = \frac{(0.5)^2 (162\ \mathrm{V})^2}{(2\pi^2 50\ \Omega)} = 6.6\ \mathrm{W}$$

with a Model 4002 phase modulator. This high power requires the use of power amplifiers and special terminators.

The advantage of a broadband modulator is the flexibility it provides the user to select any modulation frequency, or even to modulate with nonsinusoidal waveforms. Applications where this is important include optical chopping, and short-pulse mode-locking. Another common use for an amplitude modulator is as the actuator in an amplitude stabilizer as shown in Fig. 5. Here, a photodetector measures a portion of the laser intensity which the servo uses to adjust the transmission of the amplitude modulator. An important consideration in this application is the nonlinear response of the modulator. The changing slope of the modulator's response to input voltage leads to a change in the closed-loop transfer function which could destabilize the feedback loop.

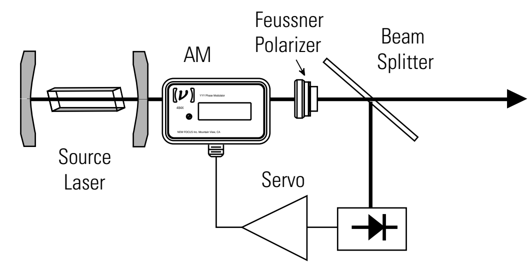

Fig. 5: An amplitude modulator can be used to reduce the amplitude fluctuations.

Resonant Modulators

Many applications require modulation at a single, fixed frequency. The frequency required in the specific application can vary from a few kilohertz to many gigahertz. In these cases, true impedance matching can be achieved, and the required drive voltage can be reduced, by using a resonant circuit. The simplest type of resonator is the LC tank, shown in Fig. 6. In this circuit, a modulator crystal and a low-loss inductor are used to form a series resonant circuit. On resonance, the resonant circuit looks like a small resistor whose value depends on the inductor's losses. The transformer is used to match this resistance to the 50-Ω driving impedance. By impedance matching to the source, and using low-loss components, the voltage across the capacitor can be more than ten times greater than the input voltage, leading to reduced half-wave voltages when compared to a broadband modulator. This reduced voltage requirement is made possible by the energy storage properties of the resonant circuit. For example, if one used a Model 4001 resonant phase modulator to produce a 0.5-radian modulation as before, the power required would only be

$$P = \frac{(0.5)^2 (16\ \mathrm{V})^2}{(2\pi^2 50\ \Omega)} = 64.8\ \mathrm{mW}.$$

Two factors limit the performance of the lumped-element resonator. The first is the power-handling capabilities of the inductor. Saturation of the inductor core places a limit on the RF-input power that can be used to modulate the optical beam. Also, most of the power dissipation occurs in the inductor and excessive input power will burn it out. Secondly, at frequencies greater than 200 MHz, ordinary lumped circuit elements are difficult to make. Circuits with dimensions comparable to the operating (RF) wavelength are efficient radiators, and therefore very difficult to analyze. Furthermore, conventional wire circuits tend to have a high effective resistance due to radiative energy loss as a result of the skin effect. Enclosures completely surrounded by conducting metal confine electromagnetic fields and furnish large areas for current flow, simultaneously eliminating radiation and high-resistance effects. Such cavities have natural resonant frequencies, and can be used to replace resonant circuits at high frequencies.[9] New Focus offers cavity-resonant, single-frequency modulators out to 10 GHz, a frequency limited by the increasing RF losses in the electro-optic material itself.[10]

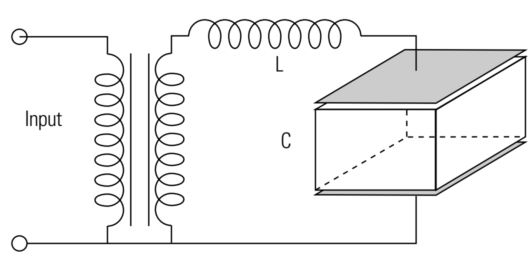

Fig. 6: A simplified impedance-matching circuit for the resonant modulators.

Applications for single-frequency modulators are quite varied. In the audio regime, these modulators are used in fiberoptic sensor and interferometric applications as well as in low-frequency lock-in detection schemes. Medium- to high-frequency modulators (to 200 MHz) find applications in mode-locking (AM and FM), laser stabilization, phase-sensitive detection, and pump-probe detection schemes. Modulators with frequencies to 10 GHz find applications in FM spectroscopy, laser stabilization, and laser linewidth-broadening experiments.

Part 2: Integrated-Optic Modulators

Like the bulk modulator, the integrated-optic modulator also works on the principle of the linear electro-optic effect.[11] All New Focus integrated-optic devices are made from lithium niobate ($LiNbO_3$), because of its relatively high electro-optic coefficient and high-quality crystals. An **integrated-optic phase modulator** is simply constructed using a dielectric optical waveguide and the linear electro-optic effect to control the index of refraction of the waveguide (Fig. 7). In the presence of an electric field, light traveling through this material will experience a change in propagation delay, $\Delta t=(\Delta nL)/c$, which is equivalent to a change in the phase of the light at the output as given by

$$\Delta\phi=\omega\Delta t=(\Delta n\omega L)/c$$

where Δn is the absolute change in index of refraction due to the applied electric field, ω is the optical frequency, L is the interaction length, and c is the speed of light in a vacuum.

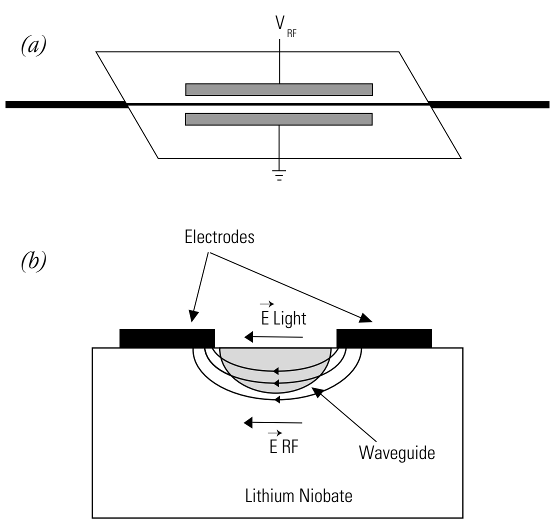

Fig. 7: Integrated-optic phase modulator (a) top view, and (b) side view

Amplitude modulators are constructed by patterning a Mach-Zehnder interferometer on a $LiNbO_3$ substrate (Fig. 8). The input optical waveguide is split into two paths and then recombined. A voltage applied to the center electrode with the side electrodes grounded (push-pull configuration) results in an electric field with opposite polarity across the two paths of the interferometer. Positive and negative electric fields change the index of refraction in opposite directions, increase the relative phase shift in one path, and decrease it in the other path. Total transmission occurs for a 0° net phase difference, and total extinction occurs for a 180° net phase difference between the two paths. For an ideal amplitude modulator, the optical power at the output of the modulator is $P_{out}=1/2\ P_{in}\ [1+\cos(\Delta\phi)]$ where P_{in} is the input optical power and $\Delta\phi$ is the phase difference between the two paths. An amplitude modulator is often biased at the half-power point (or quadrature-point) for **linear operation**.

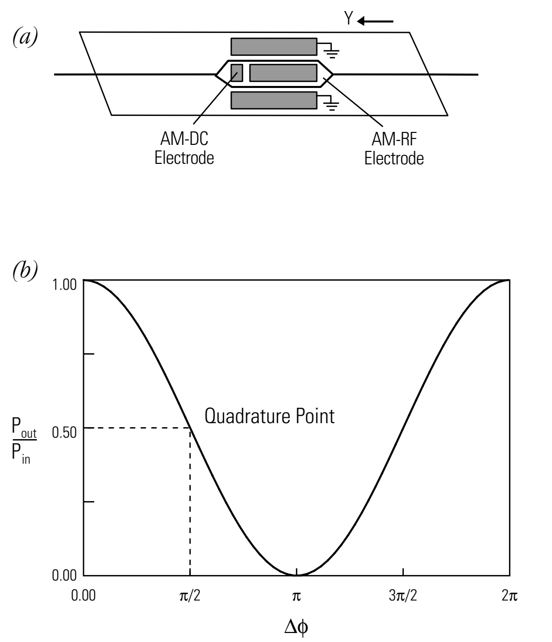

Fig. 8: Mach-Zehnder amplitude modulator (a) top view, and (b) transfer function.

Other configurations are also commercially available depending on the particular applications. For example, there are modulators with both phase and amplitude sections on the same chip (Fig. 9a). Complementary-output amplitude modulators have been designed for use in signal processing and cable television applications (Fig. 9b). One output is used for transmission while the other output can be used either for transmission or in a feedback control system to stabilize thermal drift and minimize harmonic distortion.

Modulators have also been designed for fiber-optic gyroscope applications (Fig. 9c). Even though these modulators are more complex than a basic phase modulator, they still operate using the basic principle of the linear electro-optic effect.

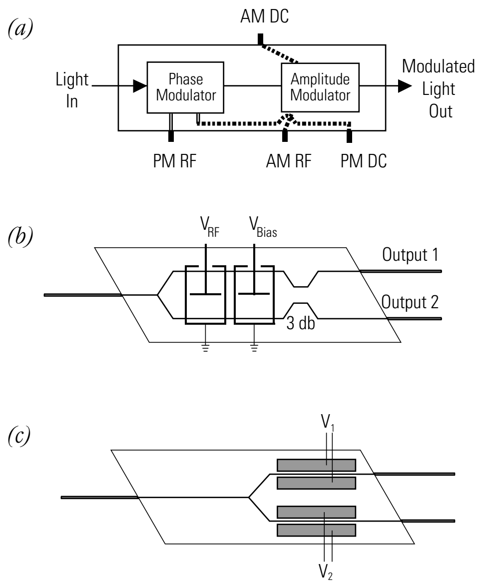

Fig. 9: (a) Amplitude and phase modulator on same chip, (b) complementary-output amplitude modulator, and (c) modulator for fiber-optic gyroscope systems.

Advantages of Integrated-Optic Modulators

Integrated-optic modulators require lower drive voltages and operate at higher frequencies than bulk modulators. Because of their small size and compatibility with single-mode optical fiber, they have been used in a variety of communication and sensor applications. Their disadvantages, compared to bulk modulators, include lower maximum optical power and incompatibility with free-space beams. However these have not limited the impressive results achieved. The following list, though not comprehensive, illustrates the wide variety of applications for integrated-optic modulators.[12]

Phase modulators have been used in digital optical communication experiments using 4-Gb/s phase-shift keyed (PSK) modulation, 4-Gb/s differential phase-shift keyed (DPSK) modulation and 8-Gb/s quadrature phase-shift keyed (QPSK) modulation. Amplitude modulators have been used in a 770 km, 2.5-Gb/s long-distance optical-communication experiment, a 20-GHz analog link, a 50-channel AM video transmission demonstration, and a novel optical clock recovery scheme. In addition, more complex integrated-optic modulators are also seen in many applications. Modulators with both phase and amplitude sections integrated on the same chip (Fig. 9a) have been used to transmit 125-Mb/s amplitude shift-keyed (ASK) data and 2.488-Gb/s PSK data simultaneously on the same lightwave. Also, multi-function integrated-optic modulators, similar to the one in Fig. 9c, are being used in advanced fiber-optic gyroscope experiments.

Details about Integrated-Optic Modulators

There are two main processes for patterning single-mode optical waveguides on $LiNbO_3$: **titanium (Ti) indiffusion** and **annealed proton exchange (APE™)**. In both cases, the waveguide pattern is defined on the surface of a $LiNbO_3$ crystal using photolithography. The more developed approach is titanium indiffusion. To create a titanium waveguide, Ti is diffused through a mask into the substrate at a temperature near 1000° C. This results in a permanent increase in the refractive index that guides the light in both width and depth. Titanium waveguides support both transverse electric (TE) and transverse magnetic (TM) optical polarizations. The APE process is an alternative to titanium indiffusion. It creates a much larger refractive index increase (5% vs. 0.5% for Ti indiffusion), but guides only one polarization. Also, it is more resistant to optical damage. APE waveguides are created by exchanging H^+ ions (protons) for Li^+ ions in the $LiNbO_3$ crystal by placing the patterned crystal in a proton-rich melt such as benzoic acid. The $LiNbO_3$ is then annealed for a few hours to cause further diffusion of the protons.

Lithium niobate is an anisotropic, uniaxial crystal with $n_o=n_x=n_y=2.23$ and $n_e=n_z=2.15$, where n_o is the ordinary index of refraction and n_e is the extraordinary index of refraction. Due to the crystal symmetry in $LiNbO_3$, there are two useful crystal orientations, **Z-cut** and **X-cut** (Fig. 10), which take advantage of the strongest electro-optic coefficient (r_{33} in the Z direction). A Z-cut device uses the vertical component of the electric field, and an X-cut device uses the horizontal component. For a Z-cut device, an optical isolation layer is required to avoid increased optical losses since one of the electrodes is placed on top of the optical waveguide. All New Focus modulators use an X-cut crystal orientation in order to provide temperature stability and a propagation direction that utilizes the largest electro-optic coefficient.

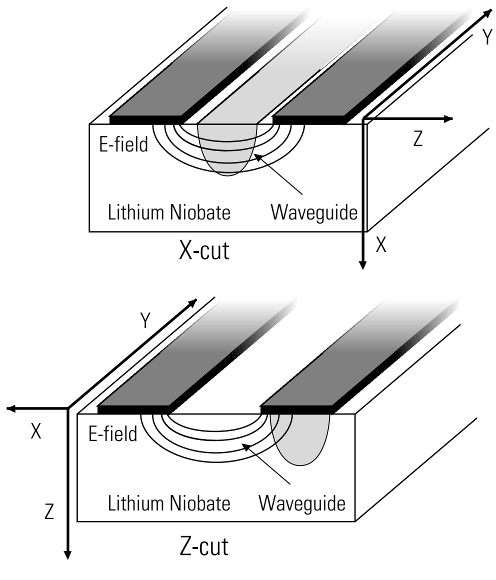

Fig. 10: Geometry of $LiNbO_3$ modulators.

To create a well-defined electric field within the optical waveguide, thick gold electrodes are deposited on the $LiNbO_3$ substrate. The modulation **bandwidth** of an integrated-optic modulator depends on the type of electrode. Lower frequency modulators use lumped-element electrodes where the electrode length is small compared to the drive-signal wavelength. The modulation bandwidth is limited by the RC time constant of the electrode capacitance and the parallel matching resistance. The parallel matching resistance is normally set to 50 Ω to allow broadband matching to a 50-Ω driving source. It is very difficult to build a lumped-element modulator with a bandwidth much higher than 1 GHz. The modulation bandwidth can be improved by using traveling-wave electrodes at the expense of fabrication simplicity. Traveling-wave electrodes are designed as transmission lines, fed at one end and terminated with a resistive load at the other end. With traveling-wave electrodes, the modulator bandwidth is limited by the difference between the optical and RF signal's transit times across the crystal rather than the lumped-element RC time constant. Much effort has been put into designing traveling-wave modulators where the RF and optical signals travel at the same speed, and thus, have a high bandwidth. Research devices have been demonstrated with over 40 GHz of electrical bandwidth.[11] A modulator with resistively matched, traveling-wave electrodes can operate down to DC. If the traveling-wave electrodes are transformer matched, the required drive voltage is lowered, but the modulator becomes a band-pass device and will not work down to DC.

The **optical wavelength** of the modulator must be specified, because the waveguides and electrodes are optimized for a particular wavelength. Wavelengths that are commonly available are 1.3 µm and 1.5 µm corresponding to the low-loss windows of single-mode optical fiber.

For maximum efficiency, the input optical field must have a **linear polarization** properly aligned with the modulating electric field. Modulator chips are typically connected to polarization-maintaining (PM) fiber at the input and either PM fiber or single-mode (SM) fiber at the output using UV-curable adhesive. These fibers are commonly referred to as pigtails. To reduce optical reflections, the modulator chip is anti-reflection (AR) coated or angle-polished before connecting the pigtails. **Optical return loss** is the ratio of the back-reflected optical power in the input fiber to the input optical power, expressed in dB. The back-reflected light is generated at the interface between the fiber pigtail and the $LiNbO_3$ crystal. With an angle-polish, the incident light is reflected at an angle and very little reflected light is coupled back into the input fiber. The optical return loss should be less than -30 dB for most applications.

Insertion loss is the optical power loss in the modulator expressed in dB. It is measured as the ratio of optical power in the input fiber to the optical power in the output fiber when the modulator is biased for maximum transmission. This value accounts for the loss between the fiber pigtails and the modulator, as well as the loss in the modulator itself. Insertion loss should be in the range of 4–7 dB. Additional loss may occur, depending on the method used to couple light into the fiber pigtails.

Working with Integrated-Optic Modulators

Note: When working with integrated-optic modulators, be aware of all manufacturer-specified safe operating levels. Exceeding the maximum electrical voltages or optical power can result in permanent damage to your modulator.

There are a few options for coupling light into a modulator: **fiber-optic connectors, mechanical splices, fusion splices,** or **free-space coupling**. When connecting a PM fiber to a PM pigtail, the axis of the two fibers must be properly aligned. If you do not have experience working with PM fiber, it is easiest to have the pigtails professionally connectorized with properly aligned connectors. Using connectors is a stable and repeatable method for connecting two PM fibers. If you have the experience and patience to work with PM fiber, mechanical splices are an alternative to connectors. Mechanical splices are available from a variety of vendors. Avoid mechanical splices with mechanical lock-downs. The screws in these types of splices can break the stress rods in PM fibers. Fusion splicers are very expensive and generally not recommended for PM fiber. In addition, if fusion splicers align the two fibers in reference to their outer diameter, the results will vary. The center of the core of many PM fibers is not within sufficient tolerance to the outer diameter to achieve repeatable, low insertion loss. If your source is a free-space laser beam, then fiber coupling using a lens and fiber positioner is another alternative.

For quick laboratory measurements, an SM fiber can be temporarily connected to the PM pigtail, but some type of polarization control, such as a mechanical, fiber polarization-controller, must be used to align the input optical polarization with the axis of the PM fiber. In addition, the polarization control will have to be periodically adjusted (on the time scale of minutes) to correct for environmentally induced polarization fluctuations in the SM fiber.

When selecting an **amplifier** to drive an integrated-optic modulator, keep in mind the bandwidth of your signal. Some applications are narrow-band and others, such as digital optical communications, require signal components down to DC. Even a pseudo-random bit stream (PRBS) can require signal components as low as 10^{-4} to 10^{-6} times the data rate. So a 3-Gb/s non-return to zero (NRZ) data stream could potentially require a bandwidth from DC to 3 GHz. Also, the output power of the amplifier must be high enough to modulate your optical signal to the desired depth at all frequencies. To fully modulate the optical signal requires an amplifier with an output power of

$$P_{\text{out}} = 30 + 10\log\left[\frac{(V_\pi/2)^2}{50}\right] \text{ dBm.}$$

As an example, consider the same 3-Gb/s NRZ signal for modulation of the amplitude section of a New Focus Model 4503 dual function PM & AM modulator. The V_π is 10 V at DC. Therefore, P_{out} of the amplifier must be at least 27 dBm to fully modulate the optical signal.

Most modulators will come from the supplier with a data sheet listing measured device parameters such as insertion loss, V_π extinction ratio, and possibly, the optical bandwidth. For an amplitude modulator, V_π and its extinction ratio are easy to measure with a good power meter.

Determining V_π for a phase modulator is not as simple. One way to indirectly measure V_π is by applying a sinusoidal-modulation voltage and calculating the modulation depth from the measured spectrum of the phase modulated optical field.[13] The electrical bandwidth can be determined by repeating the measurements for the amplitude or phase V_π at different frequencies. The 3-dB point is the frequency at which V_π has increased to $\sqrt{2}$ times its DC value.

Summary

Bulk and integrated-optic electro-optic modulators find uses in a wide variety of applications. They make it easy to modulate the amplitude or phase of an optical signal up to 10's of gigahertz. Bulk modulators are well-suited for applications with high optical powers or broad spectral bandwidth requirements.

Integrated-optic devices operate within 10% of the center wavelength, and are available in many configurations for a variety of applications such as digital optical communications, analog video transmission, and fiber sensors. Understanding how these modulators work and how to work with them will allow you to make your measurements and develop your systems in the most efficient and accurate way.

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[2] For example, Yariv, pp. 280–283.

[3] For more background on birefringent crystals, see New Focus Application Note 3 on polarization.

[4] See the analysis in A. B. Carlson, *Communications Systems*, Ch. 6.

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