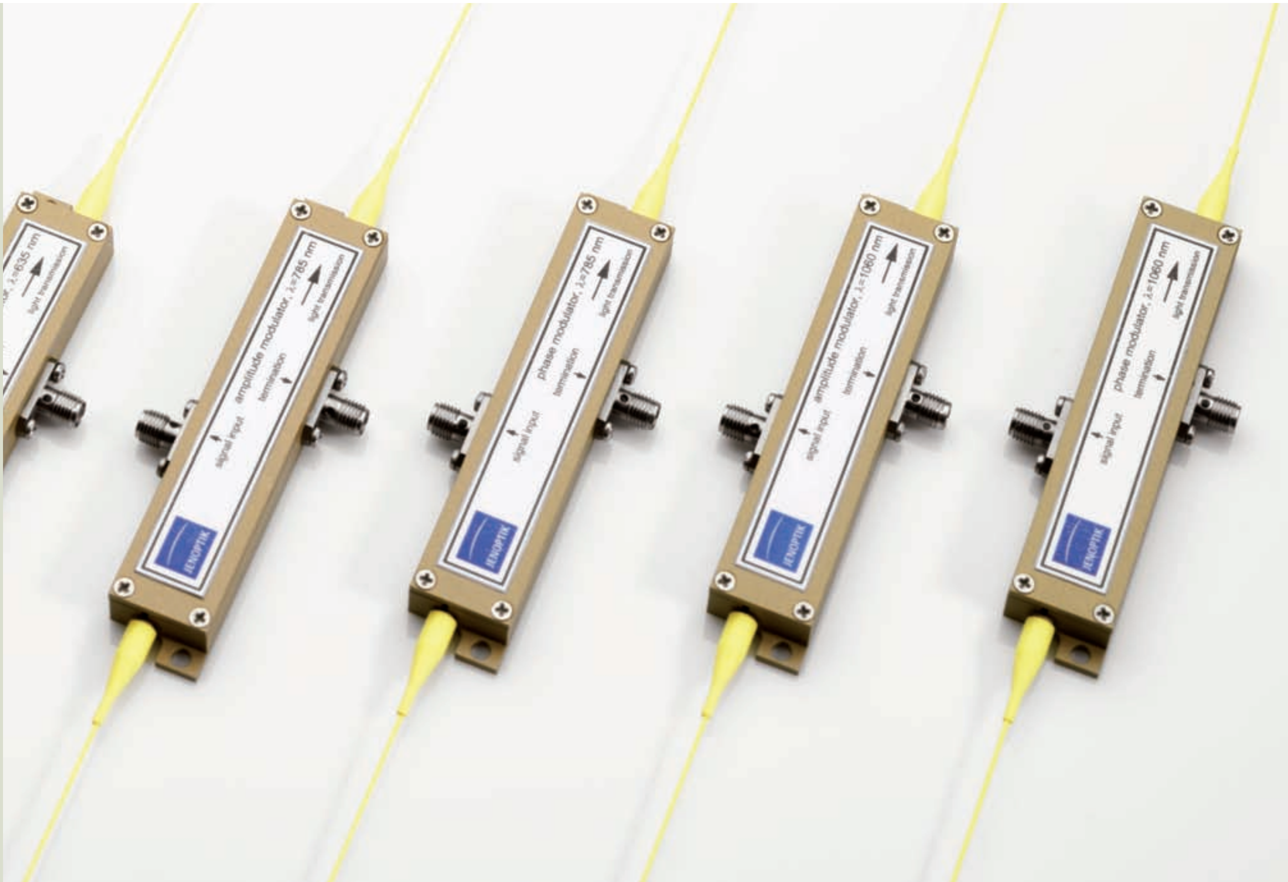
JENOPTIK

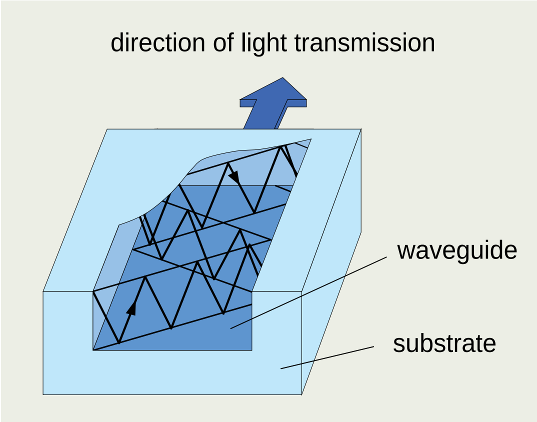
Integrated-optical Modulators
Technical Information



Digital Imaging

Description of operation

Integrated-optical modulators are light modulators based on waveguide technology.
The waveguides are fabricated in planar substrates. They are able to guide light along a determined path.
The properties of the substrate determine the waveguide properties such as electrooptical modulation essentially.



The waveguide consists of a channel with higher refractive index compared to the surrounding material. The light is guided by means of total internal reflection at the channel walls. Depending on the wavelength, substrate refractive index, refractive index increase, width and depth of the channel one or more transverse oscillation states (modes) can be excited. The single mode operation is of great interest since it is essential for the function of many integrated-optical elements.
Integrated-optical devices are coupled with optical fibers particularly in optical communication technology.
To achieve a good coupling efficiency to the fiber, single mode waveguides are typically three to nine microns in width and depth, depending on wavelength.
Various elements like Y-branches, polarizers, phase- and amplitude modulators, switches or wavelength multiplexers can be implemented using integrated-optical waveguides.

The electrooptic effect

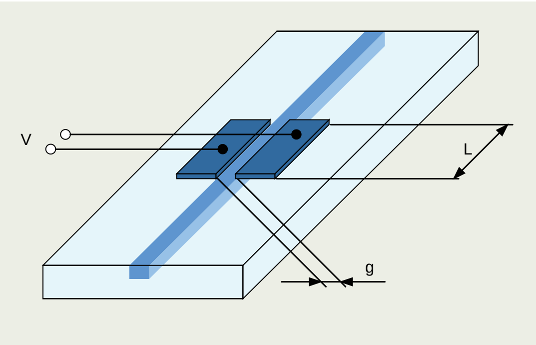
The linear electrooptic effect, also known as Pockels-Effect, describes the change of the refractive index of an optical material if an external electric field is applied. The amount of change in refractive index is proportional to the electric field strength, its direction and the polarization of the light. This interaction is described with the electrooptic tensor and is mostly anisotropic. The effect occurs in polar materials, including ferroelectric crystals. The preferred material in integrated optics is Lithium niobate ($LiNbO_3$).
In this crystal the strongest interaction occurs between the outer electric field in the crystallographic z-direction (E_3) and z-polarized light with its refractive index n_3.
It amounts to

$$\Delta n_3 = -\frac{1}{2} n_3^3 r_{33} E_3$$

The electrooptic coefficient r_{33} is 33 pm/V. The definite function requires the use of linear polarized light.

Phase modulators

If a homogeneous electric field is applied over a waveguide of length L, the phase of the guided light changes. Because of the very small waveguide cross section it is not possible to place electrodes to produce a homogeneous field. Therefore a coplanar electrode arrangement on the crystal surface is preferred.
This generates an inhomogeneous field distribution with an efficiency Γ lower than 1.



A good approximation of phase shift can be described by:

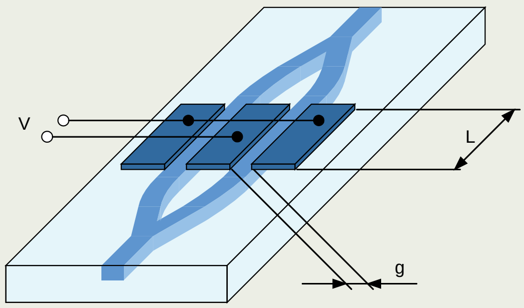
$$\Delta\varphi = -\frac{\pi L}{\lambda} n_3^3 r_{33} \frac{V}{g} \Gamma$$

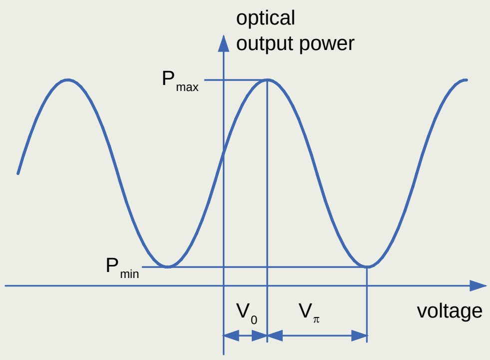
The half wave voltage V_π, which causes a phase shift of π is calculated by:

$$V_\pi = -\frac{\lambda g}{n_3^3 r_{33} L \Gamma}$$

This typically amounts to a few volts. Due to the very fast electrooptic response, together with low control voltages and the use of sophisticated electrode geometry, it is possible to achieve modulation at frequencies in the gigahertz range.

Amplitude modulators





To form an amplitude modulator a phase modulator is inserted into an integrated Mach-Zender interferometer. Applying a voltage leads to a phase difference in both branches, which causes a change of the output power at the device output by means of interference. So the device transmission can be controlled between a minimum and a maximum value (P_{min} to P_{max}). The extinction ratio is given by the ratio of maximum to minimum output.

The output power depends on the control voltage in cosine form:

$$P = P_{min} + (P_{max} - P_{min})\left(\frac{1}{2}\cos\left(\frac{\pi(V - V_0)}{V_\pi}\right) + \frac{1}{2}\right)$$

The half wave voltage is required to switch from transmission state into the off-state and vice versa. Using a push-pull electrode arrangement it is the half of that of a phase modulator with identical electrode length. The operation point differs from the theoretical value V_0=0. It is controlled by special electronics.

Selection Criteria

Integrated-optical modulators for different applications are available in the substrate material $LiNbO_3$. The selection is done depending upon the desired application.

Wavelength

Various properties of the modulators, in particular the half wave voltage and insertion loss, depend on the operation wavelength. While the half wave voltage decreases at shorter wavelengths, the insertion loss increases. Amplitude modulation is possible with extinction ratio of more than 1000:1 in the red and near infrared spectral region, in the green the extinction amounts to more than 500:1.

Usable wavelength range

The usable wavelength range (optical bandwidth) depends on the substrate material and the central wavelength. The singlemode operation and definite modulation is guaranteed within this range.
In amplitude modulators it amounts to approximately 20 nm in the green, 50 nm in the red and 100 nm in the near infrared. Phase modulators have a greater optical bandwidth.

Polarization

Linear polarized light is required for definite modulator operation. Since waveguides in lithium niobate are polarizing, transmission losses are caused if the input polarization is not linear or not sufficient adjusted.

Optical power (cw)

The transmittable optical power depends on the wavelength. For wavelengths of more than 1 µm an optical power up to 0.5 Watt at the device input is possible. In the red range it amounts to 50 mW and 10 mW in the green.

Coherence of light

The modulators are designed for operation at one wavelength since the half wave voltage depends on the wavelength. An increase of the spectral width leads to lower extinction ratios in amplitude modulators.
For example at a spectral width of 15 nm the extinction ratio is about 100:1.

Pigtailing and housing

The modulators are produced with fiber pigtails. At the input port a polarization maintaining fiber is used. The output fiber is also polarization maintaining (not polarization maintaining singlemode or multimode output fibers are available on request). The devices can be delivered with bare fiber ends or fiber connectors, preferably FC/PC-connectors. Other connectors are possible.

Description of terms

Insertion loss (D)	loss of optical power if light is transmitted through the modulator $D=10 \lg (P_{in}/P_{out})$ P_{in}: optical power which is guided in the input fiber P_{out}: optical power which is guided in the output fiber if modulator transmission is maximal (on-state) (measurement using fiber cut back method)
Extinction	in the case of amplitude modulator the ratio of transmitted optical power in on- and off-states P_{max}/P_{min} (measurement at dc-voltage)
Half wave voltage (V_π)	• in the case of amplitude modulator the voltage difference for switching the modulator from on- to off-state or vice versa • in the case of phase modulator the voltage difference for shifting the phase of the optical output signal by π (measurement frequency 1 kHz)
Offset (V_0)	lowest voltage compared to 0 V, at which the transmission of an amplitude modulator is maximal (on-state) (measurement frequency 1 kHz)
Polarization of output fiber	polarization ratio of the light in the output fiber if a polarization maintaining fiber is used
Spectral bandwidth	possible deviation of the operation wavelength from the central wavelength of the modulator without substantial diminution of extinction and insertion loss (increase of insertion loss or decrease of extinction by 10 % with respect to the central wavelength)
Upper critical frequency	frequency at which the effect of the electrical input on the optical output signal decreases by one half
Rise time	time in which the optical signal of an amplitude modulator rises or falls between the 10 % and 90 % values of maximal tranmission if an electrical step-function is applied to switch the modulator between on- and off-states

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