High-Speed Modulators for Fibre-Optic Communication

Achieving high data rate for optical transmission has been a prime area of research for more than two decades. To enable this high-speed communication, external optical modulators play an important role in the optical fibre link.

Different types of configurations are available for external modulators. Two of them—LiNbO$_3$ and GaAs/InP based modulators—have become more popular due to their high performance over microwave frequency. This article provides an overview of various configurations of these two modulators and compares their merits

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A fibre-optic communication system uses the same basic functional components as a copper-based communication system—a transmitter, receiver and transmission medium—except that a fibre-optical link (FOL) uses optical fibre (in place of copper cable) as the transmission medium.

The basic structure of an FOL is shown in Fig. 1. Here the optical fibre connects the transmitter and the receiver. It carries information in the form of light and mainly consists of three regions, namely, the core, the cladding, and the buffer or coating that is used to give strength and protection to the fibre cable. The core is the central part of the fibre through which light passes because of the process of total internal reflection. The cladding surrounds the core, with a different refractive index so that light passing through the core stays in that region.

The transmitter consists of an electrical interface, optical modulator and light emitter, and a laser diode or LED for encoding. At the other side, to convert light into an electrical signal, the receiver uses either a PIN photodiode or an avalanche photodiode (APD).

Fig. 1 shows the simplest optical fibre link. Several other components take part in establishing an optical fibre link; for example, multiplexer, de-multiplexer, signal regenerators, signal repeaters (or optical amplifiers), couplers and splitters.

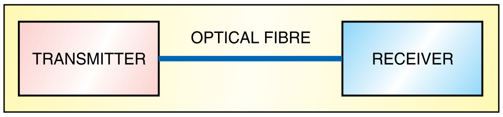
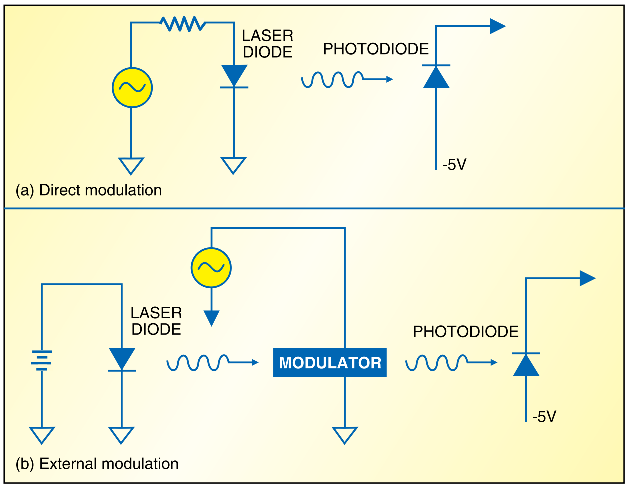


Fig. 1: Optical fibre communication link



(a) Direct modulation

(b) External modulation

Fig. 2: (a) Direct modulation and (b) external modulation

In an optical transmission system, choice of optical modulators plays an important part in the overall performance of the system. In this article, we'll focus on high-speed optical modulators, but before we dwell on them in detail have a look at the basics of optical modulators.

Optical modulators

Converting information in the form of electric signals into light waves is known as 'optical modulation.' This kind of modulation can be achieved either directly or externally.

In direct modulation, information in the form of electric signals is applied directly to the light source. Many links use this kind of technique to reduce complexity of the system, but when data rates or the length of the link increases, 'on'/'off' speed limitation of the laser generates waveguide chirp and phase modulation. This causes amplitude modulation distortion at the receiver side, which is undesirable for high-definition, high-data-rate communication. In such a situation, a continuously-'on' laser source provides a better solution. That is the basic idea of indirect modulation or external modulation.

In direct modulation, digital logic state '1'/'0' is applied directly as 'on'/'off' electric signal or two different levels of voltage to the light source. In these circumstances, factors like time constant of the driving circuitry, construction of the light source itself and the characteristics of the transmission medium (say, optical fibre) affect the highest frequency at which the light source can operate.

Using high-speed layout and microwave design techniques and high-speed short-pulse integration, the problem with the circuit and transmission medium can be minimised. But as stated earlier, the major limitation of this technique is switching of the light source itself. In a typical laser source, this switching causes electrical and thermal stress, which results in a frequency shift known as 'chirp,' transients and reduced life of the light source.

In external modulation, the laser diode itself stays unmodulated. Data is delivered directly to electrically modulate the crystalline material like lithium niobate. This device can repeatedly switch light without affecting the light source.

Three types of external modulators are commonly used: electro-absorption modulators based on gallium-arsenide or indium-phosphate semiconductor, electro-optic modulators based on polarised polymers, and modulators based on electro-optic crystals like lithium niobate and other materials.

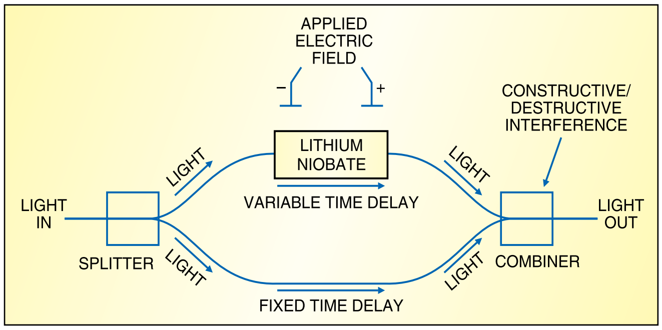


Fig. 3: Block diagram of a typical optical modulator based on LiNbO$_3$

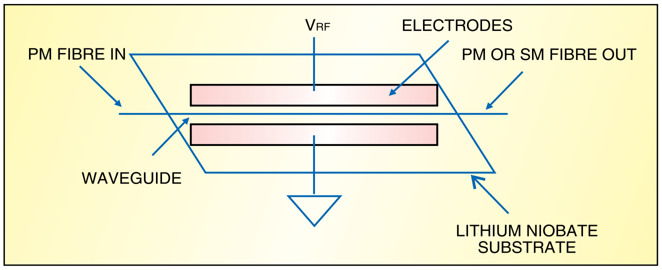


Fig. 4: Phase modulator

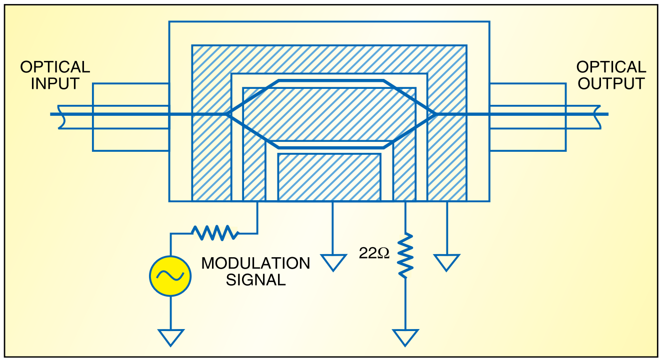


Fig. 5: LiNbO$_3$ Mach-zehnder interferometer optical modulator

Figures of Merit for Commercial Interferometric Modulators

Modulator type	E-O bandwidth (GHz)	Drive voltage (V)	Figure of merit
Lithium niobate Mach-Zehnder (wide e-o bandwidth)	30	6	5
Lithium niobate Mach-Zehnder (low drive voltage)	22	5.2	4.2
GaAs Mach-Zehnder	33	5.5	6
GaAs mode converter (wide e-o bandwidth)	40	6	6.7
GaAs mode converter (low drive voltage)	33	4	83

Fig. 2 shows the basic difference between direct and external modulators. Over the period, external modulators based on lithium niobate (LiNbO$_3$) have become more popular because of its low optical loss and high electro-optic coefficient.

Next is described the working of amplitude and phase modulators, followed by their comparison with semiconductor modulators based on GaAs (gallium arsenide) and InP (indium phosphate).

Design of lithium niobate modulators

Lithium niobate is an optically transparent dielectric material with low-loss tangent at microwave frequency. The high electro-optic coefficient, which corresponds to the electro-optic effect, changes the refractive index of the material in response to the applied electric field. The speed of light across the material depends on the refractive index of the material. So by changing the refractive index of the material, or, say, electric field in the material, you can control the speed of light.

Fig. 3 shows the block diagram of a typical optical modulator based on LiNbO$_3$. Light enters into the modulator through the splitter, which splits it into two separate beams and sends to two separate fibres.

In this kind of modulator, one fibre path travels through LiNbO$_3$ and the other is just through the normal fibre. The bottom fibre provides a fixed delay for the entire path, while the second depends on the refractive index of LiNbO$_3$.

Now as the refractive index depends on the electric field applied to the LiNbO$_3$ substrate, as the applied voltage changes, light's delay through the fibre path varies. At the end of the path, the two light beams are combined by the combiner. If beams are delayed by the same period of time, light signals reaching at the combiner should be in-phase so that they add up constructively and provide maximum amplitude for the signal. If they combine destructively, they will cancel out each other and/or, depending on the phase

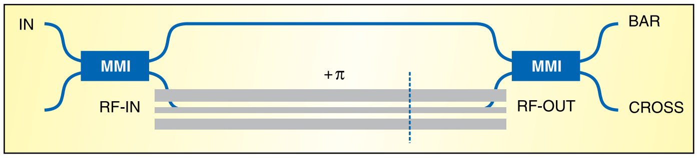


Fig. 6: Schematic top view of modulator

difference, this will change the light amplitude. This is the basic principle of an amplitude modulator.

Fig. 4 shows a phase modulator. A fibre-optic waveguide is made on the $LiNbO_3$ substrate. One electrode is grounded and the signal voltage is applied to the other electrode. Now as the voltage changes, its refractive index changes, and according to that, the phase of light changes across the path of the waveguide. This kind of modulation can be useful to remove 'simulated Brillouin scattering.'

Fig. 5 shows another modulator configuration based on the Mach-Zehnder interferometer used in Hewlett-Packard light-wave devices. Here two separate optical waveguides form two different phase modulators, due to which the co-planner microwave guide develops because of the push-pull effect in waveguides.

Modulators based on the electro-absorption technique are equally popular among the manufacturers. These modulators are based on semiconductor materials like gallium arsenide (GaAs) or indium phosphate (InP). The next section explains construction of one of such modulators.

High-speed modulators using III-V semiconductors

Fig. 6 shows a modulator based on Mach-Zehnder interferometer with 1mm long phase-shifter consisting of InGaAsP/InP ridge-type waveguide with p-i-n doping. This modulator has a 4µm optical waveguide that is etched 100 nm into the quaternary layer. It is specially designed for high-quality RF operation, with advantages like low optical and RF losses, small optical-electrical velocity mismatch and high modulation efficiency.

So which is better?

There are numerous advantages of using GaAs-based technology. First and foremost is the maturity of the technology. Benefits of lithium niobate over III-V semiconductors are low insertion loss and high bandwidth, but at the cost of large size. The InP-based modulators have small dimensions, high switching speed and low drive voltage but with the disadvantages of higher insertion loss and higher chirp.

An InP-based modulator made as per Fig. 6 can provide performance comparable to that of LN-modulators with much smaller device size. Furthermore, there are a number of other manufacturing- and operation-based advantages of compound semiconductors that are not available with LN-modulators. Waveguides in LN-devices are formed by in-diffusion of dopants, while in III-V components waveguides are usually formed by etching ridges in epitaxial layers. The accuracy of forming waveguides is higher for III-V components.

Future of modulator technology

The debate is still on over which modulation material is better and which will stand in the market, not only among the manufacturers but the researchers as well. Right now, GaAs-based technology is a few steps ahead. Many leading manufacturers are working to achieve data rate with the longest distance for transmission. Among them, Intel had recently announced its new high-speed silicon modulator. It is not first in its make but the technology is cheaper as claimed by the Intel researchers.

High-speed modulators are already used in optical and RF communication systems like radar antenna remoting and IF links. Position of high-speed optical modulation in the market is quite firm and will keep topping up as technology in the field grows wider. ●

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