

# White Paper Modulation of Light

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# Modulation of Light

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A key functionality of an optical system is the modulation operation, which consists in “converting” the electrical data signal into the optical domain. Ideal modulation is therefore equivalent to performing a frequency translation from the baseband to an optical carrier frequency, of the order of  $193 \times 10^{12}$  Hz for the usual 1550 nm transmission window. Until now, most optical communication systems made use of intensity modulation of light (i.e. its intensity or power is varied according to the data to be transmitted) since it allows to use a very simple detection process using a photodiode whose generated photocurrent is proportional to the incoming optical power. In this paper, we will exclusively focus on intensity modulation, although other types of optical modulation, such as phase and frequency modulation, are also possible and used.

We will briefly introduce two different strategies used for the optical intensity modulation operation, looking at the benefits and limitation.

## Direct vs. external modulation

The operation of modulation consists in transferring the data from the electrical to the optical domain. Two strategies can be used.

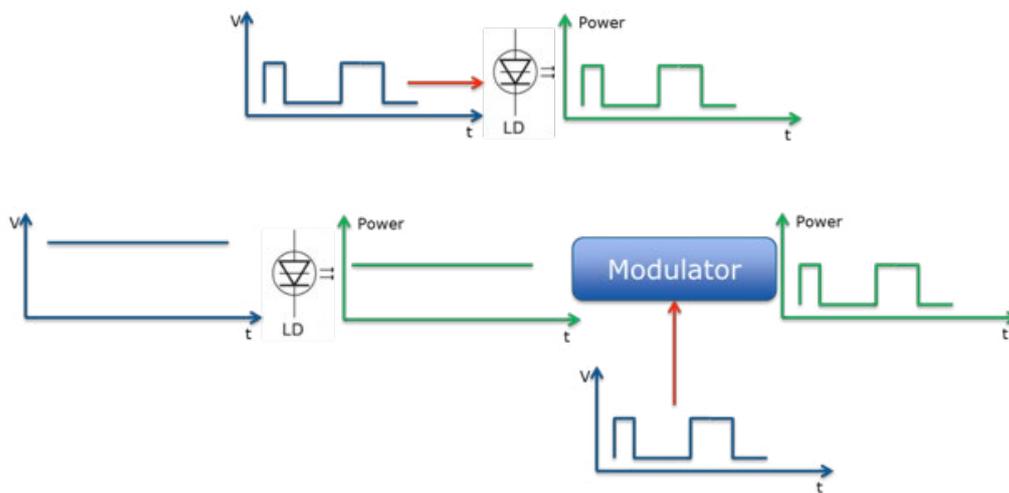
In the first technique, called direct modulation, light is emitted from a laser only when a “1” is transmitted. Ideally, no light should be emitted when a “0” is transmitted. However this is not always the case for practical implementations. In the second option, called external modulation, a continuous wave (CW) laser is used to emit light whose power is constant with time. A second component, known as modulator, is then used as a switch to let the light pass when the data corresponds to a “1” and to block it whenever the signal is a “0”. This switch can be implemented in different ways and we will briefly describe two physical effects that are used to perform external optical modulation at high bit rates. Note that here, the

key point is that the physical process that should permit the switch to toggle between its two states (“open” and “closed”) should be fast enough to allow proper operation at the desired bit rate.

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**Fig 1.** Direct vs. external modulation

**Fig 1.** schematic representation of direct vs. external modulation circuits.

The physical processes that are exploited to perform the modulation operation should be fast enough to allow proper operation at the desired bit rate. At 10 Gbit/s, the bit duration is 100 ps and we will expect the transmitter, whether a directly modulated laser or a continuous wave laser followed by an external modulator, to be able to switch between the “1” and “0” states within a fraction of this duration.

## Light modulation parameters

In this section we will briefly introduce two parameters that will be used in the following of this paper to evaluate modulation schemes: Extinction ratio (and OMA) and frequency chirping.

### Extinction ratio and Optical modulation amplitude

To measure the optical characteristics of a transmitter it is necessary to define a figure of merit for the amplitude of modulation, the principal definition used are Extinction ratio (ER) and optical modulation amplitude (OMA).

The extinction ratio of the optical signal is defined as

$$ER = \frac{P1}{P0}$$

where P1 and P0 are the power levels corresponding to the “1” and “0” levels, respectively.

It is important to achieve a good extinction ratio for the optical signal, i.e. to achieve a large separation between the power of the “1” and “0”, and ensure that as little power as possible is present in the signal when a “0” is transmitted.

The effect of a poor extinction ratio will otherwise manifest itself as power penalty at the receiver (i.e. an increased required optical power at the receiver in order to achieve a given bit-error-rate, compared to the case of an ideal signal with infinite extinction ratio) that will reduce the power budget of the system. The ER will be often expressed in logarithmic scale.

$$ER[dB] = 10 \log \frac{P_1}{P_0}$$

So the extinction ratio is used to describe the strength of the signal that the transmitter puts on the fiber. It is necessary but not sufficient to look at the average launch power—how strong the light is. We need to also consider the difference between the two digital levels (zero and one) that the transmitter puts out to properly assess the signal-to-noise ratio at the other end of the link.

The argument above presents an interesting question. Can we trade off launch power for extinction ratio, and vice versa, while maintaining the quality of the link? The answer is yes. This answer makes intuitive sense as one can see how at higher extinction ratios less power would be needed to overcome the impediments in the channel while maintaining the same quality of the link. So a new parameter called OMA (optical modulation amplitude) has been defined. OMA is the difference between the optical power in the ones and the optical power in the zeros. It is related to the average power  $P_{out}$  and the extinction ratio  $Er$  and summarizes them into one measurement:

$$OMA = 2P_{out} \frac{Er - 1}{Er + 1}$$

where  $P_{out}$  is the optical power in milliwatts and  $Er$  is the extinction ratio reported as a pure ratio.

Note the following two points about the three quantities:

- fixing two of the quantities automatically generates the third quantity, thus one only needs to measure two quantities at any one point.
- To satisfy a minimum OMA, a range of power and extinction ratio numbers can be found.
- One advantage of OMA is that it allows flexibility to trade off power for ER, increasing the yield of transmitters.

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## Frequency chirping

The operation of intensity modulation therefore consists in varying  $P(t)$  according to the modulating electrical signal. However, the desired intensity modulation of the light is often accompanied by a modulation of its phase, induced by the physical process used to produce the intensity modulation. Consequently, not only the power  $P(t)$  becomes a function of time, but also the phase  $\varphi(t)$ , which is very often an undesired feature.

The frequency of the optical carrier becomes then

$$\omega = \omega_0 + \frac{d\varphi}{dt}$$

This means that a time varying phase is equivalent to a change in the signal instantaneous frequency. This frequency modulation is usually referred to as frequency chirping. The amount of frequency chirp depends on the physical mechanism used to achieve light modulation, and on the design and operating conditions of the modulator.

Since the group velocity through an optical fibre is frequency dependent, the different frequency components of the spectrum of a pulse will travel at different speeds, hence leading to pulse broadening. In case an intensity modulated signal is transmitted, the information pulses will spread out of their allocated time slots, leading to inter-symbol interference, which will in turn introduce errors at the decision circuit (where the received signal is compared to a given threshold to decide whether a "1" or "0" has been transmitted) and lead to a degraded bit-error-rate. Intuitively, the effect of frequency chirping will be to broaden the spectrum of the modulated signal. As the effect of dispersion worsens with increasing signal spectral width, frequency chirping will, in general, result in reduced tolerance to group velocity dispersion.

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## External modulation

Two types of external modulators are commonly used in optical communication, the first type relies on the modification of the absorption of a semiconductor material when an external electric field is applied (electro-absorption modulator), while the second is based on the change of the refractive index observed for some crystals under an external electric field (electro-optic modulator). A change in refractive index itself does not modulate the intensity of light, but an interferometric structure, such as the Mach-Zehnder structure, converts the induced phase modulation into intensity modulation.

## Electro-Absorption

This type of modulator relies on the fact that the effective bandgap  $E_g$  of a semiconductor material decreases when an external voltage is applied. Consequently, if the wavelength is chosen so that its energy  $E = h\nu$  is smaller than the bandgap when no voltage is applied, the material will be transparent. On the other hand, when an external voltage is applied, the effective bandgap will be reduced, meaning that the light will be absorbed by the material when  $E > E_g$ . Shifting the absorption edge to achieve optical modulation will also induce a change in the refractive index of the material, hence in the phase or instantaneous frequency of the signal being modulated. Consequently, some amount of frequency chirping will be introduced by electro-absorption modulators, but the generated frequency chirp will usually be smaller than when direct current modulation of a semiconductor laser is used.

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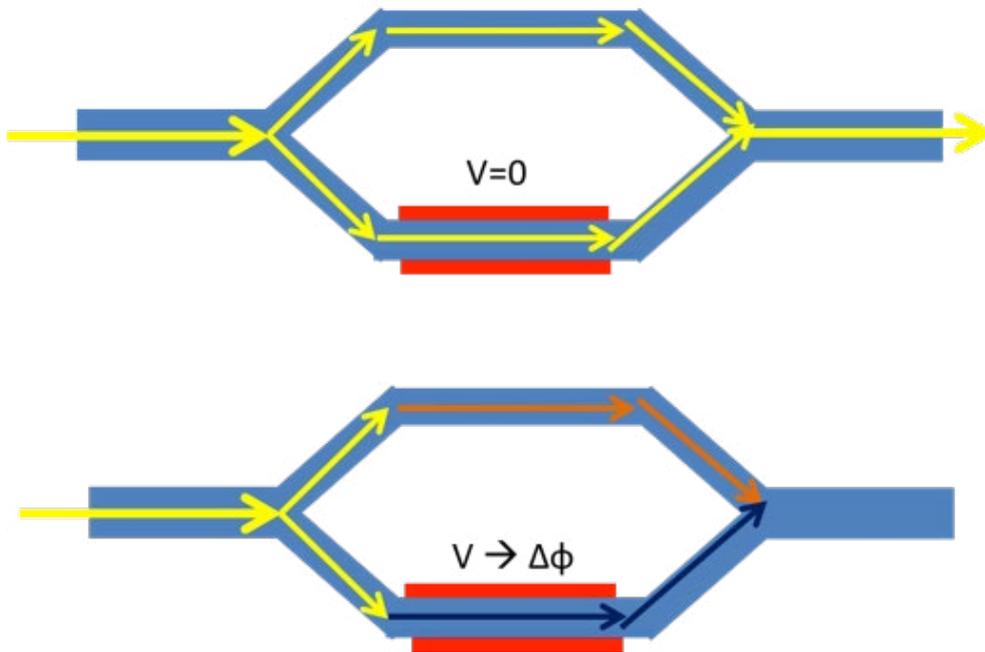
## Electro-optic modulation

The refractive index of some materials can be modified by applying an external electric field to them through the linear electro-optic effect. Since the phase shift experienced by light of wavelength  $\lambda$  propagating through a length  $L$  of a medium with refractive index  $n$  is

$$\varphi = \frac{2\pi}{\lambda} nL$$

a straightforward application is the realisation of phase modulators made from an electro-optic waveguide subjected to a time dependent electric field.

The applied voltage will modulate the refractive index of the material, causing a phase shift of the signal propagating along the waveguide. Intensity modulation can be achieved by transforming phase modulation into intensity modulation using an interferometric structure. In order to illustrate the principle, we consider the simple interferometric structure represented here below:



**Fig 2.** Mach-Zehnder modulator operation

Assuming a power splitting and combining ratio of  $1/2$  for the input and output, the power at the output of the interferometer depends on the phase shift difference of the light propagating in the upper and lower arms of the structure.

The phase shift induced in the lower arm of the interferometer depends on its refractive index, which itself depends on the applied external electric field through the electro-optic effect. If a time-dependent voltage  $V(t)$  is applied, its refractive index will become time-dependent and in turn the transmission of the Mach-Zehnder interferometer will also depend on time. If a continuous optical wave is present at the input of the modulator, the output power will thus be modulated according to the electrical data  $V(t)$ .

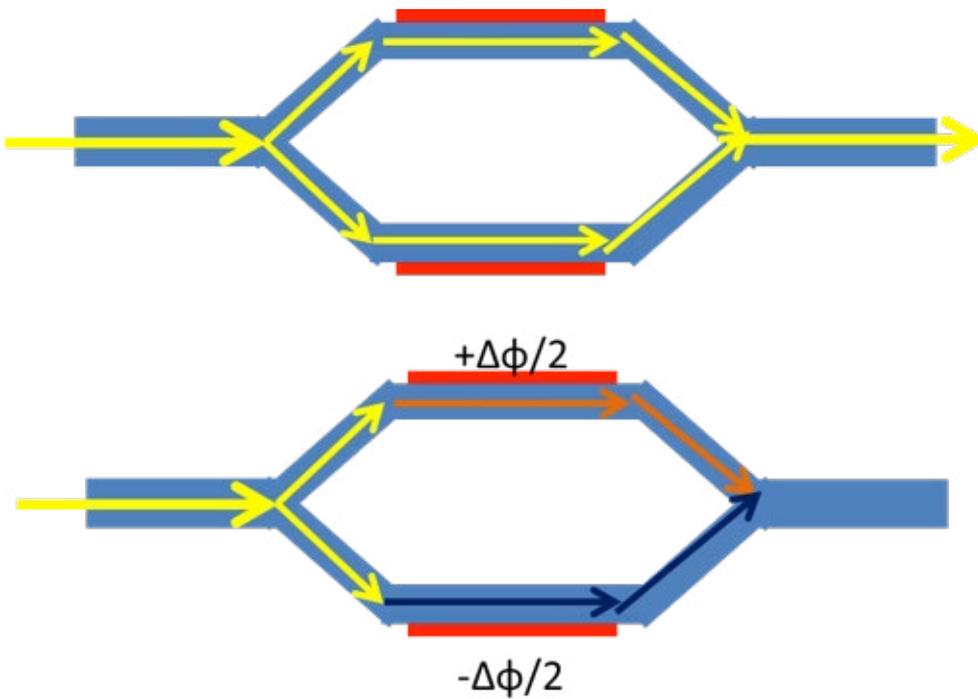
It is important to achieve a good extinction ratio for the optical signal, i.e. to achieve a large separation between the power of the "1" and "0", and ensure that as little power as possible is present in the signal when a "0" is transmitted. The value of the phase shift created by an applied external voltage depends upon many parameters, so to describe the ability of the material and chosen configuration to respond to an applied voltage it has been defined a quantity known as the half-wave voltage  $V_{\pi}$ .

**Fig 2.** Mach-Zehnder modulator operation: electrical field changes the refraction index of the material being able to create destructive interference.

Applying a voltage of  $V_{\pi}$  to the electrode of an electro-optic waveguide will result in a voltage-induced phase shift of  $\pi$ . The relation between voltage-induced phase shift and applied voltage  $V(t)$  is then

$$\varphi(t) = \pi \frac{V(t)}{V_{\pi}}$$

It possible to calculate the transfer function  $P_{out}/P_{in}$  of the modulator as a function of the applied voltage. The Mach-Zehnder described above will generate a chirped signal. The problem can be solved by applying two complementary modulating signals to the two arms of the Mach-Zehnder modulator. The chirp can be suppressed driving the modulator in push-pull configuration, either by driving the two arms of the interferometer with complementary signals, or by creating phase shifts of opposite signs.

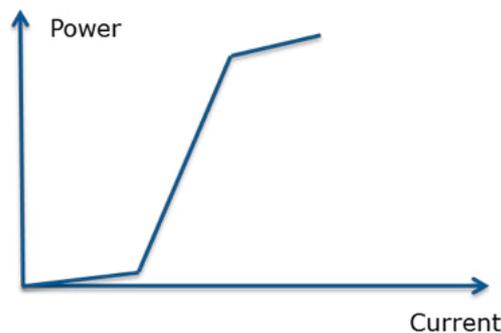


**Fig 3.** Mach-Zehnder modulator in push-pull configuration

Fig 3. In push pull configuration each arm produces half of the phase shift.

## Direct modulation

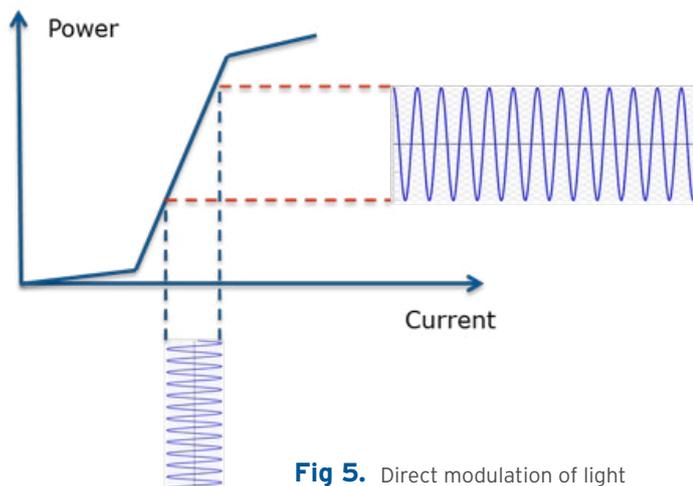
The power at the output of a semiconductor laser depends on the current injected through the laser diode according to the transfer function represented in the figure below.



**Fig 4.** Laser Power vs. Current characteristic

Fig 4. A minimum level of current is necessary to start laser action, at high current levels saturation occurs.

First, no light (apart from spontaneous emission) is emitted by the laser diode, until the current reaches the threshold value. Above threshold, population inversion is achieved, leading to lasing action. The laser output power then increases linearly with increasing current, until some saturation is reached for high bias current values. This dependence of the laser diode output power on the bias current can be exploited to convert the information from the electrical domain to the optical domain, if we let the current vary according to the data to be transmitted.



**Fig 5.** Direct modulation of light

Fig 5. A modulated current above threshold translates into modulated light.

One could in principle achieve a high extinction ratio by letting the laser driving current below threshold in order to generate "0" and increasing it to an above-the-threshold for "1", but in this case, the laser would switch from a state where no lasing occurs, to a state where population inversion is achieved, resulting in lasing operation. However, population inversion is achieved by injecting carriers into the structure and it takes some time for the carrier density to reach its threshold value when lasing begins which might not be compatible with high speed operation. The necessity to keep laser always above threshold limits the achievable extinction ratio of directly modulated sources.

Another effect present in directly modulated lasers is the relaxation oscillation: when the laser is subjected to a transient in its bias current, for instance during a transition from "1" to "0" or vice versa, its output power will exhibit damped oscillations, both the oscillation frequency and damping rate depend on the laser output power, hence on the value of the driving current. The physical origin of those oscillations is the interplay between the injected carriers and emitted photons.

When the laser is directly modulated, a change in the bias current will lead to a change in the carrier density, which in turn will lead to a change of the refractive index of the material. Since the lasing wavelength is determined from the feedback condition in the laser cavity, which itself depends on the refractive index, the instantaneous frequency of the emitted signal will be a time varying signal. Consequently, directly modulated lasers are inherently chirped. Without going into the equations of this phenomenon, we will only highlight that there are two contributions: the first one named transient chirp, only exists when the emitted power varies with time, for instance during transients of the applied current  $I(t)$  and induced relaxation oscillations, while the second term, named adiabatic chirp, is responsible for the different emission frequencies observed under steady state when a "1" or "0" is transmitted.

Source chirp combined with fiber dispersion limits the transmission distance, so directly modulated lasers, even if cheaper, are limited to short range applications.

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