Phase-Shift Keying:-

When the phase θ of the carrier is varied in accordance with the message signal $m(t)$ while keeping the amplitude A and frequency f_c constant, the resulting scheme is known as ***phase modulation***. Suppose the phase is proportional to the message signal,

$$\theta(t) = k_p m(t),$$

where k_p is called the phase sensitivity. Now, the optical carrier is said to be phase modulated. The modulated signal can be written as

$$s(t) = A\cos\left[2\pi f_c t + k_p m(t)\right].$$

For example,

$$m(t) = \begin{cases} -V & \text{for bit '1'} \\ V & \text{for bit '0'} \end{cases},$$

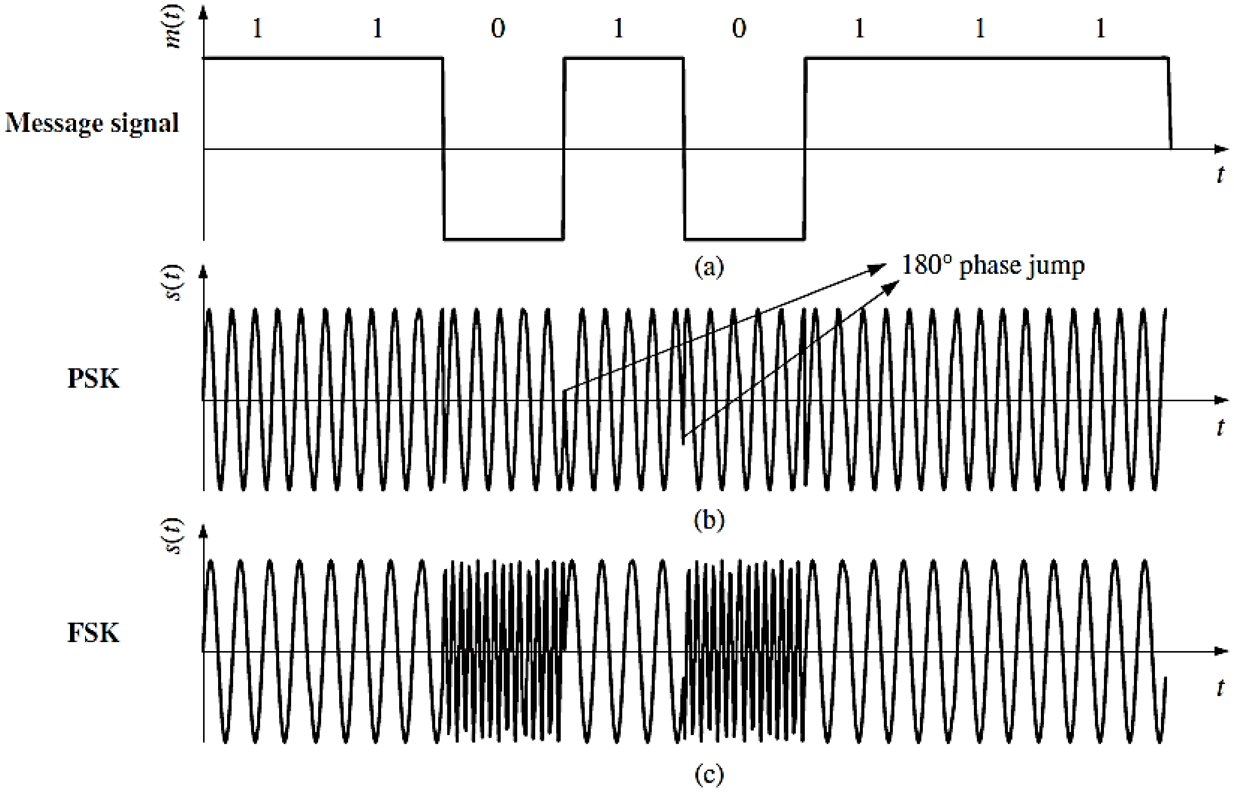
where $V = \pi/(2k_p)$. the equation above follows that:

$$s(t) = \begin{cases} A\sin\left(2\pi f_c t\right) & \text{for bit '1'} \\ -A\sin\left(2\pi f_c t\right) & \text{for bit '0'} \end{cases}.$$

When the message $m(t)$ is a digital signal, such as shown in Figure below, the modulation scheme is known as ***phase-shift keying*** (PSK) or ***binary phase-shift keying*** (BPSK). Figure shows the modulated signal when the modulation scheme is PSK. Note that there is a 180° phase jump at the bit boundaries if the digital data in the consecutive bit intervals are different. In general, PSK can be described as a scheme in which a bit '1' is transmitted by sending a sinusoid of phase θ_1 and a bit '0' is transmitted by sending a sinusoid of phase θ_2.

Frequency-Shift Keying:-

FSK can be described as a scheme in which a bit '1' is transmitted by sending a sinusoid of frequency f_1 and a bit '0' is transmitted by sending a sinusoid of frequency f_2, as shown in Figure below.



Phase and frequency modulation of an optical carrier. (a) Message signal, (b) Phase-shift keying, and (c) Frequency-shift keying.

Let the message signal be binary data of the form:-

$$m(t) = \begin{cases} m_1 & \text{for bit '1'} \\ m_2 & \text{for bit '0'} \end{cases}.$$

The transmitted signal within a bit interval [0, T_b] can be written as

$$s(t) = A\cos\left[\phi(t)\right],$$

where

$$\phi(t) = \begin{cases} 2\pi f_1 t & \text{for bit '1'} \\ 2\pi f_2 t & \text{for bit '0'} \end{cases},$$

$$f_i = f_c + k_f m_i, \quad i = 1, 2.$$

k_f is the frequency modulation index. Suppose the phase (t) in the bit interval [0, T_b] is $2\pi f_1 t$ and the phase (t) in the next interval is $2\pi f_2 t$. At $t = T_b$, (T_b −) = $2\pi f_1 T_b$ and (T_b+) = $2\pi f_2 T_b$. This could cause phase discontinuity at the bit boundaries, which is undesirable in some applications. One possible way of avoiding phase discontinuities is to choose the frequencies such that the phase accumulated over a bit interval is an integral multiple of 2π,

$$f_c + k_f m_1 = \frac{n}{T_b}, \quad n \text{ is an integer,}$$

$$f_c + k_f m_2 = \frac{l}{T_b}, \quad l \text{ is an integer.}$$

Under these conditions, the phase would be continuous throughout and such a scheme is known as ***continuous phase frequency-shift keying*** (CPFSK). Note that the ASK signal has a constant frequency and the amplitude is varying, whereas FSK is a constant-amplitude signal but the instantaneous frequency is changing with time.

➢ Optical Modulators

The simplest optical modulator we could think of is the switch of a flash light. Suppose we turn on a flash light for 1 second and turn it off for 1 second. We generate digital data '1' and '0', respectively. In this example, the bit rate of the optical data generated from the flash light is 1 bit/s. Widely used of modulators, one of these is the phase modulator.

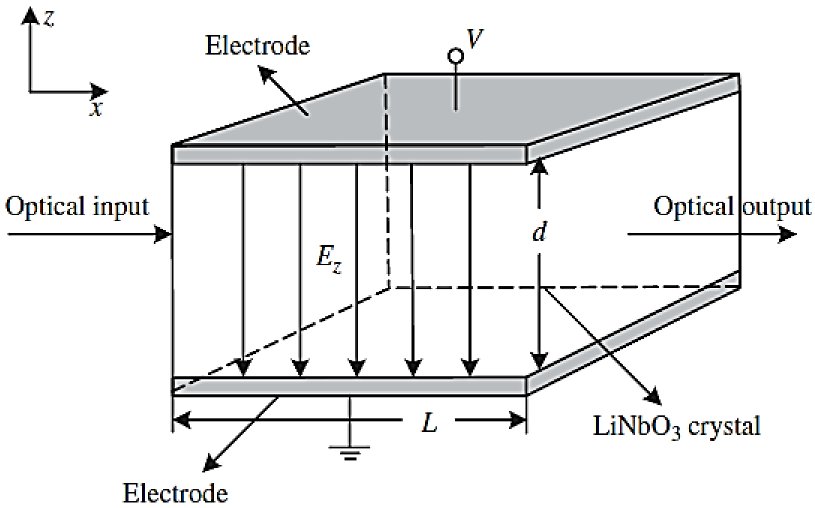
Phase modulator:-

The phase modulation of an optical carrier can be achieved in a number of ways. When an electric field is applied to an electro-optic crystal, the refractive index of the crystal changes and, therefore, the phase (∝ refractive index) of an optical carrier propagating in the crystal also changes. The refractive index change is directly proportional to the applied electric field intensity. This effect is known as the ***Pockels effect*** or ***linear electro-optic effect***.

Consider the light propagation in a $LiNbO_3$ crystal as shown in Figure below. Suppose E is the electric field intensity due to the applied voltage and an optical wave is propagating along the x-axis with its direction of polarization parallel to the z-axis. The dependence of the refractive index on the reflective field intensity is given by:-

$$n = n_0 - \frac{1}{2} n_0^3 r_{33} E_z$$

where n_0 is the refractive index in the absence of the applied electric field, and r_{33} is a coefficient describing the electro-optic effect. If V is the voltage applied across the crystal and d is the thickness of the crystal, the z-component of the electric field intensity is ($E_z = V/d$).



Suppose the optical field of the incident optical wave is:

$$\psi(t,0) \equiv \psi_{\text{in}}(t) = A_0 \exp(-i2\pi f_c t).$$

Therefore the optical wave emerging from the $LiNbO_3$ crystal is:

$$\psi_{\text{in}}(t,L) = A_0 \exp[-i(2\pi f_c t - \phi)],$$

where

$$\phi = \frac{2\pi}{\lambda_0} nL = \frac{2\pi L}{\lambda_0}\left(n_0 - \frac{n_0^3 r_{33} V}{2d}\right) = \phi_0 - \Delta\phi.$$

Here, ϕ_0 is the constant phase shift in the absence of the applied electric voltage, L is the length of the crystal, and:

$$\Delta\phi = \frac{\pi L n_0^3 r_{33} V}{\lambda_0 d}$$

is the phase change. The required voltage to yield a phase change of π is known as the ***half-wave voltage*** or ***switching voltage*** V_π, and is given by:

$$\Delta\phi = \pi = \frac{\pi L n_0^3 r_{33} V_\pi}{\lambda_0 d} \quad \text{or} \quad V_\pi = \frac{\lambda_0}{n_0^3 r_{33}} \frac{d}{L}.$$

Substituting the equations above, we obtain:

$$\psi_{in}(t, L) = A_0 \exp\left[-i\left(2\pi f_c t - \phi_0 + \frac{\pi V}{V_\pi}\right)\right].$$

Thus, we see that the phase change is directly proportional to the applied voltage. If $V(t)$ is a message signal, the phase of the optical carrier can be varied in accordance with the message signal. For the example, if $V(t) = V_\pi$, in a bit interval $0 < t < T_b$, the carrier phase is shifted by π. If $V(t) = 0$, no phase shift is introduced. Thus, the PSK or DPSK signal can easily be generated using a phase modulator.

Example: An electro-optic modulator operating at 1530 nm has the following parameters: Thickness d = 10 μm, Length L = 5 cm, Index n_0 = 2.2, Pockel coefficient r_{33} = 30 pm/V. Calculate the voltage required to introduce a phase shift of $\pi/2$.

Solution:

We have

$$V = \frac{\Delta\phi \lambda_0 d}{\pi L n_0^3 r_{33}}.$$

With $\Delta\phi = \pi/2$,

$$V = \frac{\pi/2 \times 1530 \times 10^{-9} \times 10 \times 10^{-6}}{\pi \times 5 \times 10^{-2} \times (2.2)^3 \times (30 \times 10^{-12})} \text{V}$$
$$= 0.47 \text{ V}.$$

H.W.: Explain the differences between NRZ and RZ formats. Which of these formats has a wider spectrum?

H.W.: Discuss the following modulation schemes: (i) ASK, (ii) PSK, and (iii) FSK.

H.W.: An electro-optic modulator operating at 1550 nm has the following parameters: Thickness d = 8 μm, Index n_0 = 2.2, Pockel coefficient r33 = 30 pm/V, It is desired that the half-wave voltage V_π is less than 2V. Find the lower limit on the length L.

(Ans: 1.94 cm.)