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External Modulators and Mathematical Modeling of Mach-Zehnder Modulator

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Abstract

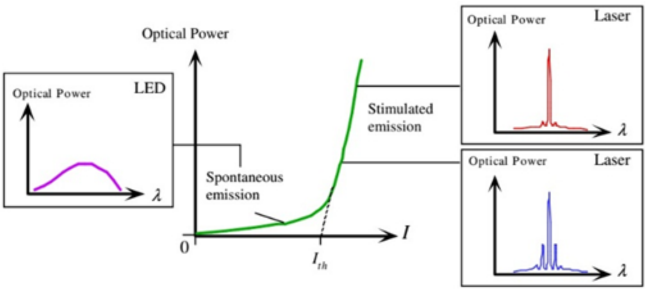
External modulation is the designer's choice over direct modulation to achieve chirp free, high data rate, long-link length optical communication. LN MZMs dominates in the wide spectrum of the external modulators available in the market for research and commercial applications, owing to its advantages like high reliability, data rate, performance, stability and excellent optical properties. The operational characteristics of which is defined by a transfer function, whose understanding is essential for proper design of MZM structures to achieve required applications. And also this transfer function is subjected to inevitable drift which causes many system anomalies. This paper gives a clear understanding of external modulators and MZM in general, MZM operational behaviour, is modelled mathematically, which can used to analyze the system's state under various operational conditions.

Keywords: *external modulation, electro-optic modulator, MZM, Mach-Zehnder modulator, intensity modulation, and MZM drift..*

1. INTRODUCTION TO OPTICAL MODULATION

In order to exploit the advantages of optical domain as a transport medium, the first step is to "transport" the high bit-rate data from electrical space to optical space. This is done through the modulation process. Thus the modulation is ideally equivalent to translating the frequency from baseband to optical carrier frequency of the order of 193 THz, for the widely used 1.55 µm band [1]. Optical systems are capable of using intensity modulation, frequency and phase modulation. However most optical systems uses intensity modulation as it simplifies the receiver system. This is since the variation in the light's intensity (power) can be captured easily by employing a photodiode, which presents it in the form of variation in it's photocurrent. Thus variation in photocurrent is proportional to the data signal [1].

When a light source is undergoing spontaneous emission, the power distribution as a function of component wavelengths is gradual and output will be non-coherent. And as optical gain in lasing cavity increases and overthrows the photon losses (referred to as optical gain threshold), the lasing oscillation begins where photon amplification is achieved by stimulated emission, resulting in coherent light intensity and corresponding input current is called threshold current Ith. The optical output intensity of the laser as a function of the laser current is as shown in Fig-1 [2]. Thus laser provides LED light when I < Ith and laser light with optical power raising sharply as I > Ith. And temperature of the junction (Tj) at which laser light is emitted is another important factor that affects the laser output behaviour. As Tj increases the optical gain threshold and hence the Ith increases. The curves in Fig-2 [3] shows this dependence on Tj. The wavelength of the laser also varies with the Tj.



. **Fig-1**: Typical output optical power vs. diode current (I) characteristics & the corresponding output spectrum of laser diode [2].

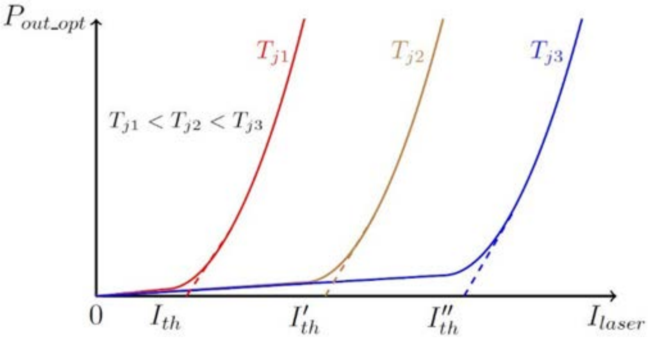


Fig-2: Temperature dependence of laser's optical power

The information can be embodied into the optical carrier by modulating it with the message signal either via direct modulation (DM) or via indirect or external modulation (EM). The two approaches are depicted in Fig-3 and Fig-4. Capability to operate at required data rate, high extinction ratio and low frequency chirp are the key specifications that a good modulator demands [1].

The former method is the simpler one, in which the source of the optical carrier (typically laser) is modulated directly by the modulating signal, but has limitations on the data rate, link length. This is mainly due to the wavelength chirp, introduced due to continuous switching of laser between ON and OFF states, which increases the spectral width of the laser source causing dispersion penalties. However, it is preferred in low data rate and low span lengths due to its simplicity [4]. It is commonly used in CATV applications for subcarrier multiplexing. Its data rate is limited to few GHz practically because of chirping and by parasitic capacitances of the laser drive electronic circuits [5]. It has limitation on extinction ratio, Relative intensity noise (RIN) of the laser source will result in the intensity variation of the modulated output & laser phase noise is introduced due to finite (f= 0) linewidth of laser sources.

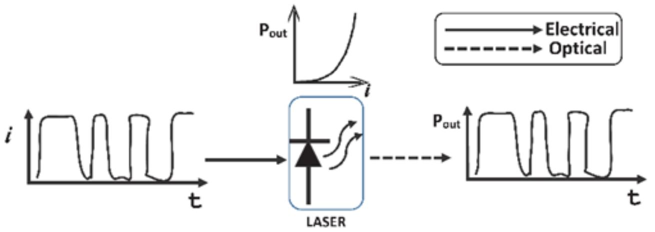


Fig-3: Conceptual illustration of direct modulation.

The latter method takes the modulation process out of the lasing device, thus eliminating switching of laser and hence the wavelength chirp. Here modulation is imposed in a component (modulator) external to source, hence the name “external modulation”. Thus here the source is a continuous wave (CW) laser whose optical output power is time invariant. External modulator is a voltage driven device (i.e optical light intensity is a function of input voltage). External modulator in effect acts as electrically triggered switch which controls the light according to the baseband electrical message signal. It increases the system performance at the expense of the complexity and cost. The downside is the insertion loss(typically 3 - 5 db) introduced into system due to the external modulator(see Fig-4, the transfer function of widely used MZM EM is used in the illustration), which effectively can be removed by providing ample laser power [4]. It is commonly used in high data rate (>10Gbps) transmission and when more stringent modulation formats like M-PPM, RZ-DPSK etc,. are used [5].

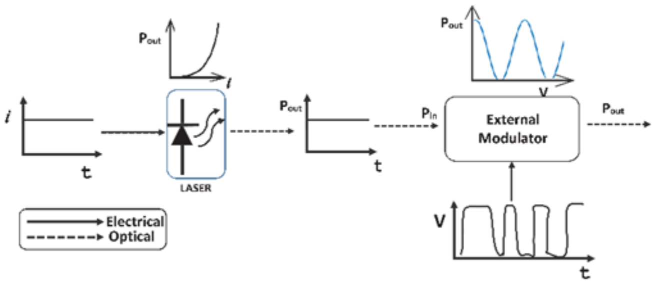


Fig-4: Conceptual illustration of external modulation.

1.1 Optical phenomenons used in modulators:

The crucial prerequisite of any external modulator is, some optical property of its material must be a function of an electrical parameter (electro-optic effect) or sound waves (acousto-optic effect) or magnetic field (magneto-optic) or temperature (thermo-optic effect). That is, external modulators are built on the basis of some physical phenomenon in which an optical property varies in response to an varying electrical(magnetic, thermal etc,.) quantity. Some of these modulation mechanisms are as shown

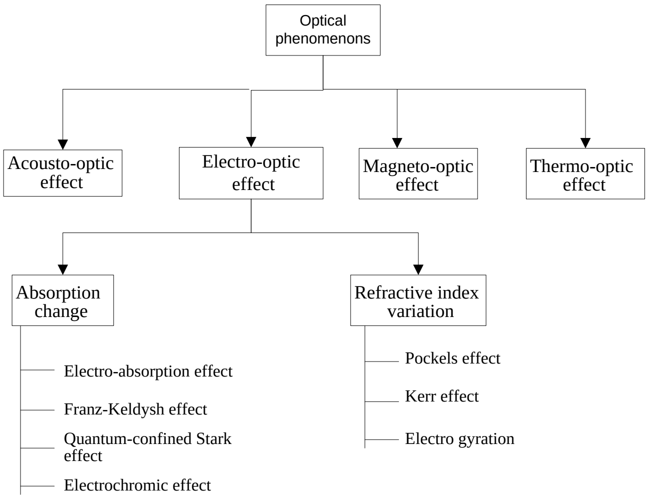


Fig-5: Optical phenomenons classification

1.2 Widely used external modulators:

External modulators which are built upon each one of the above effects are available. However only two among them are widely popular and are commonly used. A brief introduction on them.

A) Electro-absorption modulators (EAM):

These are usually built based on *FranzKeldysh-effect or Stark effect*. Change in the absorption characteristics of the material in the presence of the electric field is the principle of operation

B) Electro-optic modulators (EOM):

Shift in the phase (ϕ) of the light wave with wavelength (λ) is because of the refractive index change due to the linear electro-optic effect and is governed by the relation.

$$\phi = (nL)\left(\frac{2\pi}{\lambda}\right), \textit{ Where L is length of medium} \qquad (5)$$

Thus this modulator finds application in implementing the phase modulator as shown in the Fig-5. As refractive index **n** increases due to the applied voltage, the wavelength decreases. And for a bias of $\mathbf{2V_\pi}$ volts, an additional wave (i.e. a phase delay of 2π) will be accompanied in the waveguide for the same length. Hence the quantity $\mathbf{V_\pi}$ adds one half of the wave in the waveguide and hence termed as half wave voltage. The phase (in radians) introduced in the waveguide is related to the applied voltage given by

$$\Delta\phi = \left(V(t)\right)\left(\frac{\pi}{V_\pi}\right), \qquad (6)$$

This also finds application in long distance optical communications, to balance the phase degradation induced due to the non-linear effects like self-phase modulation.

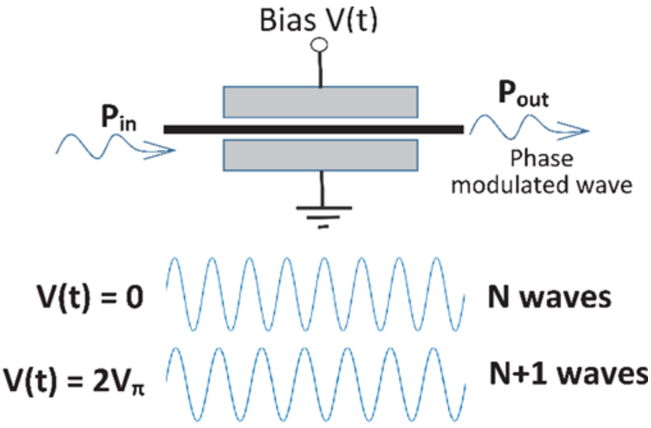


Fig-6: Phase modulation

EOMs can also be employed to produce amplitude modulation as will be discussed in Chapter 2. Polarization modulation is another application of EOMs.

2. INTRODUCTION TO MZM

Intensity or amplitude modulation can also be achieved through this phase modulation by using an interferometric structure as shown in the Fig-6. Here two arms are connected by two anti-parallel Y junction couplers and one of the two arms is an electro-optic material, and is built such that it induces a phase change of π in the signal when it reaches the 2nd junction when an bias voltage of Vπ volts is applied. And the two out of phase signals cancel each other at this junction leaving a zero Pout. When bias electrode is unbiased, there is no electro-optic effect, both the waves will be in phase and add up at the 2nd junction giving an (Pout)max. Such a modulator is called Mach-Zehnder intensity electro-optic modulator or simply Mach-Zehnder modulator (MZM). Thus the quantity Vπ is the voltage required to switch the MZM from high optical intensity (maximum transmission) to no intensity (minimum transmission) or vice versa, hence also called as switching voltage. Secondary input port and the secondary output port of the couplers are unguided waste ports, this is done to increase the fabrication yield, thus they have single input port and single output port [5] and the Y junction coupler has 50% power splitting ratio.

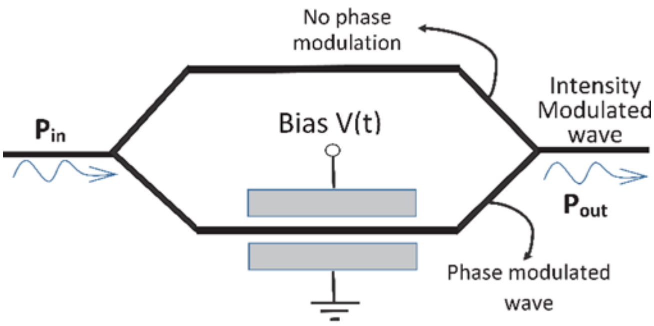


Fig-7: Intensity modulation through phase modulation

By proper biasing and/or by using multiple MZMs which are arranged in a particular architecture, various modulation formats like Amplitude modulation, BPSK, QPSK, DPSK, Analog modulation etc,. can be achieved. They are widely employed in modulators, DPSK receivers and wavelength interleavers [5]. The EAMs can directly modulate optical power hence an interferometric structure is not needed.

2.1 Push-Pull Mode:

The configuration of Fig-6 induces frequency chirp in the optically modulated signal. This is overcome by driving both arms, instead of one, by the modulating signal where

- the arms can be driven by the complimentary signals: V(t) drives one arm and $\overline{V(t)}$ drives the another
- Or by proper configuration of the electrodes and the crystal, generating phase of opposite signs in the two arms, suppressing the chirp.

These configurations are called balanced or push-pull configuration and MZMs are usually used in this structure. The change in R.I n in both arms induces a relative phase shift between the two arms (with increased optical delay in one arm and decreased optical delay in another), and it governs interference pattern and hence the optical output. If _top and _bottom are the additional phase introduced in the top and bottom arm respectively, then $\phi_{top} = -\phi_{bottom}$ in push pull configuration (for all frequencies of operation), producing chirp-free modulation.

In general, if $\Delta\phi_1$ and $\Delta\phi_2$ are the phase delays introduced in the two arms & $\Delta\phi$ is resultant output phase delay, then

$$\Delta\phi_1 = -\Delta\phi_2 = \left(\frac{V(t)}{2}\right)\left(\frac{\pi}{V_\pi}\right), \text{ with}$$

$$\Delta\phi = \Delta\phi_1 - \Delta\phi_2,$$

And when,

$$V(t) = V_\pi,\ \Delta\phi = \left(\frac{\pi}{2}\right) - \left(-\frac{\pi}{2}\right) = \pi \ radians$$

$$V(t) = 0,\ \Delta\phi = 0 \ radians$$

The interference leads to a lower order Gaussian mode (formed by those components of optical field that are in phase) which is completely passed by the output waveguide (acts as spatial filter) and completely blocks out the higher order with larger double lobed mode (result of out of phase components). When unbiased, all of the optical energy is present in Gaussian mode leading to maximum intensity; while for a drive of V_π volts, all the energy is present in higher order mode thus a minimum output intensity. Energy in these modes a hence the output intensity depends on relative phase and hence a function of the drive voltage and thus intensity modulation is achieved.

2.2 LN Modulators

LiNbO3(Lithium Niobate) crystals are extraordinary crystals, owing to their more pronounced piezoelectric, pyroelectric and ferroelectric nature, they found plethora of application possibilities in guided optics especially for external modulation due to the occurrence of acousto-optic, electro-optic and photoelectric effects in this crystal. Surface acoustic wave devices are implemented and holographic recordings makes use of LN modulators [6]. Due to high reliability, high data rate, performance, stability over changing temperature conditions, good compatibility with optical fibers, low driving voltage, low drift in the transfer function, multiple functions can be integrated into a single component, excellent optical properties, high electro-optic coefficients, easier pigtailing(butt coupling); MZMs manufactured using LiNbO3 crystals, employing electro-optic effect, are widely used [7],[8]. And these are referred to as Lithium Niobate modulators or LN Modulators. Semiconductor materials like Si [9][10], GaAs [11], InP [12][13], and optical polymers [14] are also used for MZM fabrication.

MZM can have separate pair of electrodes to drive the individual arm, or it can have a single pair of electrode and is constructed internally in such a way that it drives both the arms and also achieves the push pull configuration. Former case MZM is called Dual drive MZM, the latter one is referred as Single drive MZM.

3. MZM TRANSFER FUNCTION & ITS DRIFT

In the commercial MZMs instead of using a pair of electrodes for applying the E-field, two sets of electrodes are used, called RF port comprising RF and ground terminals/electrodes and DC port comprising DC and ground terminals as shown in Fig-10 depicting the typical architecture of such MZMs. This division is done in order to counter various impairments that are inherent and the impairments that get more and more pronounced during operational lifetime, & to achieve various modulation formats through MZM.

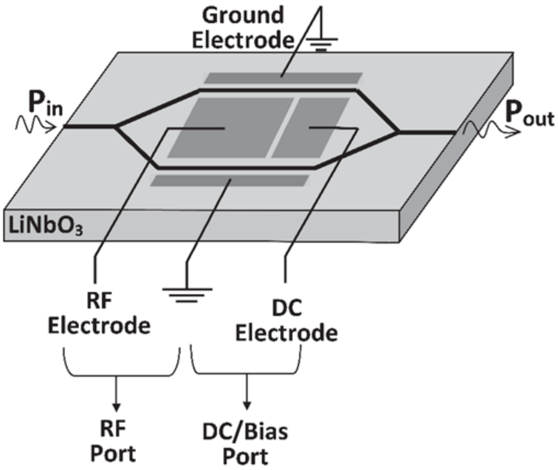


Fig-8: Integrated intensity MZM configuration

3.1 Transfer Function

The transfer function of MZM is given by

$$I_0 = \frac{T_r I_i}{2}\left(1+\cos\left(\theta(\mathrm{t})\right)\right) \qquad (9)$$

$$T_r = \frac{(I_0)_{\max}}{I_i},\ 0 \le T_r \le 1$$

$$= \textit{optical transmission co-efficient of device,}$$

$$I_0\ :\ \textit{optical intensity at the output}$$

$$I_i :\ \textit{optical intensity at the input}$$

$$\theta(t) : \textit{total phase difference between arms at time t}$$

For unbiased operation the two arms should have equal optical lengths, but in reality due to various imperfections like material inhomogeneity, manufacturing tolerances etc,. there exists an inherent phase difference in the two optical paths, modelled as $\phi_{inherenet}$ in eqn.(12), and is present for all bias scenarios(ideally $\phi_{inherenet}$ = 0). ϕ_{drift} is an another imperfection, which should be ideally 0, is dealt in next subsection. T_r is the maximum optical output intensity achievable for the given optical input after accounting for all losses in MZM, insertion loss for example.

The overall electric field applied is a function of time varying RF modulating signal $V_{RF}(t)$ applied to RF port and DC bias voltage V_{DC} applied to DC port, given by

$$V(t) = V_{RF}(t) + V_{DC} \qquad (10)$$

And the time-varying instantaneous phase difference can be decomposed as shown below

$$\theta(\mathrm{t}) = \left(\phi_{RF}(t) + \phi_{bias}\right) + \phi_{inherenet} + \phi_{drift}(t)$$
$$= \phi_{controlled} + \phi_{inherenet} + \phi_{drift}(t)$$

$$\textit{where,}$$

$$\phi_{controlled}(t) = \phi_{RF}(t) + \phi_{bias} \qquad (11)$$
$$= V_{RF}(t)\left(\frac{\pi}{V_\pi}\right) + V_{DC}\left(\frac{\pi}{V_\pi}\right)$$
$$= V(t)\left(\frac{\pi}{V_\pi}\right)$$
$$\phi_{controlled}\ \alpha\ V_{RF}(t)$$

Thus the transfer function is

$$I_0 = \left(\frac{T_r I_i}{2}\right)\left\{1+\cos\left[V(t)\left(\frac{\pi}{V_\pi}\right)+\phi_{inherenet}+\phi_{drift}\right]\right\} \tag{12}$$

$$I_0 = \left(\frac{T_r I_i}{2}\right)\left\{1+\cos\left[V(t)\left(\frac{\pi}{V_\pi}\right)\right]\right\} \qquad (ideal)$$

Above equations provide instantaneous optical output for corresponding summation of electric field applied at both ports at that instant. Fig-11 and Fig-12 represent the transfer function under ideal and practical scenarios respectively.

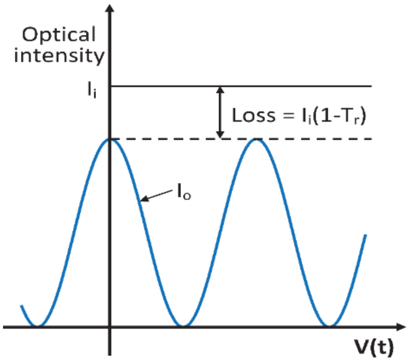


Fig-9: Transfer function curve

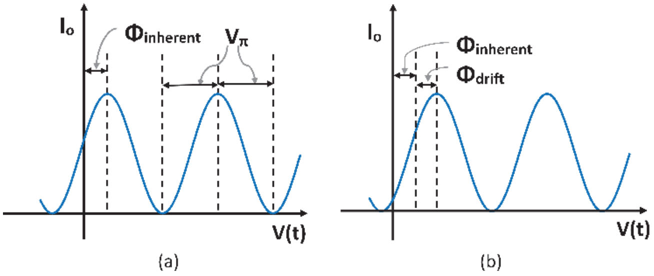


Fig-10: Transfer function curve under unavoidable impairments (a) under absence of drift, (b) under drift.

As illustrated in the figures, the transfer function is not linear, this non-linearity leads to a non-linear modulation which can be characterised by

- Expanding the T.F using Taylor series [16][17], however, it generally produces truncation errors.
- Using a polynomial function to express modulator's transmission function [18][19], it only get limited order harmonic component.
- Using Bessel series expansion to analyse MZ intensity modulator give the complete harmonic component.

3.2 Operating points

The modulating signal will be applied to the RF port and it governs the swing on the transfer curve, whereas the choice of DC voltage applied to DC port establishes the central point or operating point around which modulating swing appears. The choice of these two voltage signals are the controlling factors, which are application specific, and tweaking them produces various application possibilities like generation of simple to complex optical modulation formats, comb generation, beamforming etc,. Hence MZM is a voltage driven device, and DC electrodes are also called as Bias Electrodes and RF terminals as Modulation Electrodes.

Some typical operating points and their terminologies is as shown in Fig-13 below

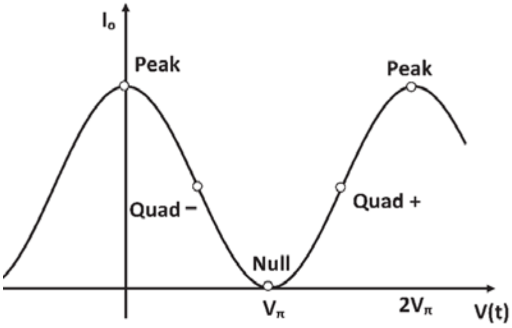


Fig-11: Typical operating points.

3.3 Drift in T.F

After establishing the target operating point and the modulating signal, the system works in accordance with expected behaviour as long as the transfer function remains static throughout the operational lifetime. But the occurrence of Pyroelectric and/or photorefractive and/or photoconductive effects in the Mach-Zehnder modulator's substrate material (like $LiNbO_3$, GaAs, or an electro-optic polymer) due to changing environmental conditions and aging cause the transfer function to "drift" in horizontal direction, represented by φ_{drift} in eqn.12, to the left or right- as shown in Fig-12.(b); such that a particular DC bias voltage (for ex.: V_π or even 0V) may, for example, yield a QUAD+ on the T.F. curve at one time and a NULL point on the curve at a later time and/or at a different temperature. This leads to variation in output optical power, extinction ratio, change in phase and the modulation signal is applied to a changing operating point, that can modify strongly the obtained modulation and sometimes a different modulation format could be generated based on the extent of drift.

However this can be overcome by changing the DC bias applied to MZM in reverse direction and with same amount as the drift occurred in the system, which will nullify the effect of the drift by shifting the operating point to the original position. This is not an one-time correction since drift is a continuous phenomenon, so an continuous correction is required to continuously nullify the effect of the drift. Thus it establishes a requirement for a dedicated bias control circuit that continuously senses the drift in the transfer function and changes the DC bias of MZM accordingly. Various techniques, like ratio-detection, harmonic detection etc,. to detect the drift and various circuits to control it have already been investigated and presented.

4. MATHEMATICAL ANALYSIS OF MZM

The instantaneous electrical field output, $E_{out}(t)$, is defined by

$$\tilde{E}_{out}(t)=\tilde{E}_{in}(t)\left[\frac{1}{\sqrt{\alpha}}\sin\left(V(t)\frac{\pi}{2V_{\pi}}\right)\right] \tag{13}$$

where $\tilde{E}_{in}(t)$ is the input electric field, α is the insertion loss (≥ 1), V(t) is given by eqn.10. The variable t will be omitted for convenience, i.e. $\tilde{E}_{in}$ implies $\tilde{E}_{in}(t)$.

And the powers at input and output are related to their corresponding electric fields by

$$P_{in}=KE\left[\tilde{E}_{in}^{2}\right]$$
$$P_{out}=KE\left[\tilde{E}_{out}^{2}\right]$$

$E\left[\tilde{E}_{in}^{2}\right]$ is the expected(mean or first moment) value of $\tilde{E}_{in}^{2}$. If E_{in} & E_{out} represents the complex envelopes of the input and output electric fields respectively and E_{o} is the amplitude of the input electric field, then [15]

$$\begin{aligned}E_{out}&=\frac{E_o}{2}\left[\left(\sqrt{1+2\varepsilon}\right)e^{j\left(\frac{V_1(t)\pi}{V_\pi}\right)}\right]\\&+\frac{E_o}{2}\left[\left(\sqrt{1-2\varepsilon}\right)e^{j(\text{mode})\left(\frac{V_1(t)\pi}{V_\pi}\right)}\right]\end{aligned} \tag{14}$$

$$where,\, mode=\begin{Bmatrix}-1\; for\;\; push-pull\; operation\\ 1\; for\;\; push-push\; operation\end{Bmatrix}$$

Imperfect splitting at the input of MZM is quantified using ε and as a result an infinite extinction ratio(ER) cannot be achieved. The ER of optical signal and ε are related by

$$\begin{aligned}\varepsilon&=\frac{1}{2}\sqrt{1-\left(\frac{ER-1}{ER+1}\right)^{2}}\\&=\frac{1}{2}\sqrt{1-\left(\delta_{ER}\right)^{2}},\; where\end{aligned} \tag{15}$$

$$ER=\frac{P_1}{P_0},\; ER_{db}=10\log\left(ER\right),\; and$$

$$\delta_{ER}=\frac{ER-1}{ER+1}=power\;\; penalty \tag{16}$$

P_1 and P_0 are the power associated with output for “mark” and “space” respectively. “mark” and “space” corresponds to bit1 and bit0 in positive logic and represents the opposite in case of logical inversion. A finite ER implies that power is not completely extinguished for “space”. Higher the ER, better (higher) will be the difference in power associated with “mark” and “spaces”. A finite ER results in an increased received power requirement at receiver to achieve the same BER as in the case of the infinite ER, this penalty is quantified by δ_{ER} as in eqn.16 [1].

The input and output powers can be obtained by E_o and E_{out} using

$$P_{in}=\frac{E_0^2}{2}$$
$$P_{out}=\frac{\left|E_{out}^2\right|}{2}$$

Under ideal operation, $\varepsilon = 0$ (perfect splitting) and ER becomes infinite now E_{out} becomes

$$E_{out}=\frac{E_o}{2}\left[e^{j\left(\frac{V_1(t)\pi}{V_\pi}\right)}\right]+\frac{E_o}{2}\left[e^{j(\text{mode})\left(\frac{V_1(t)\pi}{V_\pi}\right)}\right] \tag{17}$$

5. CONCLUSION

In this paper we gave an understanding of the types of external modulators available and compared them under various parameters. Then we gave brief understanding of the widely used LN MZMs in terms of construction, crystal orientations, push-pull operation. The transfer function and operational behaviour were clearly understood via the mathematical modelling.

We introduced to an impairment called drift in transfer function which is unavoidable and should be taken care of, for system’s long operational life. We can use in future the understandings and models presented in this paper to implement MZM in Matlab, to detect the presence of the drift in T.F and also to quantify the drift in new ways, using which various new drift control mechanisms can be developed. And also already available control mechanisms can be studied using the models presented here.

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BIOGRAPHIES

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