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External modulators and, Electro-optic Mach-Zehnder modulator - modelling and analysis using Matlab

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Abstract- **External modulation is the designer's choiceoverdirect modulation to achieve chirp free, high data rate, long-link length optical communication. LN MZMs dominatesi n thewidespectrumoftheexternalmodulatorsavailableinthemarketforresearchandcommercialapplications,owingtoitsadvantages like high reliability, data rate, performance,stabilityand excellent optical properties. The operational characteristicsof which is defined by a transfer function, whoseunderstandingis essential for proper design of MZM structures toachieverequired applications. And also this transfer function issubjectedtoinevitabledriftwhichcausesmanysystemanomalies. Thispapergivesaclearunderstandingofexternalmodulatorsand MZM in general, MZM operational behaviour, is modelledinMatlab,whichcanusedtoanalyzethesystem'sstateundervariousoperationalconditions.**

***Index Terms* — external modulation, electro-optic modulator, MZM, Mach-Zehnder modulator, intensity modulation, MZM drift.**

I. INTRODUCTION TO OPTICAL MODULATION

The paper is organized into five chapters, where in chapter I a brief introduction to optical sources and modulators is given, then the discussion is taken specifically towards the widely used MZM modulator in chapter II, the complete operational behaviour of MZM is explained in chapter III and it's behaviour modelled in matlab and various characteristics are analyzed in chapter IV and finally the paper is concluded in chapter V.

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 I_{th}. The optical output intensity of the laser as a function of the laser current is as shown in Figure1 [2]. Thus laser provides LED light when $I < I_{th}$ and laser light with optical power raising sharply as $I > I_{th}$. And temperature of the junction (T_j) at function of the laser current is as shown in Figure1 [2]. Thus laser provides LED light when $I < I_{th}$ and laser light with optical power raising sharply as $I > I_{th}$. And temperature of the junction (T_j) at which laser light is emitted is another important factor that affects the laser output behaviour. As T_j increases the optical gain threshold and hence the I_{th} increases. The curves in Figure2 [3] shows this dependence on T_j. The wavelength of the laser also varies with the T_j.

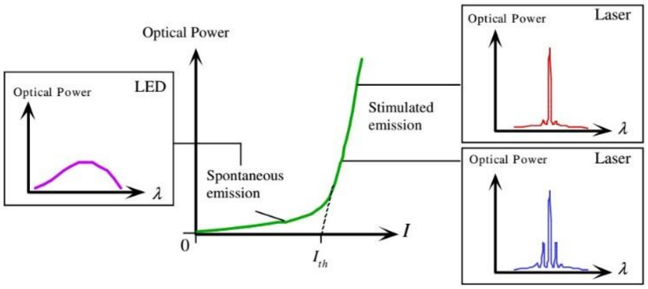


Figure 1. Typical output optical power vs. diode current (I) characteristics & the corresponding output spectrum of laser diode[2].

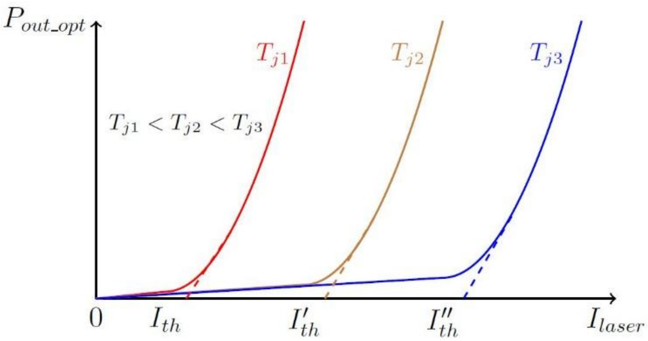


Figure 2. Temperature dependence of laser's optical power.

Theinformationcanbeembodiedintotheopticalcarrierby modulating it with the message signal either viadirectmodulation (DM) or via indirect or externalmodulation (EM).The two approaches are depicted in Figure 3 and Figure 4.Capabilityto operate at required data rate, high extinction ratio and low frequency chirp are the key specifications that agoodmodulator demands[1].

The former method is the simpler one, in which thesourceof the optical carrier (typicallylaser) is modulated directlyby the modulating signal, but has limitations on the data rate,linklength.Thisismainlyduetothewavelengthchirp,introduced due to continuous switching of laser betweenONand OFF states, which increases the spectral width of thelasersource causing dispersion penalties. However, it ispreferredin low data rate and low span lengths due to itssimplicity[4]. It is commonly used in CATV applications forsubcarriermultiplexing. Its data rate is limited to few GHzpractically because of chirping and by parasitic capacitances of thelaserdrive electronic circuits [5]. It has limitation onextinctionratio,Relativeintensitynoise (RIN)ofthelasersourcewillresult in the intensity variation of the modulated output& laser phase noise is introduced due to finite (f= 0)linewidthof lasersources.

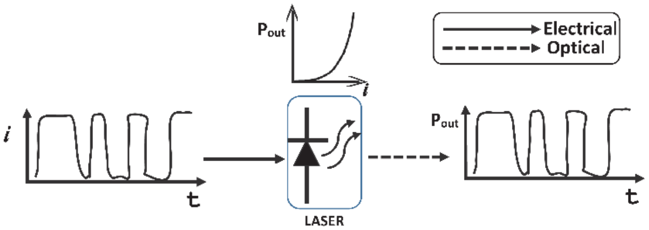


Figure 3. Conceptual illustration of directmodulation.

The latter method takes the modulation process out ofthe lasing device, thus eliminating switching of laserandhencethewavelengthchirp.Heremodulationisimposedina component (modulator) external to source, hence thename “externalmodulation”.Thusherethesourceisacontinuouswave (CW) laser whose optical output power is timeinvariant.External modulator is a voltage driven device (i.e opticallightintensity is a function of input voltage). External modulatorineffect acts as electrically triggered switch which controlsthelightaccordingtothebasebandelectricalmessagesignal.Itincreases the system performance at the expense of thecomplexityandcost.Thedownsideistheinsertionloss(typically3-5 db) introduced into system due to the externalmodulator(seeFigure 4, the transfer function of widely used MZM EM isused in the illustration), which effectively can beremovedbyprovidingamplelaserpower[4].Itiscommonlyusedinhigh data rate (>10Gbps) transmission and when morestringentmodulation formats like M-PPM, RZ-DPSK etc,. are used[5].

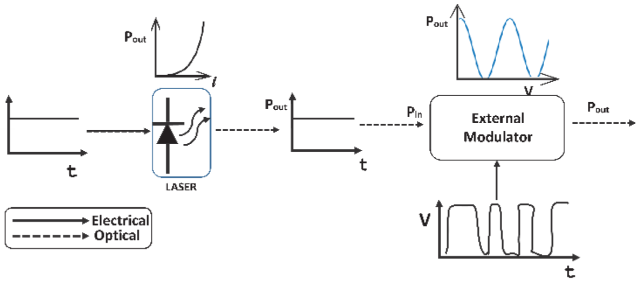


Figure 4. Conceptual illustration of external modulation.

A) 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

*1) Electro-optic effect:*Its an electro-optic phenomenonwhere some optical property of the medium gets altered in response to an slowly varying externally applied electric field. The various phenomenas can be groupedunder this effect, and can be subdivided based on the optical property which varies, as [6]

➢ Change of absorption
  - Electro-absorption effect: Change in the absorption constants of the materials.
  - Franz-Keldysh effect: Occurs in uniform, bulksemiconductors.
  - Quantum-confined Stark effect: Absorption changes in some semiconductor quantum wells.
  - Electrochromic effect: Electrochemical redox reactions in electrochromic materials, creates absorption band at some wavelengths, causing reversibly changing colour.

➢ Refractive index variation
  - Pockels effect: If there is a linear dependencybetween the refractive index and the electric field,then it is called *linear electro-optic effect orPockels electro-optic effect* (or simply *Pockelseffect*). It occurs only in non-centrosymmetricmaterials, like some crystals (ex. $LiNbO_3$, GaAs,InP, $LiTaO_3$ [7]) and in some poled polymers.
  - Kerr effect: If there is a linear dependencybetween the refractive index and square of theexternal electric field, then it is called *quadraticelectro-optic effect* (*QEO effect) or simply Kerreffect*. All materials show kerr effect, but it ispronounced in the liquids [6].
  - Electro-gyration: Optical activity (gyration) of crystals change due to applied electric field.

*2) Acousto-optic effect:*The application of mechanical stress on the transparent dielectric results in a strain, which then modifies the refractive index. This is called*photo-elastic effect or photoelasticity*. When sound waves are used to produce the required stress, it is called *acousto-optic effect*.

3) Magneto-optic effect:[6],[8] Similar to many effects present in electro-optic phenomenon, there are many such effects in this category. However, in the context of modulators used in optical applications, the *Faraday effect (Faraday rotation)* is the one with real importance. This effects results in polarization plane of the light experiencing an rotation. The extent of rotation depends linearly on the component of magnetic field which is parallel to the direction of propagation. In general, ferromagnetic materials (ex. terbium gallium garnet and yttrium iron garnet (YAG)) are used to achieve this effect in the practical devices.

*4) Thermo-optic effect:*Here shift in the operating temperature results in a change of real part of refractive index (dn/dT). Thus temperature controls the behaviour ofthe material to the incoming optical beam.

B) 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.

*1) 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. The absorption (α) of incoming light wave by an material is a function of the wave's energy **E** and the bandgap energy $\boldsymbol{E_g}$ of the material, where

$$E = h\upsilon \text{ or } \frac{h\omega}{2\pi}, \upsilon \text{ is the frequency of the wave. (1)}$$

And when

$$E > E_g \text{, the wave is absorbed by the material,(2)}$$

$$E < E_g \text{, the wave passes through the material,} \qquad (3)$$

Thus $\mathbf{E_g}$ defines the absorption spectrum of the modulator.And further, $\mathbf{E_g}$ is related to external voltage V by an inverserelation. If E_{g0}& E_{g1} are the bandgap energies at V = 0& V $\neq 0$ respectively, then $E_{g1} < E_{g0}$. Thus if we selectan signal wavelength such that in the absence of the externalagent it satisfies the eqn(3), and satisfies the opposite relationon the application of the external voltage, i.e. the signal energyE lies in between the 2 boundaries of the E_g variation ($E_{g1} < E < E_{g0}$). Then there will be an appreciable change in theabsorption of the wave (α) with respect to the electric controlsignal.

This absorptional shift induces arefractive indexshift ($\Delta\alpha$), given by Kramers-Kronig relation as in eqn.4,and hence modulating the signal's phase or instantaneous frequency.This feature is used to produce the optical modulationdriven by the control voltage. But also an frequency chirp willemerge in the system. However, this is small in comparison tothe same, introduced when direct modulation scheme is used.

$$\Delta n(\omega) = \frac{c}{\pi}\int_0^{+\infty} \frac{\Delta\alpha(\omega')}{(\omega')^2 - \omega^2} d\omega' ,(4)$$

*2) Electro-opticmodulators(EOM):*Shift in the phase (ϕ) ofthe lightwave with wavelength (λ) is because of the refractive index change due to the linear electro-optic effect and is governed by the relation.

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

Thus this modulator finds application in implementing the phase modulator as shown in the Figure5. 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 thewave 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.

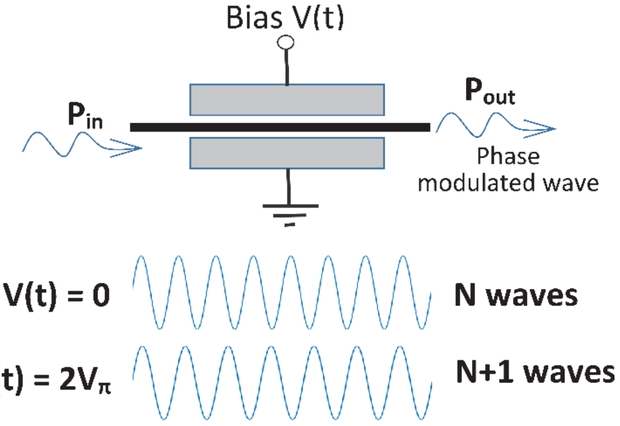


Figure 5. Phase modulation

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

C) Comparison between EAM and EOM:

A brief contrast between the two widely used external modulators is given in table I [5],[9].

Table 1
Comparison Between EOM And EAM

EOM	**EAM**
Employs *Pockels effect*	Employs *Franz and Keldysheffect* and *Stark effect*
Frequency chirp is lower, well-behaved and has good control over chirp	Frequency chirp is high and varies dynamically with bias
Optical source (laser) connected externally via optical fiber.	Optical source can be integrated on same chip.
V_π required is 5-7 V	V_π is lower than(3-4 V)
High extinction ratio (27–30db)	Poor extinction ratio(10-14db)
Adjustable chirp, high-rate, high-fidelity waveforms. Hence used in fiber-optic & FSO links	Not preferred in high-sensitivity FSO applications.
Low insertion loss (3-4 db for a	High insertion loss (5-10 dB)

single MZM, upto 11 dB for complex modulators like PDM-IQ modulator)	
Loss compensated using Er-doped fiber amplifier (EDFA)	Compensated by semiconductor optical amplifier (SOA) (integrable in the same chip)
Linear response characteristic(cos^2 transfer characteristics)	Linearity of the transfer curve is much better
For M-ary PAM, poor total harmonic distortion	Provides better total harmonic distortion.
Wide-band device	Wide-band devices, but they can introduce parasitic chirp

Highly controllable chirp, low loss and low driving voltage are the key factors that favoured the widespread use of the EOMs. Whereas even though EAMs have higher loss, inferior modulation performance & weakly controllable chirp, its ability to integrate the laser with modulator monolithically (thus compact in size) and lower cost w.r.t (laser+EOM) combination has led to its widespread presence [10].

II. INTRODUCTION TO MZM

Intensity or amplitude modulation can also be achieved through this phase modulation by using an interferometric structure as shown in the Figure6. 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 $V_\pi$volts is applied. And the two out of phase signals cancel each other at this junction leaving a zero P_{out}. 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 $(P_{out})_{max}$. Such amodulator is called **Mach-Zehnder intensity electro-opticmodulator** or simply **Mach-Zehnder modulator (MZM)**. Thus the quantity $\mathbf{V_\pi}$ is the voltage required to switch the MZM from *high optical intensity (maximum transmission) to no intensity (minimum transmission) or vice versa*, hence alsocalled as **switching voltage**. Secondary input port and thesecondary 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.

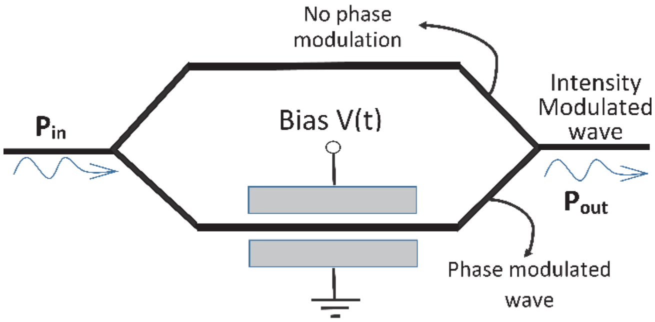


Figure 6. Intensity modulation through phase modulation

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 modulateoptical power hence an interferometric structure is not needed.

A) Push-pull mode:

The configuration of Figure6 induces frequency chirp in the optically modulated signal. This is overcome by driving both arms, instead of one, by the modulating signal $V(t)$ 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 Gaussianmode (formed by those components of optical field that areinphase) which is completely passed by the output waveguide (acts as spatial filter) and completely blocks out the higher order with larger double lobedmode (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.

B) LN Modulators:

$LiNbO_3$(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 andphotoelectric effects in this crystal. Surface acoustic wave devices are implemented and holographic recordings makes use of LN modulators [11]. 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 transferfunction, multiple functions can be integrated into a single component, excellent optical properties, high electro-optic coefficients, easier pigtailing(butt coupling); MZMs manufactured using $LiNbO_3$ crystals, employing electro-optic effect, are widely used [12],[13]. And these are referred to as LithiumNiobate modulators or LN Modulators. Semiconductor materials like Si [14][15], GaAs [16], InP [17][18], and optical polymers [19] 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.

C) Crystal orientations of Lithium Niobate-integrated MZM structures:

Based on the crystal cut or the electrode architectures the MZM can be classified into x-cut and z-cut. Z-cut can be fabricated to have single or dual drive architecture, whereas x-cut is always single drive. The chirp parameter _ is defined by the equation [8]

$$\alpha = \frac{V_{top} - V_{bottom}}{V_{top} + V_{bottom}} \quad (8)$$

1) x-cut: Here device surface and crystal x-axis are perpendicular to each other. In x-cut crystal cut design,single line electrode or modulation drive electrode orhot electrode drives split internally to drive both thewaveguides providing push-pull action as shown in Figure7 [5],[9],[20]. The field lines are parallel to Z-axis and optical waveguides are in between the drive electrode & ground electrode.

This symmetrical design has equal field distributionin the waveguides, with opposite signs, providing anintrinsic balance leading to a zero chirp (α = 0). Abuffer layer, typically SiO_2, whose refractive index islower than that of $LiNbO_3$, is added for matching thevelocities between the electric field and optic waves, tooptimize the optical modulation bandwidth.

Careful design and fabrication is needed to ensure that the drive voltage appears on the both arms simultaneouslyresulting in zero chirp. But in case of fabrication errors, there is mismatch in phase induction and modulator output distorts and there is no means to compensate it since individual arm can't be driven independently. The Ti indiffusion method and annealed proton exchange method (APE) are the main methodologies employed for waveguides fabrication.

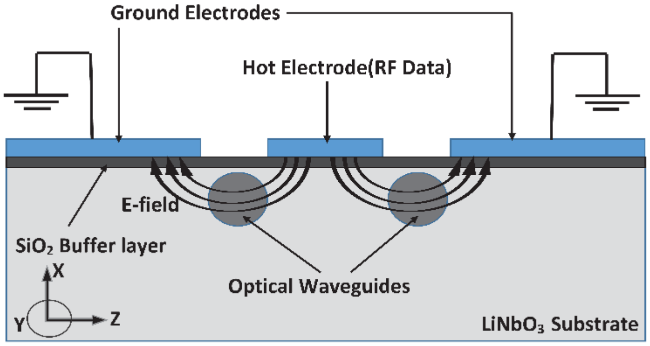


Figure 7. X-cut crystal orientation

2) z-cut single-drive: Here device surface and crystal z-axis are perpendicular to each other. In z-cut designs, electrodes are placed directly above the optical waveguides leading to an better coupling between the E-field & the MZM arms. DC-drift is higher than x-cut designs.

Z-cutdesigns (both single and dual drive) have lower voltage drive requirement (with approximately 20% lower V_π). The electric field distribution profile is asymmetrical in the waveguides, and is more concentrated with nearly 85% of the field in the central waveguide (the waveguide beneath the hot electrode) and nearly 15% in the other waveguide (secondary waveguide). Thus there will be an unequal phase delay in the arms which can't be aligned since its an single drive, resulting in residual chirp with $\alpha = -0.7$. Hence cannot employed to generate PSK modulation.

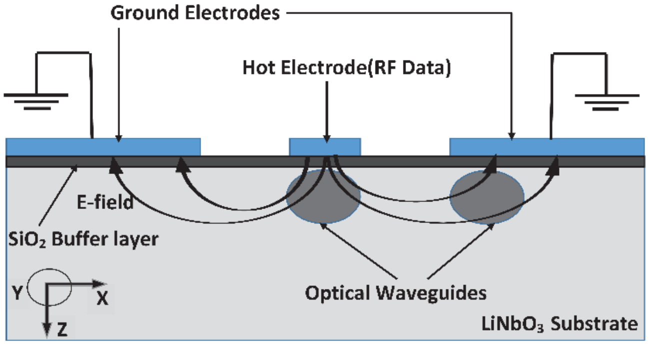


Figure 8. Crystal orientation of z-cut single drive

3) z-cut dual-drive: Here chirp can be controlled to meet the specific value (adjustable chirp) or can obtain chirp free signals as givenby eqn(8), as both the quantities,V_{top} and V_{bottom}, are independently controllable sincehot electrodes are mutually exclusively controlled i.e. independent of each other. Such an design provides adjustable chirp parameter in the range $-\infty < \alpha < \infty$ theoretically, but is varied in the limited range of $-2 < \alpha < 2$ practically. This configurability is used to combat the degradation of the signal in dispersive and non-linear optic links to achieve lowest dispersion penalty, thus improving performance.

It has added advantage in temperature controlled environments, as in space projects, because the power load is spread across larger area in dual-drive, thus reducing heat density and hence the local temperaturein comparison to single drive operation for the same V_π but at the cost of larger layout size, and drive power requirement is half in comparison w.r.t to its single drive counterpart and almost one fourth of its x-cutcounterpart [5]. The z-cut design architectures is as

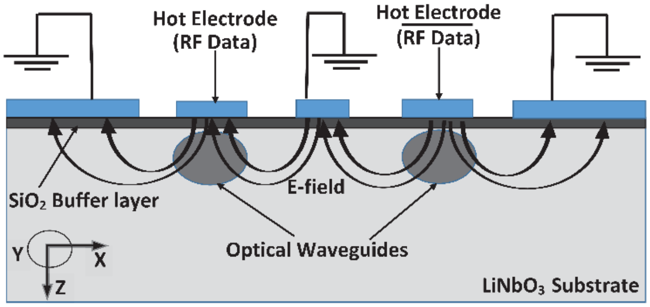


Figure 9. Crystal orientation of z-cut dual drive

D. Y-fed Balanced bridge modulator (YBBM):

While MZM is a single output intensity modulator, YBBM can be used as dual output intensity modulator in which coupler replaces the 2nd Y junction and provides two outputs which are complimentary.

III. MZM TRANSFER FUNCTION AND ITS DRIFT

In the commercial MZMs instead of using a pair ofelectrodes 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 Figure10 depicting the typical architecture of such MZMs. This division is done inorder 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.

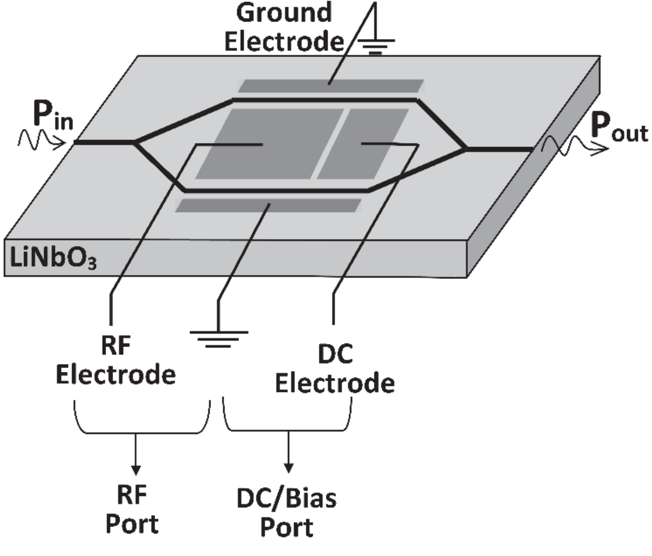


Figure 10. Integrated intensity MZM configuration

A) Transfer Function:

The transfer function of MZM is given by

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

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

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

I_0 : *optical intensity at the output*

I_i : *optical intensity at the input*

$\theta(t)$: *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 innext 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

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

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

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

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

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

Above equations provide instantaneous optical output for corresponding summation of electric field applied at both ports at that instant. Figure11 and Figure12 represent the transfer function under ideal and practical scenarios respectively.

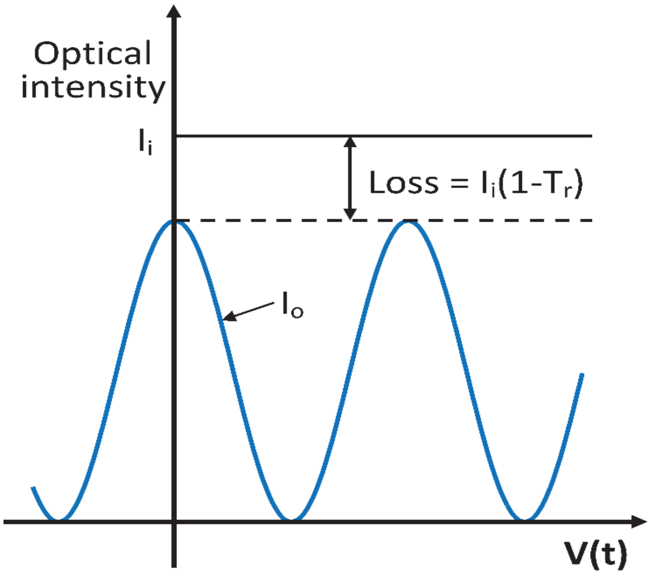
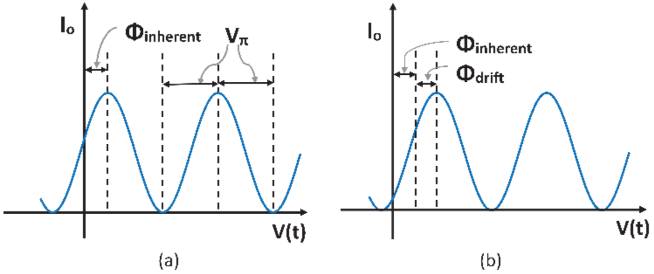


Figure 11. Transfer function curve



(a) (b)

Figure 12. Transfer function curve under unavoidable impairments (a) underabsence 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 theT.Fusing Taylor series [24][25], however, it generally produces truncation errors.
- Using a polynomialfunction to express modulator's transmission function [26][27], it only get limited order harmonic component.
- Using Bessel series expansion to analyse MZ intensity modulator give the complete harmonic component.

B) 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 Figure13 below

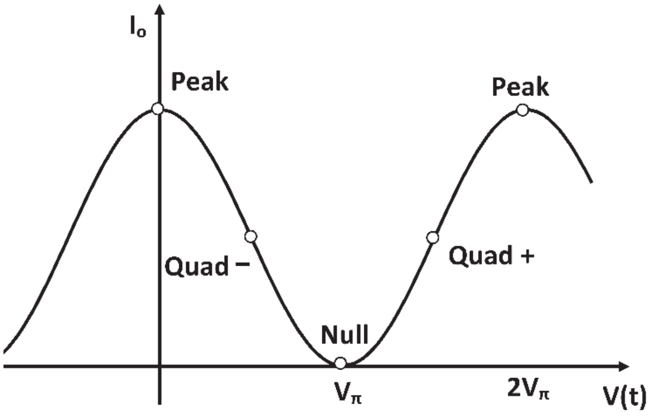


Figure 13. Typical operating points.

C) 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 Figure 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 operatingpoint, that can modify strongly the obtained modulationand sometimesa 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 driftand various circuits to control it have already been investigated and presented.

IV. MATLAB 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 theamplitude of the input electric field, then [23]

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

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

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

$$\varepsilon = \frac{1}{2}\sqrt{1-\left(\frac{ER-1}{ER+1}\right)^{2}} = \frac{1}{2}\sqrt{1-\left(\delta_{ER}\right)^{2}},\ where \quad (15)$$

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

$$\delta_{ER} = \frac{ER-1}{ER+1} = power\ penalty \quad (16)$$

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, ε = 0 (perfect splitting) and ER becomes infinite now E_{out} becomes

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

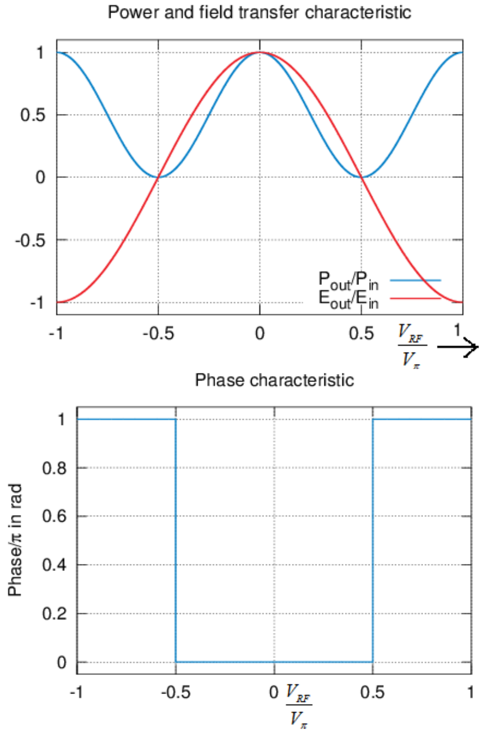


Figure 14.Transfer characteristics (Field, Power& Phase) of MZM at no drift condition.

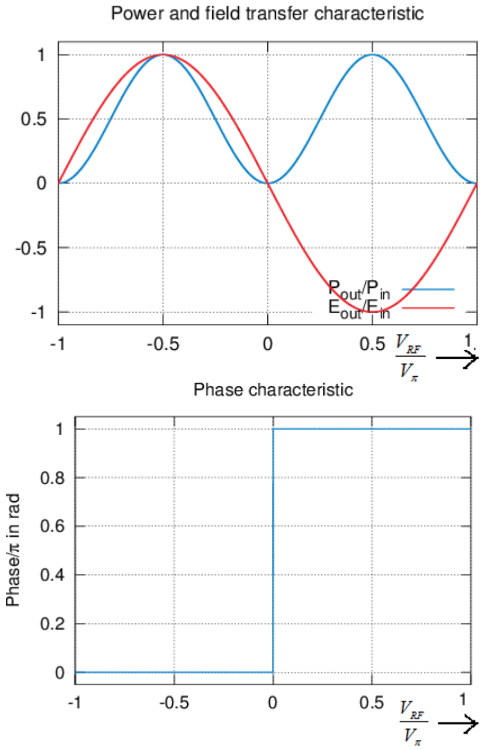


Figure 15.Transfer characteristics (Field, Power& Phase) of MZM when there drift of V_π in horizontal right direction.

The mathematical relations presented above were used in developing a Matlab code, which modelled the working (operational) behaviour of the Mach-Zehnder modulator under any drift condition. The transfer curves under ideal condition (no drift) is shown in Figure 14 and the same at an drift of switching voltage in Figure 15.

In single-tone modulation where the carrier (optical) is modulated with the continuous sine wave of frequencyω_0, the harmonic analysis of the output signal(modulated carrier) shows harmonics, i.e. output is composition of frequency components whose frequencies are integer multiples of ω_0.

With few computational operations using Matlab commands on the modulated carrier output, results in its harmonic decomposition revealing the component frequencies, which is helpful in understanding the effects of the non-linearity of the transfer curve. For single tone modulation, the MZM is operated in quadrature point where the output field lies is in normalized range of -1 to 1. Harmonic analysis (power spectral density) of the MZM for single tone modulation is shown in Figure 16, where an high extinction ratio, 1Gbps driving signal is varying between ,u_{max} and u_{min}(say),.

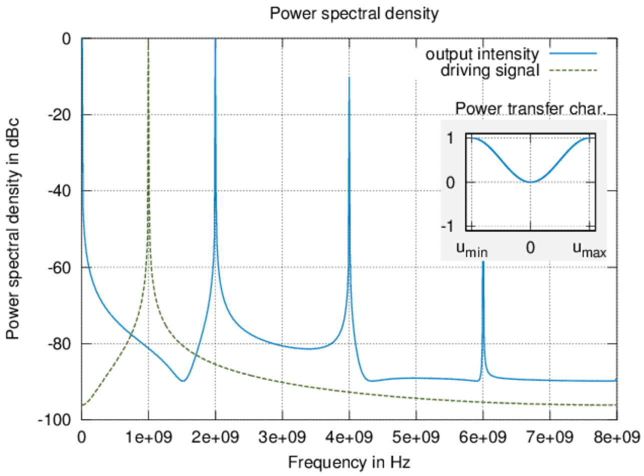


Figure 16. Power spectral density of output light intensity

V. 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 matlab 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 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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