

Biasing Techniques for LiNbO₃ Mach–Zehnder Modulators with Emphasis on RFoF/AM, DSB-SC, and BPSK Modulation Schemes with Quad and Null Point Biasing

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Abstract

Lithium niobate (LiNbO₃) Mach–Zehnder modulators (MZMs) are an important part of modern optical communication and microwave photonics systems due to their high linearity, wide bandwidth, and electro-optic stability. A critical aspect governing the performance of an MZM is its biasing technique, which directly determines modulation efficiency, linearity, spectral purity, and noise performance. This paper gives a review and comparison of various biasing techniques for LiNbO₃ MZMs with emphasis on radio-frequency-over-fiber / analog modulation (RFoF/AM), Double-Sideband Suppressed-carrier (DSB-SC), and Binary Phase-Shift Keying (BPSK) modulation schemes. The operating principles, different bias point selection for optimum operation, biasing requirements, comparative analysis and laboratory procedures for implementing the above-mentioned modulation schemes are discussed in detail.

Keywords: BPSK, DSB-SC, Lithium niobate, Mach–Zehnder modulator, RFoF/AM.

1. Introduction

The Mach–Zehnder modulator (MZM) based on lithium niobate (LiNbO₃) exploits the linear electro-optic (Pockels) effect to modulate the phase of an optical carrier, which is subsequently converted into intensity or phase modulation through optical interference [1]. Because of the properties such as low chirp, high extinction ratio and large bandwidth the MZM is extensively used in applications such as long-haul optical communication, microwave photonics applications, radio-over-fiber, etc. [2]. An important characteristic of the MZM is its nonlinear sinusoidal transfer function, with different bias points such as Quadrature bias point, Null bias point, Peak bias point, which makes the choice of bias point crucial. Due to proper biasing different modulation formats such as conventional intensity modulation, carrier-suppressed modulation, and pure phase modulation are enabled. In case the biasing is not proper or there is any drift due to aging or thermal effects, the optical signal at the output will be distorted [3].

This paper focuses on various biasing techniques for LiNbO₃ MZMs and studies their role in realizing three modulation schemes namely: RFoF/AM, DSB-SC, and BPSK. These three schemes share the same MZM

modulator but their biasing requirements and system-level implications are very much different [4]. LiNbO₃ MZMs use the linear electro-optic effect for conversion of the electrical signals into optical signal via interferometric phase-to-intensity conversion. As compared to direct modulation of laser beam, the external modulation of laser beam using LiNbO₃ MZM has better results w.r.t. linearity and bandwidth in case of RFoF and microwave photonics. Various applications require different bias points on the transfer function curve, for example the quadrature point on transfer function in linear region for the RFoF / conventional AM and null bias point on transfer function curve i.e. minimum-transmission for double side band carrier-suppressed or Binary phase-encoded formats.

Because of the benefits such as low drive voltage, simple fabrication process and high bandwidth the MZMs are widely used for external modulation. Proper DC biasing is very important to optimize linearity, carrier suppression and phase encoding. The transfer function of LiNbO₃ MZMs and the quadrature and null biasing conditions for the three modulation schemes namely analog modulation in RFoF systems (RFoF/AM), double-sideband suppressed-carrier (DSB-SC) modulation, and binary phase-shift keying (BPSK) is reviewed in this paper.

2. Principle of Operation of LiNbO₃ Mach-Zehnder Modulation

A typical LiNbO₃ MZM consists of an optical waveguide which is divided into two arms, each integrated with electrodes. An applied voltage induces a refractive index change via the electro-optic effect, which results in a differential phase shift between the two arms.

The normalized optical output power of a single-drive MZM is given by:

$$P_{out}(t) = \frac{P_{in}}{2} \left[1 + \cos \left(\frac{\pi V(t)}{V_{\pi}} + \phi_b \right) \right]$$

Where,

P_{in} is the Input Optical Power.

V is the applied RF voltage.

V_{π} is the Half-Wave voltage.

ϕ_b is the Bias Phase determined by the DC Bias Voltage.

The ϕ_b defines the operating point on the transfer function such as maximum transmission, minimum transmission, or quadrature. By appropriately selecting the ϕ_b , various modulation schemes can be generated by using the same MZM.

3. Biasing Techniques for LiNbO₃ MZMs

Maximum Transmission Bias

In this type of biasing the MZM is biased at the peak point of the transfer function. It is usually used for optical subcarrier modulation such as frequency-quadrupling. Although it maximises the power but it can lead to the increased even order distortion. This type of biasing is often used for non-linear optical processing.

Minimum Transmission Bias

Minimum transmission bias point or null point is the operating point where the optical output power is at its lowest. This provides maximum value of the extinction ratio. The null point occurs when the optical phase difference between the two arms of the MZM is an odd multiple of the 180 or π radians.

Quadrature Bias

Quadrature transmission bias of the MZM is usually set to the mid-point between the maximum and minimum optical transmission levels. This type of biasing ensures maximum modulation efficiency and linearity for

analog communication links. At quadrature the relation between the input voltage and the optical output is linear which results in the minimizing of the distortions in the optical signal.

Push-Pull Biasing

For push pull transmission biasing dual-drive MZM is required. In these biasing signals with opposite phases are applied to the two arms of the interferometer. This configuration enables a lower half-wave voltage as compared to the single drive MZM.

Active Bias Control Techniques

The active bias control techniques include pilot-tone/dither modulation, dither-free or optical power monitoring, digital/algorithm-based control. These methods are often implemented through feedback loops to maintain optimal performance.

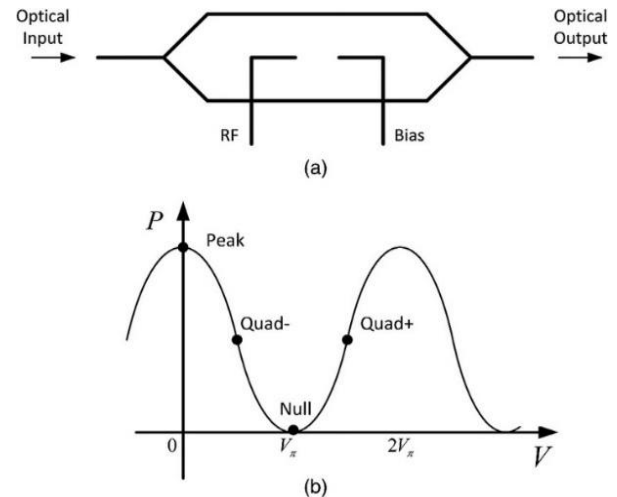


Fig. 1 a. MZM Input Output RF and Bias port Fig.1 b. Various biasing points of MZM

Bias Locking Using Monitor Photodiode:

When Monitor current is greater than target current, the bias voltage applied to the MZM should increase wrt optimum bias voltage. In order to understand this, the key is understanding how output intensity (& thus monitor photodiode current, which is proportional to it) changes with bias voltage.

1) MZM Transfer function:

The optical output intensity ($T(v)$) vs Bias Voltage (V_{bias}) is as follows:

$$T(v) = \cos^2 \left(\frac{\pi V_{bias}}{V_{\pi}} \right)$$

(For single drive, $V_{\pi dc} = 6.5V$ typical for LN81SFC Thorlabs MZM Modulator)

When, $V_{bias}=0V$, T is maximum (100% transmission and constructive interference)

$I=I_{max}$ (Highest monitor current)

As V_{bias} increases to $V\pi/2$ (ie. 3.25V): T decreases to 0.5 (Quad Point)

$I_{monitor} = 50\% * I_{max}$

As V_{bias} increases further to $V\pi$ (6.5V): T decreases to 0.

Lowest $I_{monitor}$ current ($I_{min}=0\mu A$)

The shape of the transfer function is as given in the Fig. 1. The curve starts high at low V_{bias} (peak transmission) & decreases to low at high V_{bias} (Null transmission). Quadrature is in the middle with Max. Slope.

Table 1: Variation of $I_{monitor}$ wrt V_{bias}

V_{bias}	Optical Transmission	$I_{monitor}$ (Monitor Current)
Increases	Decreases	Decreases
Decreases	Increases	Increases

2) What Happens when Monitor Current > Target Current

Target current is the setpoint (eg. $60\mu A \rightarrow 1mW$ for RFOF at Quad, $0\mu A \rightarrow$ DSBSC Null). If $I_{monitor}$ is greater than the Target current, then transmission is too high and Bias point has drifted towards the peak (lower V_{bias} than optimum). Eg. For RFOF/AM: Optimum= $3.25V$, $60\mu A \rightarrow$ Target $V_{bias}=1.95V$, $90\mu A \rightarrow I_{monitor}$. To compensate for this we need to reduce transmission back to target. Increase V_{bias} (move towards Null / higher voltage). This pushes the operating point back to optimum (eg. From 1.95V to 3.25V).

3) The Controller Error Signal

Higher Voltage = lower transmission = lower current

Lower Voltage = Higher Transmission = Higher current

Table 2: Controller Error Signal

Condition	Initial Voltage Action	Target Outcome
Current increases ($I > Target$)	Voltage is decreased	Increase voltage to decrease current

Current decreases ($I < Target$)	Voltage is increased	Decrease voltage to increase current
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The controller error signal is simply ($I_{monitor}-I_{target}$) with sign determining direction.

4) Practically:

Table 3: Error Signal= $I_{monitor}- I_{target}$

Error Condition	Monitor Current Status	Action (V_{bias})
Error > 0	$I_{monitor} > Target$	Increase V_{bias}
Error < 0	$I_{monitor} < Target$	Decrease V_{bias}

4. Biasing Requirements for RFOF/AM

In RF over fiber analog modulation systems, the objective is to linearly map an RF signal onto the optical intensity. This is achieved by biasing the MZM at the quadrature point.

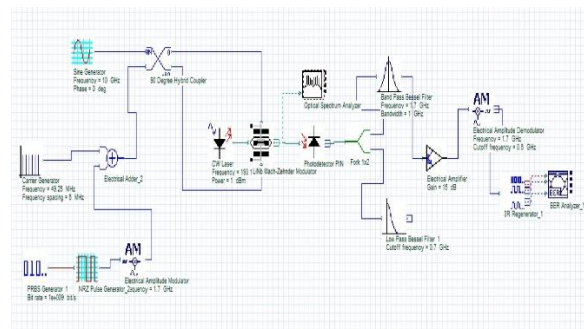


Fig. 2 a. Circuit Simulation of RFOF/AM modulation

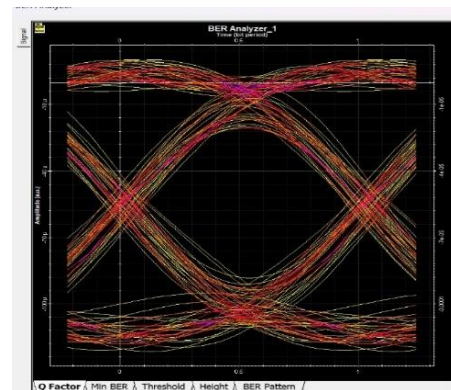


Fig. 2 b. Eye Diagram of RFOF/AM System

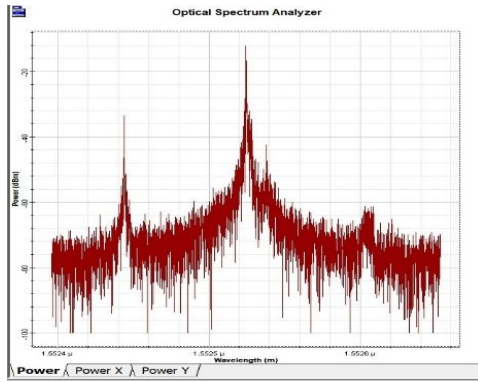


Fig. 2 c. Optical Spectrum of RFOF/AM System

The transfer function is linear for small signal modulation at the quadrature bias point. The biasing at quadrature results in low harmonic distortion and high noise free operating range. To further improve the linearity and reduce chirp in the system Push-pull configuration can be used. operation further improves linearity and reduces chirp, making it the preferred configuration for analog RFOF links.

5. Biasing For DSB-SC Modulation

Double-sideband suppressed-carrier (DSB-SC) modulation requires elimination of the optical carrier while retaining the modulation sidebands. This is achieved by biasing the MZM at the minimum transmission point.

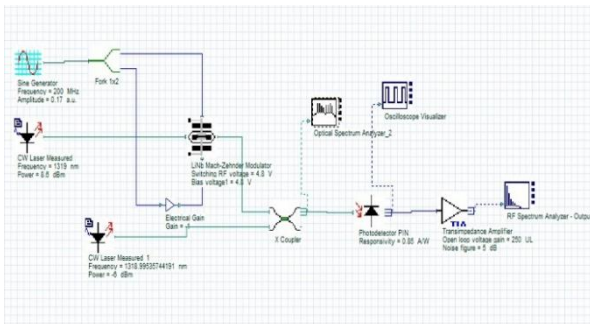


Fig. 3 a. Circuit Simulation of DSB-SC modulation

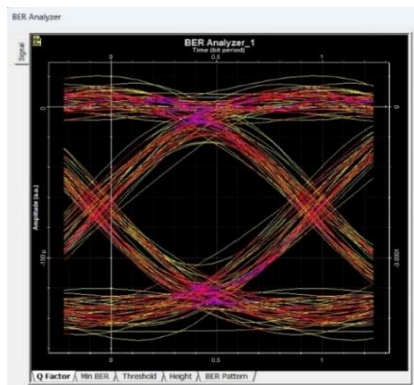


Fig. 3 b. Eye Diagram of DSB-SC System

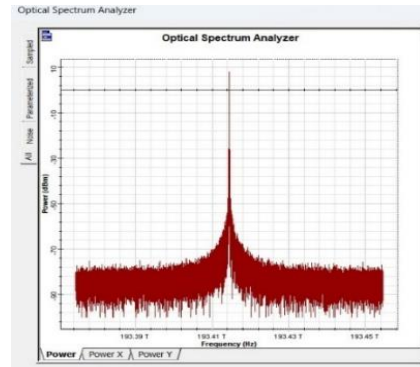


Fig. 3 c. Optical Spectrum of DSB-SC System

At MITB, the optical carrier is theoretically suppressed, and the output spectrum consists predominantly of the upper and lower sidebands. This technique is commonly used in microwave photonics for frequency conversion and harmonic generation.

However, even small deviation from the null point will result in carrier leakage from the system, and this makes the DSB-SC modulation extremely sensitive to the bias drift. Hence, bias control and stabilization are must for use in practical systems.

6. Biasing For BPSK Generation

Binary phase-shift keying (BPSK) is a phase modulation scheme where the optical carrier phase is switched between 0 and 1 according to the data sequence.

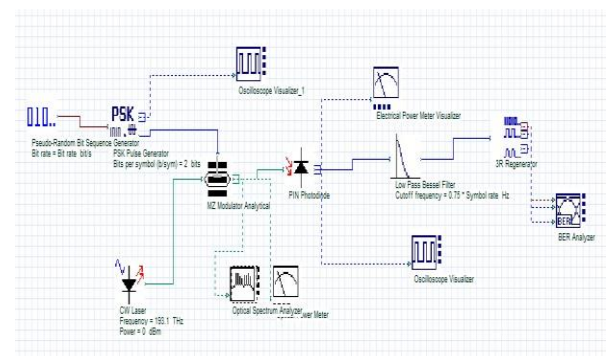


Fig. 4 a. Circuit Simulation of BPSK modulation

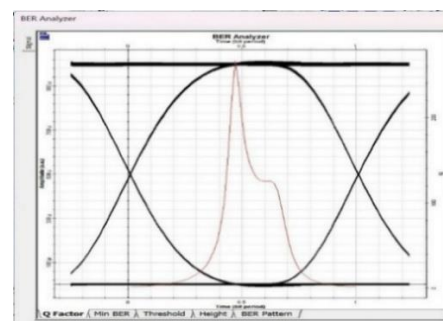


Fig. 4 b. Eye Diagram of BPSK System

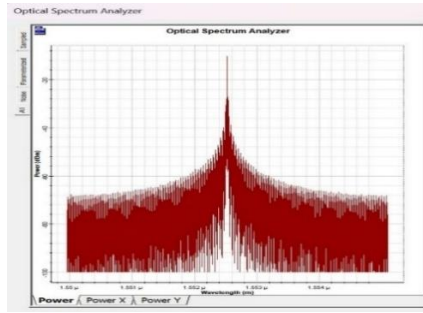


Fig. 4 c. Optical Spectrum of BPSK System

BPSK can be generated using a dual-drive or push–pull LiNbO₃ MZM biased at the null point. By applying complementary electrical signals to the two arms, pure phase modulation is achieved with minimal residual amplitude modulation.

Biasing at the null point ensures that the optical power is equally distributed in both the phase states, which is important for the coherent detection at the receiver. As compared to RFoF/AM and DSB-SC the BPSK modulation offers improved receiver sensitivity and robust performance against optical fiber nonlinearities.

7. Comparative Discussion

For biasing in the linear region in RFoF/AM modulation Quadrature bias is optimal whereas null point biasing is used in case of DSB-SC and BPSK modulation to achieve minimum transmission. Hence, the selection of biasing technique mainly depends upon the modulation type used and the system requirements such as linearity and spectral efficiency.

Table 4: Modulation Schemes and their corresponding biasing types

Sr. No.	Modulation Scheme	Type of Bias	Modulation Type
1	RFoF/AM	Quadrature bias	linear intensity encoding with carrier.
2	DSB-SC	Null bias	carrier-suppressed sidebands, frequency doubling.
3	BPSK	Null bias	optical phase encoding.

All the above schemes suffer from the effects such as photoemissive effect, photorefractive effect, aging, temperature changes, etc. Active controllers which basically use the pilot-tone method/dither or the neural-network based methods maintain the bias point stable by either monitoring the average output power

or by performing the harmonic analysis. The RF signal applied to MZM is the baseband message signal, which serves as the electrical driving voltage to modulate the optical carrier. This baseband signal (e.g. an NRZ data stream or analog message) directly controls the phase shifts in the MZM arms, resulting in the desired optical modulation format at the output, such as AM, BPSK or DSBSC. In AM, the baseband signal is applied with the MZM biased at the quadrature points for linear response. In BPSK, the baseband signal (e.g. bipolar NRZ data) is applied with an amplitude of $2V\pi$ and the MZM biased at the minimum transmission point to achieve 180 phase shifts. In DSBSC, the baseband signal is applied with the MZM biased at the Null point to support the optical carrier and generate sidebands.

Bias Voltage Independence

Bias voltage is independent of the Input Laser power and Bit rate. The reason for this is that Bias voltage sets phase difference between the MZM arms via the electro-optic effect (Pockels effect) in LiNbO₃. This effect depends on the applied electric field (voltage across electrodes), waveguide geometry, material coefficients (r_{33}) and temperature/ wavelengths. Not on optical intensity/ laser power.

MZ Photodiode Biasing:

To measure photodiode current from the integrated monitor photodiode, apply a reverse bias. If the device does not provide an internal voltage source for this; so, we need to supply it externally. Thus, quadrature biasing is optimal for RFoF/AM linear intensity modulation, while null-point biasing (with push–pull drive) is essential for both DSB-SC carrier suppression and BPSK phase encoding.

8. Laboratory Procedure for RFoF/AM, DSB-SC, and BPSK Modulation Schemes

Consider an LiNbO₃ Mach Zehnder Modulator with typical $V\pi$ as 6.5V. The Laser used is 1550nm CW TEC Stabilized with typical Optical Powers as 10mW & 50mW. The Photodiode has a Responsivity of 0.3 A/W typically. The RF- Sinewave 1KHz is chosen for RFoF/AM test. The Power Limits Typically are optical input $\leq +10$ dBm. Bias applied is in the range of ± 10 -15V depending on modes.

Preparation and Calibration Phase for all schemes:

1) Connect the Optical Chain as follows:

Laser → Inline polarization controller → VOA → Input fiber → MZM input.

MZM output → Optical fiber → Photodiode (or optical power meter/ OSA depending on measurement)

2) Connect the RF & Bias

RF Generator → MZM RF ports. Use Coax adapters with proper impedance (Typically 50Ω). For push pull operation use two RF ports with matched cables & equal amplitudes, opposite phase (180°) via splitter / 90-degree hybrid or two synchronized channels with inverted polarity.

3) For the Static Transfer Curve & V_π

Feed a low frequency sweep (e.g. 100Hz triangle, amplitude $\pm V_\pi$) into the RF or simply sweep DC bias across the expected V_π range while measuring optical power on power meter. Plot the optical power vs bias voltage to locate maximum (peak), minimum(null) and quadrature points. Quadrature is at the midpoint between peak and null (i.e. where slope is maximum). If for example $V_\pi=4V$, quadrature bias=2V Null=4V. Save these baseline values.

4) Set Laser and RF

Stabilize the Laser TEC and current. Use clean RF source and set initial RF amplitude to yield desired modulation index.

5) Instrument Checks

Scope with bandwidth and sample rate must be sufficient to capture 1KHz modulation and any other test signal. OSA/ESA resolution should show carrier and sidebands for DSBSC test. Record the baseline parameters such as V_{bias} at Quadrature, V_{bias} at Null, Half Wave Voltage (V_π) and Input optical power.

Datasheet Confirmation for LN81S-FC Thorlabs MZM:

V_π (DC bias $V_\pi@1KHz$: Typical 6.5V max. 10V). Operating points (e.g. Quad at $V_\pi/2=3.25V$, Null at $V_\pi=6.5V$) are specified without any dependence on input power. (max. 100mW). Optical input power is listed separately as a damage threshold, not a parameter affecting V_π or bias. Practical behaviour in experimental setup:

The required Bias voltage to reach quad (for RFOF/AM) or Null (for DSBSC/ BPSK) is fixed for the device (e.g. 3.25V quad, 6.5V Null). Changing Laser power (1 mW to 100mW) scales the output optical power and monitor photocurrent linearly (due to fixed insertion loss

approx. 4dB) but does not require adjusting the bias voltage to maintain the operating point. Bit Rates: Bit rates (100 MHz, 1GHz) do not affect the DC bias or monitor current. They only impact RF drive amplitude (via RF V_π 5.6V). Bit Rate affects only AC swing on the PD current.

9. Conclusion

A detailed discussion about the importance of biasing technique for LiNbO3 MZM with special emphasis on the RFOF/AM, DSB-SC and BPSK modulation is presented in this paper. The selection of bias point directly affects the system performance. In case of Analog modulation, the Quadrature bias is best suited which provides linear output whereas for carrier-suppressed and phase modulation schemes minimum transmission and push-pull biasing are essential. A comparative discussion and laboratory procedure for different biasing schemes is discussed in detail. The insights provided in this paper will serve as practical guidelines for providing biasing to the LiNbO3 MZM based photonic systems.

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