PERFORMANCE ANALYSIS OF MACH-ZEHNDER MODULATOR IN RADIO OVER FIBER SYSTEMS

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ABSTRACT
Radio over Fiber (RoF) is a next generation wireless broadband Internet access technology. In Radio over Fiber system the radio signal is generated at the central station is modulated on to light and transmitted over optical fiber cable to various base stations. The base station has to convert the optical signal to an electrical signal, amplify and transmit it. Modulation of RF signal onto light is a key function of the system. Both direct and external modulations are employed in RoF systems. External modulators are preferred in high performance RoF systems due to many advantages. The Mach-Zehnder Modulator (MZM) is a versatile external modulator which makes it attractive for Radio over Fiber systems. By using different combinations of applied electric fields, the Mach-Zehnder modulator can be used to generate phase modulation, amplitude modulation, or a number of other modulation formats. Here both simulative and experimental study of Radio over Fiber (RoF) system employing the Mach Zehnder Modulator (MZM) as external modulator is done. The modulator performance in various configurations are analyzed in this paper.

Key words: Mach-Zehnder Modulator, Radio over Fiber, LiNbO3, Amplitude Modulation, Phase Modulation, Double sideband with Optical carrier Suppression

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1. INTRODUCTION
Wireless communication has an immense growth in the past and present decade. There is an increased demand for high performance wireless connectivity and broadband services. To meet explosive demands of high capacity data and broadband wireless access, the number of cells is increasing and there is a utilization of high frequency bands. Several technologies have been introduced for the purpose. The Radio over Fiber (RoF) [1] is one such emerging technology which makes use of radio frequency generated at the central station is modulated on to light and distributed over optical fiber cable to various base stations. The base station has to convert the optical signal to an electrical signal, amplify, filter and transmit the radio signal. RoF increases the capacity, coverage and mobility and also simpler base stations.
In RoF light is modulated by the RF signal and transported through optical fibers. Modulation of RF signal onto light is an important part of the RoF system. Both direct and external modulations [2] are employed in RoF systems. Through direct modulation of lasers only intensity modulation can be achieved and the band width is limited. Hence external modulators are preferred in high performance RoF systems such as Mach Zehnder Modulator (MZM) or Electro Absorption Modulator (EAM)[3] etc. Here both simulative and experimental study of Radio over Fiber (RoF) system employing the Mach Zehnder Modulator (MZM) as external modulator is done.

An overview on RoF is given in Section II. Then a detailed analysis of the MZM modulator is done in Section III. Section IV summarizes the experimental and simulation results for various configurations and then conclusion.

2. RADIO OVER FIBER

Radio over Fiber (RoF) system consists of a Central Station connected to many Base Stations (BS) through optical fiber. The central station performs almost all the signal processing like modulation, demodulation, routing etc [4]. Since a large number of Base Stations are to be deployed, BSs are made functionally simple. A Base Station converts optical signal to wireless signal and vice versa. This greatly reduces the equipment complexity and maintenance cost of the network. Low complexity, low attenuation, lower cost, larger bandwidth etc. are some of the advantages of RoF system.

Research have been going on in the area of high speed modulation of the laser source in RoF. Modulation of the optical carrier can be done by using directly modulated laser or by using external modulators such as Mach Zehnder Modulator (MZM) or Electro Absorption Modulator (EAM).

Direct modulation is to let the signal directly modulate the laser diodes current as shown in Fig.2a. Limitations of direct modulation are pulse spreading, information loss and limited bandwidth. External modulation requires an un-modulated laser source and an external modulator as shown in Fig.2b. Though external modulation is costly and complex, it offers a more robust performance compared to direct modulation.
Two commonly used external modulators are Mach Zehnder Modulator (MZM) and Electro Absorption Modulator (EAM) each having a different principle of operation. The Mach Zehnder Modulator performance in Radio over Fiber systems are analyzed in this paper.

3. MACH ZEHNDER MODULATOR

The physicists Ludwig Mach and Ludwig Zehnder devised the apparatus Mach–Zehnder interferometer which is used to determine the relative phase shift variations between two collimated beams derived by splitting light from a single source. The Pockels effect (after Friedrich Carl Alwin Pockels who studied the effect in 1893), a linear electro-optic effect, changes or produces birefringence in an optical medium induced by an electric field[6]. This electro optic effect is incorporated in a MZ interferometer, wherea beam splitter divides the laser light into two paths, one of which has a phase change induced by an applied electric field. The beams are then recombined. Changing the electric field on the phase modulating path will then determine whether the two beams interfere constructively or destructively at the output, and thereby control the amplitude or intensity of the exiting light. This device is called a Mach-Zehnder modulator.

Some materials like LiNbO$_3$ (Lithium Niobate) shows large Pockels effects that is the presence of an electric field show a change in the refractive index[7]. This change in refractive index is utilized for amplitude, phase and frequency modulation. Lithium niobate is a colorless solid insoluble in water. It exhibits Pockels effect, piezoelectric effect, photoelasticity and nonlinear optical polarizability making an ideal choice for the construction of electro optical modulators. It is transparent for wavelengths between 350 and 5200 nanometers. BaTiO$_3$ is another such material for fast and low power modulation [8].

The Mach-Zehnder Modulator (MZM) is a versatile external modulator which makes it attractive for radio-on-fiber systems. It has two variants single drive and dual drive. Its versatility comes from the fact that the two electrical inputs can be controlled independently to generate a number of different optical modulation formats. It consists of an input waveguide which is split up into two nonlinear waveguide interferometer arms, and then they are combined at the optical output. It is the non-linear medium that allows the electrical and optical fields to mix.

![Image](image_url)

**Figure 3 A) Single Drive MZM**

**Figure 3 B) Dual Drive MZM**

If a voltage is applied across one arm, the refractive index changes due to electro optical effect. Hence a phase shift is induced for the wave passing through that arm. When the two arms are recombined, the phase difference between two waves can be converted in to some form of modulation.

$$E_{out} = 0.5E_{in} \left( e^{\frac{V_a}{V_x}} + e^{\frac{V_b}{V_x}} \right)$$

(1)

In this expression, the first term represents the upper phase modulator with an applied electrical voltage of $V_a=V_{dc1}+V_j(t)$ and the second term represents the lower phase modulator with an applied voltage of $V_b=V_{dc2}+V_2(t)$. The output optical field $E_{out}(t)$ of a MZM depends on the applied voltage, input signal $V(t)$, optical carrier frequency $f_c$, switching voltage $V_x$ and input optical power to Mach Zehnder Modulator $P_{in}$. $V_x$ is the voltage which introduces a $\pi$ radians phase change when applied to the arm of MZM. In case
of dual drive, the bias voltage $V_{bias}$ and modulating voltage $V(t)$ can be applied differentially. The 0.5 constant arises from the fact the optical power is split between the two arms.

### 3.1. MZM as Amplitude Modulator

A single drive MZM can generate Optical Double Side Band (ODSB) signal where as a dual drive capable of generating many other modulation. A dual drive dual port MZM is a highly efficient modulator for multiple forms of modulation and can be used for simultaneous modulation of laser diode by wired and wireless data [9].

$$E_{out} = 0.5E_{in} \left( e^{j\frac{\pi V_{bias}}{V_x}} + e^{-j\frac{\pi V_{bias}}{V_x}} \right)$$

$$= E_{in} \cos \left( \frac{\pi V_{bias}}{V_x} + \frac{\pi}{4} \right)$$

(2)

Consider the case where the modulating signal is a sub-carrier of the form $V_{in} = m \cos(2\pi f_c t)$, where $m$ represents the modulation index, $f_c$ is the frequency of the signal, and $t$ is time. Equation 2 can be expanded using the Bessel function consider the portion of the signal at $f_c$,

$$E_{out}(f_c) = \frac{E_{in}}{\sqrt{2}} \left( 2J_1 \left( \frac{m\pi}{V_x} \right) \cos(2\pi f_c t) \right)$$

(3)

which is amplitude modulation for small values of $m$ ($m < 0.4$) for which the first order Bessel function is almost linear

### 3.2. The Mach-Zehnder as a Phase Modulator

The MZM can be used as a phase modulator by applying the same voltage ($V_{dc1} = V_{dc2}$) to each of the arms. In this case the modulator’s transfer function, Equation 1, reduces to and the phase of the output will be proportional to the applied electric voltage.

$$E_{out} = E_{in} \left( e^{j\frac{\pi V_{bias}}{V_x}} \right)$$

(4)

Phase modulation is desired when a coherent optical detector is used, or when other optical components are used to translate the phase modulation into amplitude modulation. Phase modulation’s primary advantage is that the two applied electrical signals are identical so they require no special external hardware to generate one from the other. Unfortunately, the coherent detector that must usually be used to recover a phase modulated signal is much more expensive than a simple photodiode, limiting the use of optical phase modulated systems.

### 4. SIMULATIVE AND EXPERIMENTAL RESULTS

The simulations are carried out using Opt system v13, a high end optical communication simulation package. It can be used for design, testing and optimization of virtually any type of optical link. Opt system enables users to plan, test and simulate realistic models of Fiber optic communication system including RoF. It has advanced visualization tools like OSA, Eye diagrams, BER analyzer, constellation diagram etc.

Here the MZM bias voltages are adjusted to provide different modulation formats. A PRBS generator is used for generating the data signal at the rate of 1Gbps. The data signal is then BPSK modulated at
20GHz and this RF signal is fed to the MZM which will modulate an optical carrier generated by a CW laser at 1550nm.

This signal is then transmitted through a single mode fiber. Single mode fiber allows only one mode and it has a core size of about 10 micrometers. Hence single mode fiber eliminates intermodal dispersion. It also supports transmission over much longer distances.

![Image](image.png)

**Figure 4** Simulation Setup of RoF System

At receiver end the signal is detected by a simple $p-i-n$ photo detector. The detected RF signal is then passed through a Gaussian filter and then demodulated. The received bit stream is then fed to BER and eye diagram analyzer and the performance of various configuration are studied.

![Image](image.png)

**Figure 5**

A) MZM harmonics  
B) eye pattern

To study various effects a dual drive Mach Zehnder Modulator is selected. The bias voltages are kept arbitrarily $V_{dc1}=-1V$ and $V_{dc2}=-3V$. Figure 5 shows the harmonics generation due to the nonlinear behavior of MZM. The eye pattern is very much blurred that eye opening could not be identified. It has a very high bit error rate too. The spectrum shows energy at all multiples of the fundamental frequency. This implies that such a scheme can be used to do frequency up-conversion. Using proper filtering at the receiver end the desired frequency band can be selected.

Next MZM is modelled as Amplitude modulator. Here the difference of bias voltages kept at $V\pi/2$. As shown in Eq.3 the phase change is converted in to amplitude modulation and side bands are generated. Figure 6 illustrates this configuration. Here a good eye opening and BER of $1.7x10^{-12}$ obtained for a distance of 10KM. Here other factors like splicing loss, connector loss, receiver noise etc are not taken in to consideration.
The DC bias voltage is kept at $V_{\pi}$ and fed to both the arms. An interesting feature is obtained. The signal is now modulated as Double Sideband with optical Carrier Suppressed (DSBCS)[10]. This modulation has the advantage of better receiver sensitivity and both base band and RF signals can be simultaneously generated when detected by a photodiode [11]. The simulation result is shown in Figure 7. A BER of $7.6 \times 10^{-10}$ obtained in this case.

An experimental study of RoF system is carried out using iXBlue Photonics NIR-MX-LN-10 model MZM. A Pump laser of 980nm at 1mw power is connected as optical source and RF signal is fed from Agilent N9310ARF Signal Generator. The results are observed using Yokogawa AQ6370 Optical Spectrum Analyser and Rohde & Schwarz’s FSL3 Spectrum analyser.
5. CONCLUSION

The characteristics of Mach Zehnder Modulator is studied and different modulation formats are analysed. Improper biasing creates harmonic distortion and the modulated signal cannot be recovered. But other modulation formats like AM and Suppressed carrier showing satisfactory performance over a distance up to 10KM without using amplifiers. The experimental analysis verified the transfer characteristics of MZM.

Real MZM’s have a number of possible deficiencies. The optical power may not be split evenly between the two arms, one of the arms may be longer resulting in a different phase delay, the $V_x$ of the two arms may not be the same due to differences in the construction of the non-linear medium, or the loss in one of the arms may be larger than the other, but the largest degradation can come from the fact that the materials used to build current MZM’s are polarization sensitive. If the polarization of the input optical electric field is not aligned on the correct axis, then the optical signal in the modulator is less affected by the applied electric field, reducing the modulation efficiency. This problem can be dealt with in real systems by preceding the MZM by a polarization controller. Once the polarization of the input light has been correctly aligned, the Mach-Zehnder modulator can be used to generate phase modulation, amplitude modulation, or a number of other modulation formats by using different combinations of applied electric fields.
REFERENCES


