Analysis of Optical Modulators for Radio over Free Space Optical Communication Systems and Radio over Fiber Systems

Prabu K; Sumanta Bose, *Student Member, IEEE*; Dr. D. Sriram Kumar

***Abstract* — Radio over Free Space Optics (RoFSO) and Radio over Fiber (RoF) are recent technologies in optical communication systems. Both these technologies require some form of external optical modulator in the transmitter side. The commonly used optical modulators are Mach-Zehnder modulator (MZM) and Electro absorption modulator (EAM). In this paper, we analyze the performance of both Mach-Zehnder modulator and Electro absorption modulator for Radio over Free Space Optical Communication systems and it is compared with Radio over Fiber systems. We also discuss about the choice of optical modulator based on the intensity of output light signal.**

***Keywords* — Electro Absorption Modulator (EAM), Free Space Optics (FSO), Mach-Zehnder Modulator (MZM), Radio over Fiber (RoF), Radio over Free Space Optics (RoFSO)**

I. Introduction

A. Radio over Free Space Optical Communication

Free Space Optics is a line of sight technology which involves the transfer of data from one point to another point using optical radiation in free space [1]. The intensity and phase of the optical carrier signal can be modulated based on the message signal. FSO provides the flexibility of wireless communication and the speed of fiber optic communication. An FSO unit consists of optical transceivers with a laser transmitter and a receiver to provide full duplex connectivity between them. Each FSO unit uses a high power optical source and a lens that transmits the lights through the atmosphere to another lens receiving the signal. The advantages of FSO are high bit rate, ease of deployment, license free operation, high transmission security, full duplex transmission and protocol transparency. Shielding from electro-magnetic interference should also be mentioned as a significant advantage in saturated RF spectrum environments [1]. Important features of FSO include huge modulation bandwidth, narrow beam size, low cost, easy implementation and unlicensed spectrum.

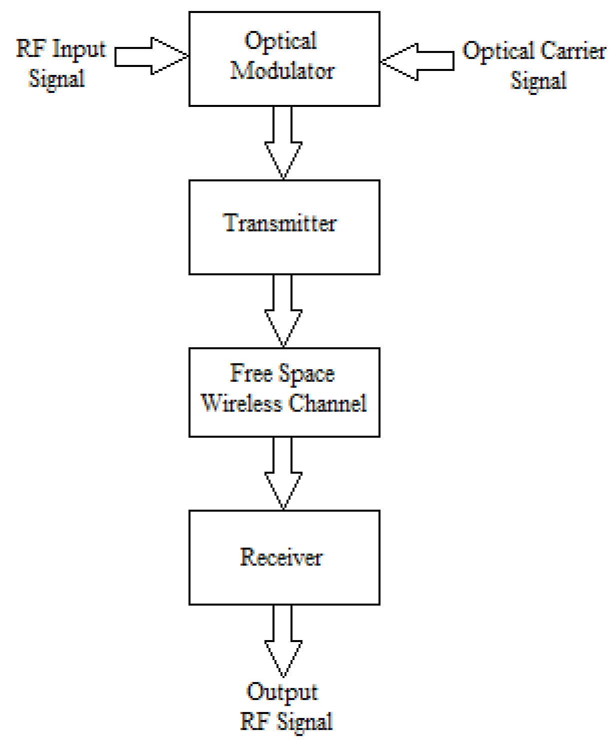

Figure 1. Block diagram of RoFSO communication system

Radio over Free Space Optics (RoFSO) is the technology in which it is possible to transmit and receive multiple RF signals simultaneously over FSO links using wavelength division multiplexing (WDM) technology. RoFSO can be used as a backup of RoF technology, in case of failure or absence of the fiber network [2]. A simplified block diagram for radio over free space optical communication system is shown in Figure1.

B. Radio over Fiber System

Radio-over-fiber (RoF) technology has emerged as a cost effective approach in which the central site and multiple number of remote sites are connected by using optical fiber. RoF technology is a technology by which microwave signals are distributed by means of optical components and techniques [3]. If the application area is in a 'Global System for Mobile' communications network, then the central site could be the

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Mobile Switching Centre (MSC) and the remote site the base station (BS). A simplified block diagram for radio over fiber communication system is shown in Figure 2.

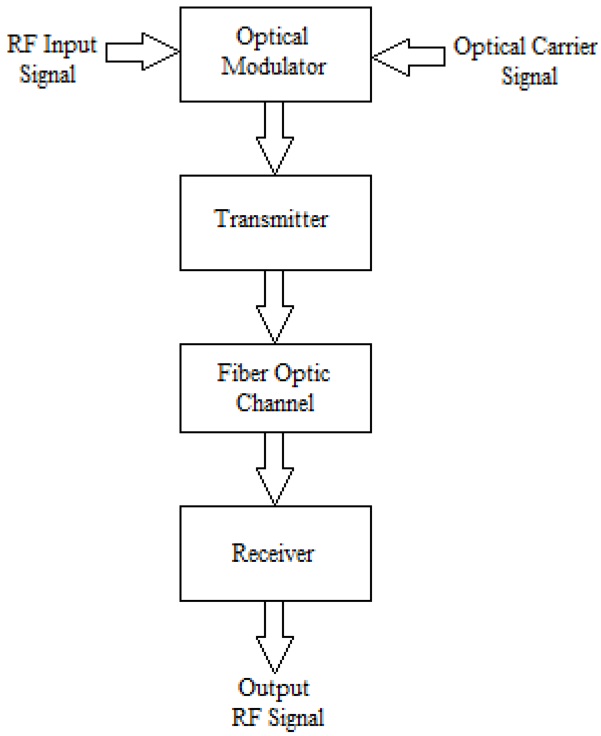

Figure 2. Block diagram of RoF communication system

For a multifunctional RoF system, the choice of the electrical signal at the input depends on the type and functionality of the system. The electrical signal is modulated with the optical carrier signal. The modulated signal is carried over optical fiber link to the remote stations. Here, the original data is recovered from the modulated signal by using photo detector. Avalanche photo detector is commonly used.

The benefits of the RoF system are low attenuation loss, large bandwidth, easy installation and maintenance and operational flexibilities. Some of the applications of RoF technology include mobile radio communications, cellular networks, satellite communications, broadband access radio, Multipoint Video Distribution Services (MVDS), Mobile Broadband System (MBS), vehicular communication and wireless LANs over optical networks.

II. OPTICAL MODULATORS

A. Mach-Zehnder Modulator

Mach-Zehnder modulator (MZM) is an Electro Optic Modulator (EOM) [4] which works on the basis of Pockel's effect. In MZM the incoming optical signal is split equally and is sent to two different optical paths. Applying an electric voltage to one of the optical path produces a refractive index variation in accordance with the applied voltage, which introduces a phase shift in the wave travelling in that optical path. The amount of electric voltage required to produce a phase shift of 180° is called half-wave voltage or Swing voltage. After a certain distance, the two optical paths recombine, causing the optical waves to interfere with each other. Such an arrangement is known as an interferometer. The individual signals interfere constructively or destructively depending on their relative phase differences, which determines the amplitude of the output optical signal. A simplified block diagram of Mach-Zehnder modulator is shown in Figure 3.

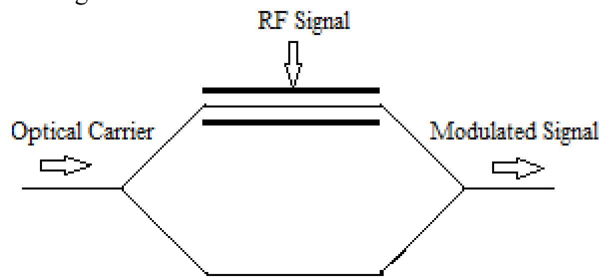

Figure 3. Mach-Zehnder modulator

We have modeled the Mach-Zehnder modulator according to power relationship between input and output power [4] which is given as:

$$P_{out} = \left(\frac{P_{in}}{2}\right) \cdot \left(1 + \cos\left\{\frac{\pi * u(t)}{V_\pi}\right\}\right) \quad (1)$$

where P_{out} is the output optical power, P_{in} is the input power of Mach-Zehnder modulator and $u(t)$ is the applied RF input signal and V_π is the half wave voltage.

B. Electro Absorption Modulator

Electro absorption modulators [5] are based on electro absorption effect, which is defined as the change of material absorption in the presence of an electric field. EAM is used for modulating the intensity of laser beam via an electric voltage. The basic principle of EAM is Franz-Keldysh effect. It provides high data rate with low chirp. EAM have low driver voltage, large maximum extinction ratio and high figure of merit. The highest 3-dB bandwidth reported for EAM is 50 GHz. It can be monolithically integrated with driver circuitry and/or laser sources. A simplified block diagram of the Electro Absorption Modulator is shown in Figure 4.

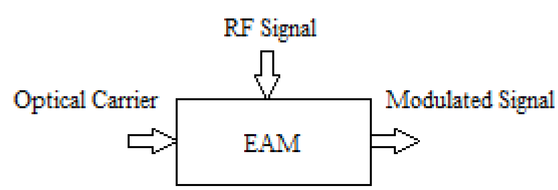

Figure 4. Electro absorption modulator

The mechanism of EAM is such that if an external RF signal is applied to the light propagating through the waveguide, the resulting electric field changes the electric absorption coefficient of the medium. This varies the intensity of the output optical signal.

Electro absorption modulators are widely used due to their low driving voltage, large bandwidth and feasibility of monolithic integration with laser diodes. The transfer function of the EAM [5] can be expressed as:

$$T(\nu) = \frac{P_{out}}{P_{in}} = \exp\{-\alpha_1 \nu - \alpha_2 \nu^2\} \qquad (2)$$

where P_{in} is the input optical power and P_{out} is the output optical power. The linear term $\alpha_1 \nu$ comes from the Franz-Keldysh effect and the quadratic term $\alpha_2 \nu^2$ comes from the Quantum Confined Stark effect. $\nu = \nu_b + \nu_m$ is the total voltage applied to the modulator, where ν_b is the bias voltage and ν_m is the modulating voltage.

C. Comparison of EOM and EAM

Electro-optic modulators are based on linear electro-optic effect, which is defined as the change of material refraction index under the presence of an electric field. By varying the electric field, the optical phase can be modulated [6], which in turn results in intensity modulation as in the Mach-Zehnder interferometer configuration. The latter is widely used for making electro-optic intensity modulators and is usually made with traveling-wave electrode structures in order to achieve high-speed operation [7]. Electro absorption modulators are based on electro absorption effect, which is defined as the change of material absorption in the presence of an electric field. It is called the Franz-Keldysh effect in bulk materials and Quantum Confined Stark Effect (QCSE) in quantum-well materials [8, 9]. The QCSE type has much higher modulation efficiency and further research is elicited in this direction.

III. Channel Models

A. Optical Fiber

In this work single mode fiber is used to carry the optical signal. The single mode fiber is used as a medium between the base station and main switching centre. The transfer function of single mode fiber [10] is expressed as:

$$H(t) = (i+1) \cdot \frac{1}{\sqrt{4\pi\beta_2 L}} \cdot \exp\left\{\frac{-it^2}{2\beta_2 L}\right\} \qquad (3)$$

where L is the length of the fiber. β_2 is expressed as $\beta_2 = \frac{\partial^2 k(\omega)}{\partial \omega^2}$ where $k(\omega) = \frac{\omega}{c} n(\omega)$ and $n(\omega)$ is refractive index of the single mode fiber. Alternately β_2 can be derived in terms of Group Velocity Dispersion (GVD) parameter D_λ [10] as:

$$\beta_2 = \frac{-D_\lambda \lambda_o^2}{2\pi c} \qquad (4)$$

A very narrow bandwidth laser source is used in this model. The output optical power at end of the fiber is obtained by using convolution (equation 5). The impulse response $H(t)$ is truncated and smoothed by window function (equation 6). The window functions are applied to avoid the discontinuity at the beginning and end of the signal [11].

$$P_{Out\ Of\ Fiber} = A \cdot |E_{in}(t) \cdot H(t)|^2 \qquad (5)$$

$$h_w(t) = 0.54 + 0.46 \cos\left\{\pi \cdot \left|\frac{t}{T_{max}}\right|^3\right\} \qquad (6)$$

where A is the attenuation in the fiber and $E_{in}(t)$ is the input electric field, T_{max} is the maximum window duration.

B. Free Space

The light signal when passed through wireless channel is greatly affected due to natural turbulence and fading. Fading is caused by the interference between two or more versions of the transmitted signal. Rayleigh fading and Ricean fading may be used to model the wireless channel effects. Rayleigh fading statistical model assumes that the magnitude of signal passed through such transmission medium varies randomly according to the Rayleigh distribution. As the carrier frequency of message signal is varied, the amplitude varies.

Rayleigh model is convenient to estimate signal propagation in troposphere and ionosphere as well as consider the effects of congested urban environments on radio signals. Rayleigh fading is best applicable when there is no dominant propagation along a line-of-sight between the transmitter and receiver. In this paper the free space channel is considered as a Rayleigh faded channel and modeled using the probability density function $P_R(\mathrm{r})$ as:

$$P_R(\mathrm{r}) = \frac{2\mathrm{r}}{\Omega} \exp\left\{\frac{-\mathrm{r}^2}{\Omega}\right\} ; \mathrm{r} \geq 0 \ ; \ \Omega = E(R^2) \qquad (7)$$

IV. Numerical Results & Discussions

GSM signal at 900 MHz at a data rate of 270.8 Kbps is generated and the wireless channel effects implemented include Rayleigh fading effect and additive white Gaussian noise. GSM signal is applied to the MZM and EAM and the corresponding outputs are shown in Figure 5.

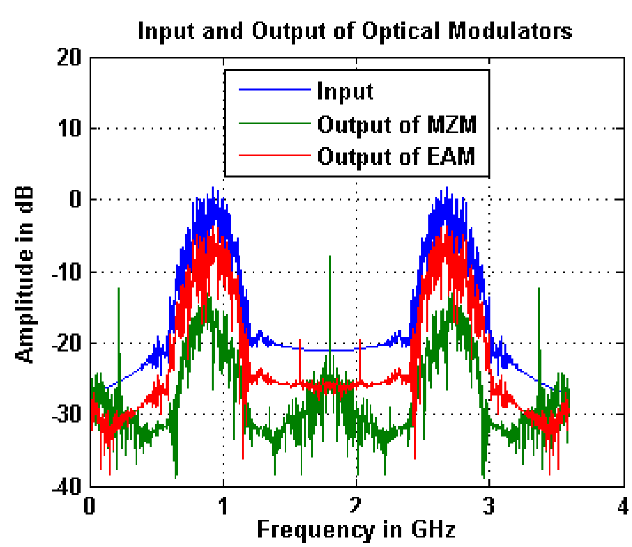

Figure 5. Input and Output Signal of Optical Modulators

The simulation is done for EAM with bias voltage equal to 1.12V and the values of the EAM parameters taken as $\alpha_1 = 0.5745$ and $\alpha_2 = 0.5700$. The outputs of both the modulators are transmitted through the optical fiber and amplitudes of the output optical signals at the receiving end are compared and shown in Figure 6. The length of the fiber used for simulation is $L = 1km$. From the comparison we conclude that EAM has lesser dispersion or noise at the receiving end, after the fiber. It is found that the amplitude of the optical signal in case of EAM over RoF is 7dB higher than MZM over RoF.

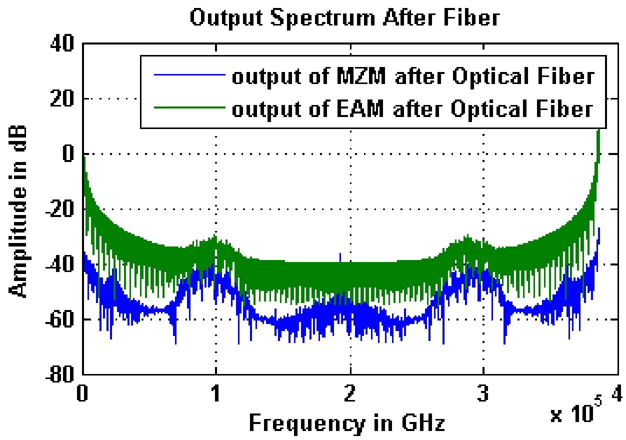

Figure 6. Output Spectrum after $1km$ of Fiber

The outputs of both the modulators can be transmitted through the FSO atmospheric channel and the amplitudes of the optical signals are compared as shown in Figure 7. From the comparison we conclude that EAM has lesser dispersion or noise at the receiving end, after the free space channel. It is found that the amplitude of the optical signal in case of EAM over RoFSO is 17dB higher than MZM over RoFSO.

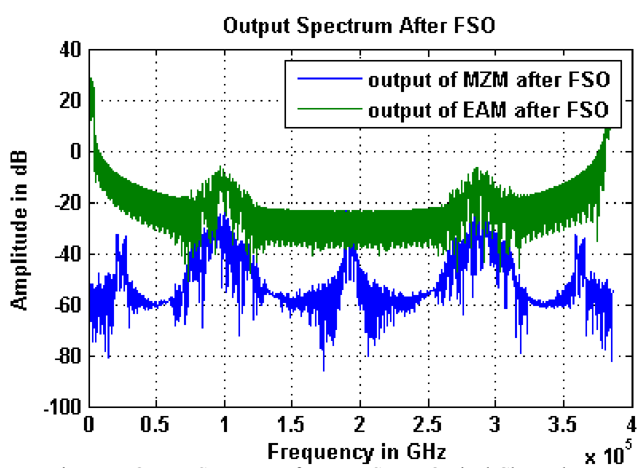

Figure 7. Output Spectrum after Free Space Optical Channel

V. CONCLUSION

The Mach-Zehnder modulator, Electro absorption modulator, optical fiber and wireless free space channel have been modeled and simulated. A GSM signal was generated and it was modulated with the optical carrier signal by using optical modulators and the output signal intensities were compared. The modulated signals were applied to the transfer functions of the optical fiber and free space optical communication channel. After transmission through the channel the output intensity of both the modulators were compared. The numerical and graphical results show that Electro absorption modulator provides comparatively higher intensity output signal after the channel compared to the Mach-Zehnder modulator.

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