Examination of Power Penalty due to Chromatic Dispersion Effect on mm-Wave Optical-Communications Fiber-Link with Mach-Zehnder Modulator

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***Abstract**. Analog optical fiber link is one of the common configuration to transmit high frequency signals in the microwave (μ-W) and millimeter wave (mm-W) ranges. In the mm-W signal range, only external modulation can be used, with the intention to overcome the limited bandwidth of a directly modulated laser. Such an external modulation can be implemented by using a Mach-Zehnder modulator (MZM). In mm-W optical fiber links, one of the main issues is the power penalty due to the chromatic dispersion of the optical fiber. This problem is thoroughly analyzed in this paper.*

1 Introduction

In today's communication technology, optical transmission is widely adopted due to the low losses and the high bandwidth characterizing optical fibers. To transfer mm-W signals over the optical domain, one of the possibilities is using analog optical fiber links (AFOL). This technique, makes use of several components such as laser diodes, opto-electronic modulators, optical fibers and photodetectors (Fig. 1).

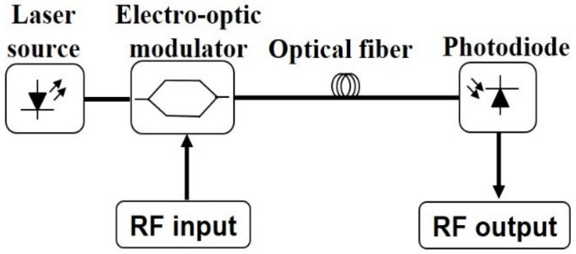

Figure 1. AFOL configuration with external modulation.

The optical loss of the fiber depends on the wavelength of the light source. For example, the G.652D optical fiber has a loss of only 0.2 dB/km at the wavelength of 1550 nm. Hence, the power penalty due to attenuation is low but additional power penalty occurs due to the fiber chromatic dispersion [1-3]. In addition, the chromatic dispersion is more dominant in the mm-W range compared to the μ-W range [4]. In the mm-W range, the light source needs to be modulated with an external modulator such as the MZM [5-6] or an electro-absorption modulator [7-8], as an alternative to the direct laser modulation which is affected by frequency chirp. For the purpose of effectively transmitting the mm-W signal through analog optical links, the external modulation and power penalty need to be analyzed.

2 Optical signal transmission from Laser diode to MZM

In this section, the transmission of optical signals from a distributed feedback laser (DFB) to a MZM is investigated. We have shown how the input signal changes with a mm-W modulated signal, and we observe the optical signal behavior at the output of the MZM. These calculations are based on [3] and [9-14].

The optical field at the input of the MZM $[E_{in}\,(t)]$ can be described as:

$$E_{in}\,(t) = E_0 \cos(\omega_0 \mathrm{t}) \tag{1}$$

where E_0 is the electric field amplitude and ω_0 is the angular frequency of the light produced by the laser. The output of the MZM can be written as

$$\mathrm{E_{out}(t)} = \mathrm{E_0} \Big\{\Big\{\cos\left(\beta\frac{\pi}{2}\right)\cos\left(\alpha\frac{\pi}{2}\cos(\omega_{\mathrm{RF}}\mathrm{t})\right) - \sin\left(\beta\frac{\pi}{2}\right)\sin\left(\alpha\frac{\pi}{2}\cos(\omega_{\mathrm{RF}}\mathrm{t})\right)\Big\}\cos(\omega_0\mathrm{t}) \tag{2}$$

where ω_{RF} is the modulation angular frequency, β is the normalized bias, and α is the normalized radio frequency (RF) amplitude driving the MZM. The normalized drive voltage can be defined [13] as:

$$\frac{\mathrm{U}}{\mathrm{U_\pi}} = \mathrm{u_0} + \mathrm{u}\cos(\omega_{\mathrm{RF}}\mathrm{t} + \varphi_{\mathrm{m}}) \tag{3}$$

where U_π is the half-wave voltage and U is the drive voltage, u_0 is the normalized bias voltage, u is the normalized voltage amplitude, φ_m is the initial phase. Fig. 2 shows the transfer function of MZM versus applied bias voltage u.

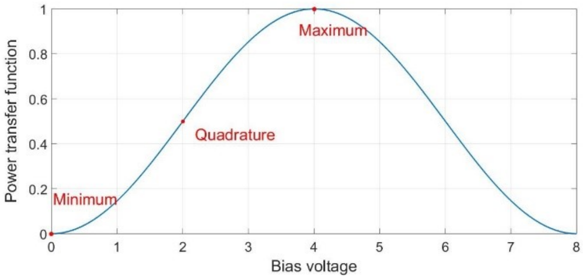

Figure 2. Transfer Function of MZM versus applied bias voltage where the half-wave voltage is 4 V.

There are three major points of interest from the transfer function curve of the MZM when a bias is applied (Fig. 3). These are maximum (when transfer function is 1), quadrature (when transfer function is 0.5) and minimum (when transfer function is 0) points. The quadrature point is preferred for mm-W signal applications [14]. The Fast Fourier Transform (FFT) of the transfer function versus modulation frequency is shown in Fig. 3.

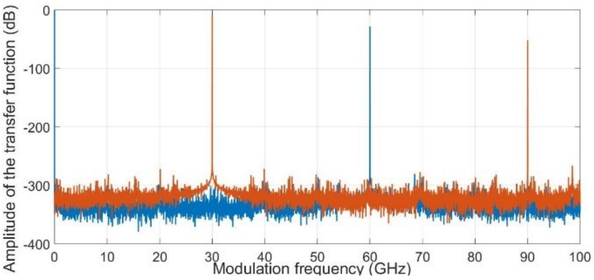

Figure 3. Power of the transfer function versus the modulation frequency.

In Fig. 3, blue lines show the amplitude of the maximum and minimum points and orange lines show the quadrature points.

3 Optical Signal transfer from MZM to Photodiode via optical fiber

The optical field at the output of SMF can be written [14] as:

$$E_{out}(\omega) \approx E_{in}(\omega) e^{-j(\beta_0+\beta_0'\Delta\omega+\beta_0''\frac{\Delta\omega^2}{2})L} \tag{5}$$

where β_0 represents the phase delay and $\beta_0'\Delta\omega$ represents the group delay. The $\beta_0''\frac{\Delta\omega^2}{2}$ is the phase change related to the chromatic dispersion where

$$\beta_0'' = \frac{-\lambda^2 D}{2\pi c} \tag{6}$$

and the photocurrent after photodetection can be written [14] as:

$$i_{PD}(t) = R_{PD}\left\{E_0^2 + 2E_{RF}^2 + 4E_0 E_{RF}\cos\left(\frac{LD}{4\pi c}\lambda^2\omega_{RF}^2\right).\cos[\omega_{RF}(t-\tau)] + 2E_{RF}^2\cos[2\omega_{RF}(t-\tau)]\right\} \tag{7}$$

where E_0 is the field amplitude, E_{RF} is the radio frequency amplitude, R_{PD} is the photodetector responsivity, L is the fiber length, c is the speed of light in vacuum, D is the fiber-dispersion coefficient at the wavelength of the optical carrier, τ is the fix delay λ is the optical carrier wavelength. With some approximations, (7) can be represented as (8) in electrical domain [1], [14] as:

$$P \propto 20log\left(cos^2\left(\frac{\pi L D_0}{c_0}\left(\frac{f_{RF}}{f_0}\right)^2\right)\right) \tag{8}$$

where f_0 is the optical carrier frequency and f_{RF} is the modulation frequency.

Fig. 4 describes how the signal behavior changes during the transmission via optical fiber from laser diode to photodetector.

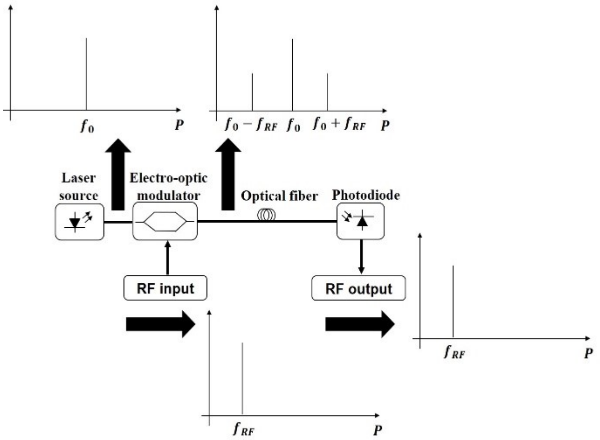

Figure 4. Electrical and optical signal behavior during the transmission via AFOL.

When 1550 nm wavelength is used for optical signal transfer from laser diode to photodetector, the chromatic dispersion is very dominant and has an approximate value of 17 ps/nm/km. Eqn. (8) describes the dispersion penalty [2], [15]. Recently, the 1550 nm wavelength window has become quite popular for optical application because of its low optical loss characteristics to other regions. In addition, below 20 GHz, chromatic dispersion poses a minimal problem to the transmission of optical signal. Coherent beating can help to generate μ-W and mm-W signal optically. In Fig. 5, we demonstrate how the chromatic dispersion affects the signal transfer on the first, third and fifth harmonics. The even harmonics cannot be obtained in the MZM if it is biased on quadrature point (linear region). Also shown in Fig. 5 is the dispersion effect with a 10 GHz modulating signal.

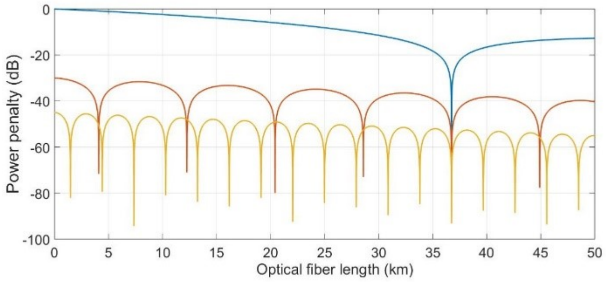

Figure 5. Power penalty of the 1st harmonics (blue) and 3rd (red) and 5th harmonics (orange).

Fig. 5 shows how the chromatic dispersion affects the main mode and harmonics. We have already generated µ-W and mm-W signal in this example. If we compare the µ-W with mm-W signals, it is clearly seen that the chromatic dispesion is less dominant in the µ-W range (especially below 10 GHz). This challenge is very crucial for signal distribution from central station to base stations in the 5G mobile and wireless networks [16]. The reason is that the mm-W signals are preferred to use for next generation mobile systems. In the next example, the optical fiber length is changed from 0 to 10 km and two frequencies are selected; 3-GHz and 39-GHz. The results are shown in Fig. 6.

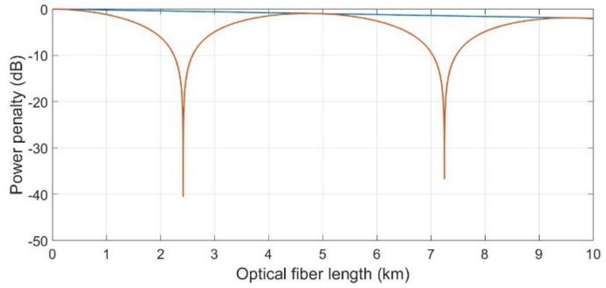

Figure 6. Power penalty of the 3-GHz (blue) and 39 GHz (red).

As can be seen from the graph, there is no power penalty in 3 GHz, and there are two deep points in 39 GHz due to the power penalty. That simulation supports the theory on the power penalty due to the chromatic dispersion.

4 Conclusion

In this paper, we have explained the basics of AFOL. We described the operational regions of MZM and presented simulation studies, highlighting the quadrature bias region as the most useful area for mm-W signal applications. In addition, we have shown the equations for photocurrent after quadratic photodetection and described the electrical power penalty. Finally, we have performed simulations to demonstrate how the µ-W signal and its harmonics in mm-W range are affected by chromatic dispersion and how power penalty affects µ-W and mm-W signals.

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