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Design and Simulation of an Efficient Linearization Technique for mm-wave Radio Over Fiber Link

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ABSTRACT

Dynamic increase in the growth of wireless communication for various applications demands transmission of millimeter and microwave signals for long distance with low loss. Direct and external modulators are used in ROF systems. External modulators are preferred in high performance systems because of many advantages. Mach-Zehnder Modulator (MZM) is a versatile external modulator which gains attraction for ROF systems. Modulator has a very high non-linear transfer function which results in generation of many harmonic components and intermodulation distortion components. Out of these third order Inter Modulation Products (IMD3) dominates the distortion factor and results in degradation in the dynamic range of the system. Proposed architecture has highly linear ROF system with very low IMD3 components using a Dual Parallel Single Drive MZM Modulator (DP-SDMZM). Proposed DP-SDMZM modulator approach has gained SFDR of further 34 dB when compared to conventional MZM modulator.

Key words: DP-SDMZM, SFDR, IMD3, non-linear transfer function, dynamic range, EVM.

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INTRODUCTION

Radio over optics provides larger bandwidth and low loss transmission path link. Reduced sensitive to noise and electro-magnetic interference when compared to electro-magnetic signal transmission. ROF uses highly linear system to transmit the RF signal over the fiber from the central station to the remote (base station) antenna units. MZM is one of the external modulator that gain attractions for ROF systems. MZM modulator works on the basis of changes in refractive index of the material. Some of the materials like Lithium Niobate shows large changes in Pockels effect in the presence of electric field, this changes results in changes in refractive index. This changes in refractive index is used for amplitude, phase and frequency modulation. MZM modulator exhibits the IMD3 non-linearity feature and this components has several impact on the system performance [1, p.1]. IMD3 products gets generated when the multiple signals are being transmitted in the modulators, results in generation of several components called as Four wave mixing (FWM). FWM results in the generation of multiple frequency components [6, p.5],

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$$F_{fwm} = F_1 \pm F_2 \pm F_3 .... (1)$$

Where, F_1, F_2 and F_3 are RF frequency components.

The IMD3 products of two tone signal is represented by [5, p.2],

$$2\omega_1 + \omega_2, 2\omega_2 + \omega_1, 2\omega_1 - \omega_2,\ 2\omega_2 - \omega_1 \ (5)$$

Where ω_1 and ω_2 are composite signal fundamental frequencies.

The usable dynamic range of any transmitter can be characterized by very small signal level by noise floor and at large signal level by interference between the signal frequencies. The main non-linearity in the optical modulator is Inter Modulation distortion and mainly these products are being generated when multi-tone signals are being modulated.

Linearization Scheme

Electrical linearization is one of the best approach to be followed to enhance the system performance. Many linearization schemes are available but most of them consists of some combination of MZM modulators. Linearization can be achieved by varying the MZM modulator structure. By considering the SFDR requirements, Dual Parallel linearization scheme is implemented.

Dual Parallel Linearization scheme

Dual parallel single drive MZM modulator is established to increase the system linearity. Proposed DPSDMZM modulator consists of two single drive MZM modulator that are biased at different voltages and fed with combined RF input signals. Output of these parallel MZM to applied to third MZM modulator. Simulation of DPSDMZM modulator scheme is provided in the following sections.

DPSDMZM modulator Simulation using Opti-system

Simulation of dual parallel SDMZM modulator response is carried out using Opti-system software (Version 7.0). Structure of DPSDMZM modulator is shown in the Figure 1.

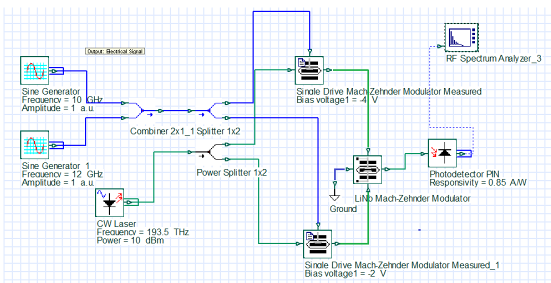

Figure 1 : DPSDMZM using Opti-system for linearization

Two frequency components 10 GHz and 12 GHz that are generated using signal generator are combined using power combiner. Combiner output is applied to both the MZM modulator (Parallel MZM modulator) using power splitter. Signals applied to both the modulators are with same amplitude and satisfying the same phase relationship. Phase difference between each arm is controlled by dc bias. Each path optical modulator outputs are applied to third MZM modulator. Final MZM modulator is passed through photo detector and Photo detector provides the two tone output signal. Two tone signals are measured using spectrum analyzer.

The output signal equation [2, p.4286] is written as,

$$V_{11}(t) = V_m\left[Cos\left(\omega_1 t + \frac{\pi}{2}\right) + Cos\left(\omega_2 t + \frac{\pi}{2}\right)\right] + \frac{V_\pi}{4} \quad (3)$$

$$V_{12}(t) = V_m[Cos(\omega_1 t) + Cos(\omega_2 t)] - \frac{V_\pi}{4} \quad (4)$$

$$V_{21}(t) = V_m\left[Cos\left(\omega_1 t - \frac{\pi}{2}\right) + Cos\left(\omega_2 t + \frac{\pi}{2}\right)\right] + \frac{V_\pi}{4} \quad (5)$$

$$V_{22}(t) = V_m[Cos(\omega_1 t) + Cos(\omega_2 t)] - \frac{V_\pi}{4} \quad (6)$$

The output field of first and second MZM modulator [3, p.47] is represented as,

$$E_{out1}(t) = E_{in}(t)\left[\exp\left(j\pi\frac{V_{11}(t)}{V_\pi}\right) + \exp\left(j\pi\frac{V_{12}(t)}{V_\pi}\right)\right] \quad (7)$$

$$E_{out1}(t) = E_{in}(t)\sum_{k=-\infty}^{\infty}\sum_{l=-\infty}^{\infty} J_k(m)J_l(m) * e^{j(k\omega_1 t + l\omega_1 t)}\left[(-1)^{k+l}e^{j\frac{\pi}{4}} + (j)^{k+l}e^{-j\frac{\pi}{4}}\right]E_{out1}(t)$$

$$= E_{in}(t)\sum_{k=-\infty}^{\infty}\sum_{l=-\infty}^{\infty} J_k(m)J_l(m) * e^{j(k\omega_1 t + l\omega_1 t)}\left[(-1)^{k+l}e^{j\frac{\pi}{4}} + (j)^{k+l}e^{-j\frac{\pi}{4}}\right] \quad (8)$$

$$E_{out2}(t) = E_{in}(t)\sum_{k=-\infty}^{\infty}\sum_{l=-\infty}^{\infty} J_k(m)J_l(m) * (-1)^l e^{j(k\omega_1 t + l\omega_1 t)}\left[e^{j\frac{\pi}{4}} + (j)^{k+l}e^{-j\frac{\pi}{4}}\right] \quad (9)$$

Final output of DPSDMZM can be represented as,

$$E_{out} = (E_{out1} + E_{out2}) + sqrt(2) \quad (10)$$

The output photocurrent after the photodiode can be represented,

$$I_{pd} = Real(\dot{E}_{out}) * 2 \quad (11)$$

By using the Taylor series the photocurrent [4, p.2] can be represented as,

$$I_{pd}(t) = \frac{1}{2}RP_i * \Big[(8 + 8m(\cos(\omega_1 t) + (\mathrm{Sin}(\omega_1 t)) + 2m^2(-2 + \cos(2\omega_1 t) - \cos(2\omega_2 t) - \frac{2}{3}m^3(9\cos(\omega_1 t) - \cos(3\omega_1 t) + p\cos(2\omega_2 t) + \mathrm{Sin}(3\omega_2 t))\Big] \quad (16)$$

$$I_{pd}(t) = \frac{1}{2}RP_i * \Big[(8 + 8m(\cos(\omega_1 t) + (\mathrm{Sin}(\omega_1 t)) + 2m^2(-2 + \cos(2\omega_1 t) - \cos(2\omega_2 t) - \frac{2}{3}m^3(9\cos(\omega_1 t) - \cos(3\omega_1 t) + p\cos(2\omega_2 t) + \mathrm{Sin}(3\omega_2 t))\Big]$$

From the photocurrent equation, the IMD3 components are completely eliminated. By further expanding the Taylor series, nth order components are also eliminated. But, second order harmonics is still exists and these components are removed by using band pass filters as this lies far away from the intended frequency. Third modulator output is observed through the spectrum analyzer shown in the Figure 2.

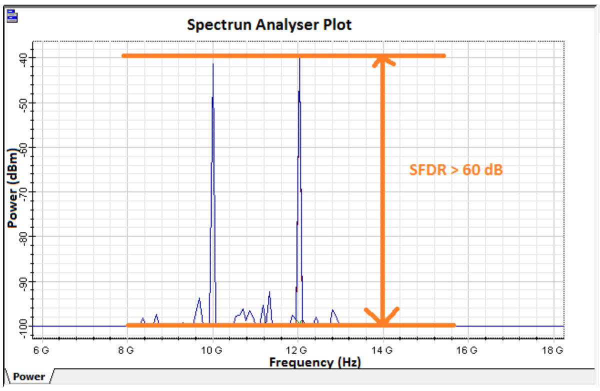

Figure 2 : Linearized RF output signal at the modulator output

An optical carrier of 193.1 THz is sent to a dual parallel MZM modulator. The bias points of two MZM arms are adjusted in such a way that they perform single side band modulation. To achieve the expected performance (IMD3 removal), both the RF signals applied with the modulator are with same amplitude, imbalance bias voltage for both the sub-MZM's and phase deviation against the specified phase values using dc bias to each arm. MZM modulator structure is designed using Lumerical tool (Interconnect version 8.5.1809, Device Version 7.3.1809 and FDTD Version 8.21.1809) and DPSDMZM modulator simulation is also performed using Lumerical tool (Shown in the Figure 3) to validate the performance of the proposed system.

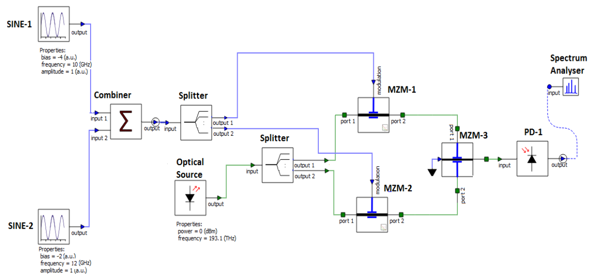

Figure 3 : DPSDMZM modulator simulation using Lumerical interconnect tool

Dual parallel single drive MZM modulator is considered for the simulation and the compensated RF output power is measured using the spectrum analyzer at the output of photo detector. Measured spectrum analyzer plot is shown the Figure 4.

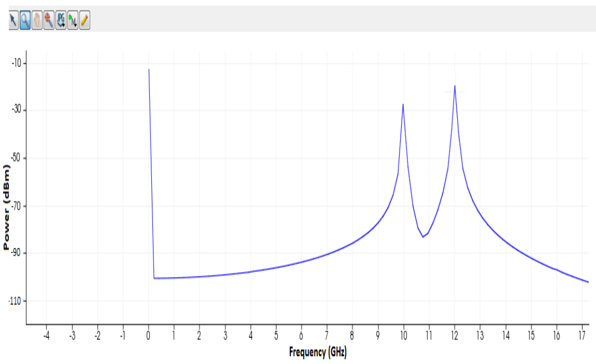

Figure 4 : MZM modulator output after IMD3 compensation

From the measured spectrum, the IMD3 components are removed from the RF signal path, and is buried under the noise floor of the system. IMD3 suppression is done by a factor of 34 dB compare to conventional modulator [4, p.3].

Results and Discussion

Proposed DPSDMZM modulator structure is shown in the Figure 5.

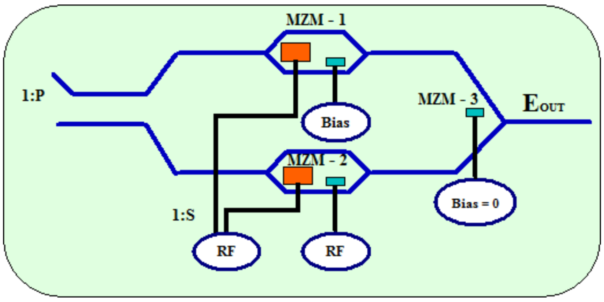

Figure 5: DPSDMZM modulator structure

The parameters "P" and "S" are Optical and RF power splits, respectively and E_{out} is the output signal. Optical and RF signals are passed through power splitters with different splitting ratio. Optical and RF splitter outputs are applied to MZM modulator. Multi (Seven) tone signals are fed to the proposed DPSDMZM modulator and the RF spectrum output of the multi tone signal is shown in the Figure 6 (a) and (b).

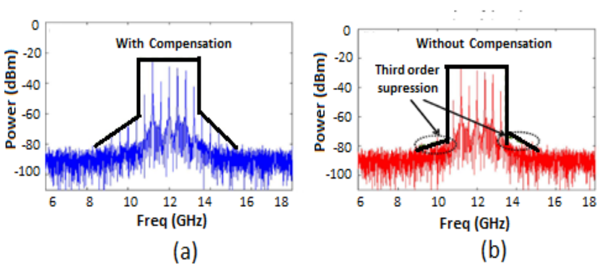

Figure 6 : Multi tone signals with and without non-linearity compensation

Multi-tone signal is applied to conventional MZM modulator, intermodulation components are generated due to the non-linearity behavior of MZM modulator. Modulator output with several intermodulation products is shown in the Figure 6 (a). Same multi-tone signal is applied to the proposed DPSDMZM modulator and the intermodulation products are suppressed. Figure 6 (b) shows the suppression in intermodulation components. SFDR and Error Vector Magnitude (EVM) comparison of conventional and proposed MZM modulator is shown on the Table 1. IMD3 suppression is done by a factor of 34 dB compare to conventional modulator and EVM is reduced by a factor of 1.76%.

Table 1: Performance parameter comparison of conventional and DPSDMZM modulator

SL No.	Performance parameter	Conventional MZM	DPSDMZM
1.	SFDR	24 dB	> 60 dB
2.	EVM	3.70%	1.94 %

Conclusion and Future Directions

The MZM modulator characteristics has been studied and impact of non-linearity on the ROF link has been identified. Improper electrode biasing may lead to the IMD3 products generation and the signals at the receiver at far distance may not be recovered as expected. The simulation analysis shows that by using dual parallel MZM modulator with quadrature biasing points it is possible to remove the IMD3 products and increases the system SFDR by further 34 dB when compare to conventional method. Designed MZM modulator structure using Lumericals tool is capable of producing the output by removing the IMD3 products. Compensated modulator performance can be evaluated for higher frequency by considering the 5G requirement.

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