Nonlinearities and their Distortion Effects in COherent-OFDM Systems

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Abstract: Nonlinear Mach-Zehnder Modulator and single mode fiber distort the transmitted signal. Their distortions were examined with VPIphotonics and the results of the two cases were compared with each other. It is important to know which element has higher effect to signal. Orthogonal Frequency Division Multiplexing modulation was used because next generation optical network will use this modulation form.

1 INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is extensively used in electrical domain. Wi-Fi routers, terrestrial TV broadcast (in Europe) and so many other applications use OFDM modulation because the distortion of the channel (i.e. fading) can be easily compensated by DSP (Digital Signal Processing). The drawbacks of OFDM are the sensitivity for nonlinearity in the signal transmission and the high PAPR (Peak to Average Power Ratio).

The optical systems require a higher-order modulation format with high capacity because of the amount of transmitted data is growing rapidly. OFDM modulation can solve the problem as it did in the electrical domain. However, the structure of the optical systems, which use OFDM modulation, are more complex, because the phase cannot be detected directly with a photodiode.

In this paper we give a short overview of the OFDM method in section 2. The coherent optical OFDM (CO-OFDM) transmission system is presented in section 3, which is simulated by the VPI TransmissionMaker (VPI). Our study focuses on the distortion of the nonlinear Mach-Zehnder Modulator (MZM) and the signal degradation which is caused by nonlinearities of Single Mode Fiber (SMF). We investigate whether their distortion effect is the same and which has stronger influence on the transmitted signal.

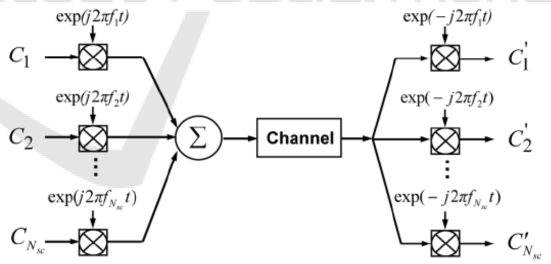

Figure 1: Theoretical implementation of OFDM modulation. (Shieh, 2011).

2 PRINCIPLE OF OFDM

OFDM is a special class of multi carrier modulation. Figure 1 shows its theoretical implementation. This structure contains a lot of oscillators and filters on both transmitter and receiver sides. The transmitted signal is represented as (Shieh, 2011):

$$\begin{aligned} s(t) &= \sum_{i=-\infty}^{\infty}\sum_{k=1}^{N_{sc}} c_{ki} s_k\left(t - iT_s\right) \\ s_k(t) &= \exp(j2\pi f_k t) \quad if \quad 0 \le t \le T_s \end{aligned} \tag{1}$$

N_{sc} is the number of the subcarriers, c_{ki} is the i^{th} information symbol at the k^{th} subcarrier, s_k is the waveform of the k^{th} subcarrier, T_s is the symbol period, f_k is the frequency of the subcarrier. The optimum detector can be a matched filter or a correlator. The detected information of a subcarrier is given by (Shieh, 2011):

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$$c'_{ki} = \int_0^{T_s} r(t - iT_s) \cdot s_k^* dt = \int_0^{T_s} r(t - iT_s) \cdot \exp(-j2\pi f_k t) dt \qquad (2)$$

The subcarriers are orthogonal to each other. Its result is that the spectrum of the OFDM signal is smaller than a traditional multicarrier multiplexed signal because the channels can be overlapped. The channels are orthogonal to each other if:

$$f_k - f_l = m\frac{1}{T_s}; \quad m \in 1,2,3,... \qquad (3)$$

OFDM modulation/demodulation can be done by Inverse Discrete Fourier Transform (IDFT)/ Discrete Fourier Transform (DFT), which costs less than using huge number of filters and oscillators (Figure 1). A typical OFDM transmitter can be seen in Figure 2. Data stream is split up N_{sc} part by a serial-to-parallel converter, and the next block creates the transmitted symbols of the subcarrier from the bit sequence. OFDM modulation is made by the IDFT block. If the subcarriers are not orthogonal to each other (i.e. there is synchronization failure), ISI (Inter Symbol Interference) and ICI (Inter Carrier Interference) will appear in the demodulated signal. This can be avoided if Guard Interval (GI) is applied. It is also called as Cyclic Prefix (CP). A small time period from the end of symbol is copied down. This is the CP and it is placed at the beginning of the symbol. Until the time difference between the subcarriers is smaller than the GI there will not be ISI and ICI in the demodulated signal. After GI is added to the signal, its digital samples are converted into an analogue signal. The optical carrier is modulated by it. The structure of an OFDM demodulator is similar to Figure 2 but the signal flow is reversed so there is a DFT block instead of the IDFT and it is extended with a clock restore or synchronization block.

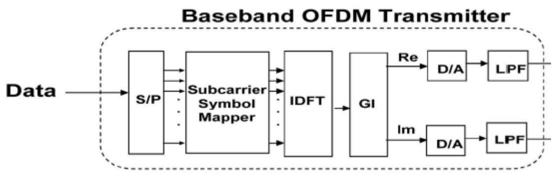

Figure 2: Baseband OFDM transmitter. OFDM modulation is created by IDFT. (Shieh, 2011).

Transmitters and receivers need to have huge dynamic range if the PAPR is high. It is not possible to create a device which has large and linear dynamic range. Therefore the value of PAPR must be decreased by coding technique or clipping. The clipping method is usually used, which cuts off the level of the signal above a given value. However, this increases the noise level outside of the signal spectrum.

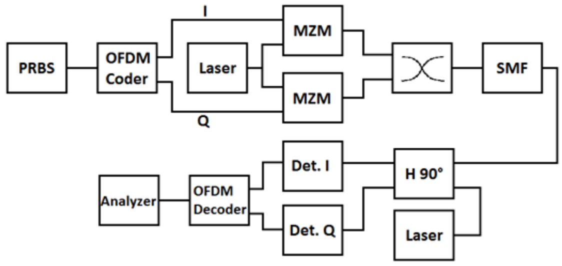

Figure 3: Block scheme of the simulated CO-OFDM system in VPI.

3 SIMULATION

Simulations were made in VPIphotonics (VPI). Block diagram of our transmission is shown in Figure 3. Pseudo random bit sequence with 80Gbps data rate was used in the simulations. OFDM coder used 16-QAM modulation and created separately the real (I) and imaginary (Q) parts of the OFDM signal. There is no 90° phase shift between I and Q. The laser signal is modulated separately by I and Q signals. Mach-Zehnder Modulators (MZM) are applied which have sinusoidal transfer characteristic. They are biased at the quadrature point, where the transfer characteristic is linear. I and Q arms are summarized by an optical coupler. Its behaviour is similar to an electrical one. The input signal intensity from both input ports is halved at the output and it creates 90° phase shift between the input ports signals. It means that the necessary 90° phase shift is done by the coupler. So the optical I-Q modulator is built up by two MZMs and an optical coupler. After the coupler a standard Single Mode Fiber (SMF) is placed, when its distortion is examined. In the other cases it is left out from the network. Signal detection is based on the heterodyne detection method. There is a small frequency difference (Δf) between the laser on the transmitter side and the laser on the receiver side. It causes that the detected signal (at the output of photo diodes) is converted down at Δf frequency. This signal is demodulated by the OFDM decoder. The analyzer shows the constellation diagram of the detected signal. In this article we focus on the nonlinearity of MZM and SMF. The linewidth of the applied lasers were 10 kHz. It means that the simulation contains the effect of the phase noise.

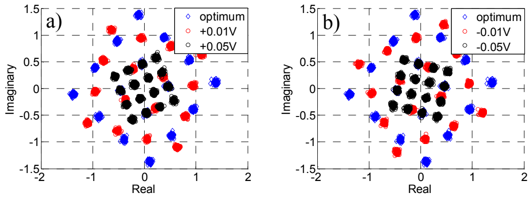

Figure 4: (a) Constellation turns right, if the bias error is positive and it turns left (b) when the bias changes negatively.

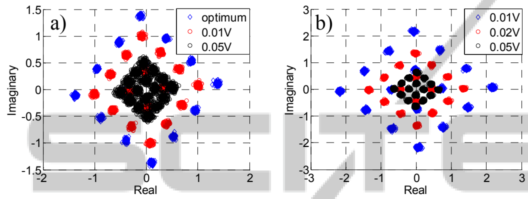

Figure 5: Asymmetrically biased MZMs. (a) Both MZMs are biased at the same arm. (b) MZMs are biased at different arms and the phase change has opposite sign.

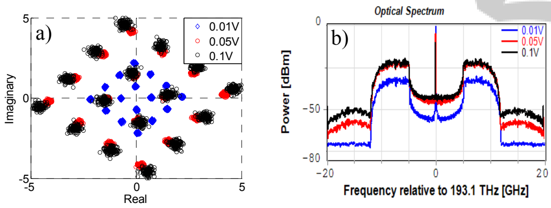

Figure 6: (a) Larger drive amplitude increases the distance between symbols but (b) outside of the OFDM spectrum the noise level also increases.

3.1 Distortion of Mach-Zehnder Modulator

Two arms of the MZMs can be driven independently from each other in VPI. The relation between arms can be positive or negative. If it is positive then the sign of phase change is the same in both arms. In the other case the sign of the phase change is opposite. Figure 4 shows those cases when MZMs upper arm are driven. MZMs are biased with 0.5V, which causes 90° phase shift (optimum point) in the controlled arm. Both MZM bias points are similarly changed. If the phase delay is less than 90°, the constellation is turned clockwise (Figure 4b). It is rotated the opposite way (Figure 4a), when the phase shift is more than 90°. This rotation can be compensated by DSP after detection. Another way to eliminate this rotation is the differential driving of MZMs. In this case only the distance between constellation points will decrease when the bias changes (Figure 5a). However, the standard deviation of constellation points is growing linearly (Table 1).

There is another MZM driving method when one MZM is driven in the upper arm and the other is driven in the lower arm with negative sign of phase changes. It does not cause any difference in the output light intensity but the electrical field is different. Between the electrical fields there is a 90° phase difference. The optical coupler which summarizes the I and Q signals (Figure 3) also makes 90° phase shift between them. Its result is that if MZMs are biased at the optimum point, there will be no carrier in the transmitted spectrum. In this case we need an outside clock signal to demodulate the received signal which highly complicates the receiver. It can be avoided, if MZMs are not driven in the optimum point. Slightly shifted from the optimum the carrier will appear in the spectrum but the symbols will be closer to each other as Figure 4 shows it. Figure 5b shows the received constellation when MZMs are driven asymmetrically (same bias point but the sign of the bias change is the opposite). This driving method minimizes the rotation of the constellation. The standard deviation of symbols does not increase outside from the optimum point of operation.

Larger drive amplitude increases the distance between the symbols of the constellation (Figure 6a) but it does not grow linearly. It has saturation because of the MZM sinusoidal characteristic. Large drive amplitude causes bigger standard deviation of the symbols, too. 0.05V and 0.1V drive amplitude are near to the saturation point because the distance between the symbols changed minimally but the standard deviation of the symbols is twice as big. Between the two constellations there is a 3.8° angle. The noise level also increases outside of the signal spectrum (Figure 6b). It comes from the clipping and nonlinearities. This growing noise is harmful in WDM systems, because the channels have to be placed far from each other.

3.2 Fiber Nonlinearity

Signal shape mainly degrades by the fiber dispersion. Chromatic dispersion (CD) is the significant effect in SMF. It rotates the constellation and spreads the symbols (Figure 7a). Constellation of the received signal will be a circle because of the dispersion (Figure 7b). CD has much stronger effect on the transmitted signal than the MZM. 6km fiber rotates the constellation with angle of 8°. It is twice larger than the rotation caused by differential driving of the MZM.

Table 1: Rotation of the constellation.

MZM's driving method	Bias [V]	Angle [deg]	Deviation
at the same	optimum	0	0.024
	+0.01	25	0.024
	+0.05	-26	0.024
	-0.01	-25	0.023
	-0.05	26	0.024
differential	0.01	0.2	0.028
	0.05	1	0.048
differential, phase change in the MZM's arm is opposite	0.01	0	0.037
	0.02	0.9	0.029
	0.05	3.6	0.025

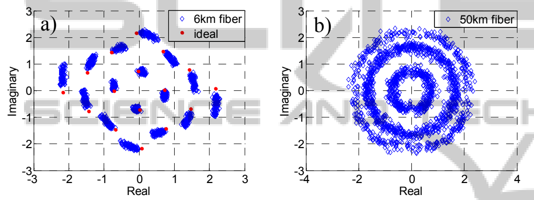

Figure 7: (a) Dispersion spreads the symbols and rotates the constellation. (b) Constellation diagram after 50km fiber, if dispersion is not compensated.

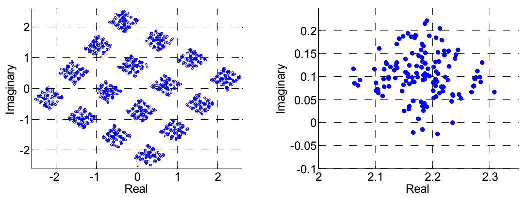

Figure 8: (a) Symbol deviation caused by SPM and FWM. (b). Only FWM caused symbol spread at one symbol.

Dispersion can be compensated by DSP or Dispersion Compensation Fiber (DCF). Doing it by DSP is much comfortable because it can be done electronically beside doing other signal processing steps. Using of pilot tones this rotation can be calculated and the correction also can be done. Four wave mixing (FWM) and self-phase modulation (SPM) make smaller signal degradation than CD. Their effect can be seen if the fiber dispersion is set to zero. Laser power was 20W and fiber length was 50km. Increasing the laser power will not improve the quality of transmission. Noise level increases outside of the OFDM spectrum because of FWM. Constellation symbols highly spread and it seems they contain the full constellation diagram in small size (Figure 8a). This kind of modulation mainly comes from the SPM and in smaller extent from the FWM. Decreasing the laser power the SPM effect will be negligible and FWM will be dominant. FWM causes ICI and it spreads the symbols along both axes (Figure 8b). It is similar to the effect of white noise. Standard deviation is 0.0472 which is twice as much as that one caused by the MZM.

4 CONCLUSIONS

MZM and SMF have quite the same distortion effects. Both rotate the constellation but the CD influence on the degradation is much stronger and it highly spreads the symbols. These rotations can be compensated by the same algorithm because of the similarity. The rotation caused by MZM can be easily eliminated by differential driving. It minimizes the rotation but the standard deviation of symbols is increased slightly. If the electrical field of MZM provides opposite rotation this effect does not exist and the rotation stays small. Dispersion compensation always needs additional equipment. It can be done electronically using a DSP after demodulation. Other nonlinearities of SMF (i.e. four wave mixing, polarization mode dispersion) cause smaller distortion and they are covered by the distortion effect of MZM nonlinearity and CD. We usually use low laser power so only FWM will influence the transmission. Its effect has to be compensated by a DSP.

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