Abstract We show that PMD degrades the transmission performance of an optical OFDM system which is based on direct-detection and single side-band transmission. Maximum PMD tolerance can be achieved applying polarization diversity together with polarization control.

Introduction
Optical transmission systems deploying orthogonal frequency division multiplexing (OFDM) have gained interest recently. Two principle architectures have been proposed in order to preserve linearity of distortions in the optical domain beyond opto-electrical conversion: A setup using coherent detection was shown to be robust against chromatic dispersion. Transmission over 3000 km SSMF is possible with less than 2 dB OSNR penalty at a bit error ratio of $10^{-3}$ [1]. Extending this approach to a polarization diversity receiver yields a PMD tolerant transmission system [2].

An alternative setup which is less demanding from optical component point of view is based on single side-band (SSB) transmission and direct detection (DD) [3], which also shows chromatic dispersion tolerance. This contribution examines the influence of PMD on the transmission performance of this architecture. It turns out that PMD causes fading which leads to performance degradation. We propose a PMD tolerant extension which uses a polarization diversity receiver.

Investigated Setup
The basic building blocks of the investigated setup are depicted in Figure 1 [3]. A certain number of sub-carriers are modulated using a 4-QAM-constellation occupying the upper half of the upper side-band. Lower sub-carriers are not modulated; the spectral part of negative frequencies is fed by corresponding complex-conjugates. Hence, after inverse discrete Fourier transform, cyclic extension, and digital to analogue conversion we obtain an up-converted, real valued signal $s(t)$. Alternatively, the signal can be generated by up-converted the original complex valued base-band signal in the electrical domain through RF mixing. The resulting signal is modulated onto an optical carrier by a Mach-Zehnder modulator; then the lower side-band of the optical signal is suppressed (see insets of Figure 1). The SSB signal propagates over the optical link and is received through direct detection. Even after squaring there are no beat-products within the used spectrum. In contrast to the architecture based on coherent detection laser phase noise is not an issue. The received signal $r(t)$ is sampled; after cyclic prefix removal and DFT one retrieves distorted symbols $Y_{k,l}$. Zero-forcing equalization uses estimates of the respective channel coefficients (which are supposed to be perfectly known to the receiver in our simulations)

$$\hat{X}_{k,j} = \frac{Y_{k,j}}{H_{k,j}}.$$  \hspace{1cm} (1)

Simulations
For our simulations we set the total bit rate to 10 Gb/s; 128 sub-carriers shall be used. Thus the OFDM symbol duration yields 25.6 ns. The cyclic prefix length was set to 2.8 ns. As we want to concentrate on polarization effects, all simulations were carried out without incorporating chromatic dispersion. Furthermore the modulator, as well as the fibre were assumed to be perfectly linear; quantization noise is neglected. Figure 2 shows bit error ratio (BER) versus optical signal to noise ratio (noise bandwidth: 12.5 GHz) when the differential group delay (DGD) is increased up to 40 ps for worst case coupling. We observe an OSNR penalty of approximately 3 dB for DGD $= 30$ ps at a BER equalling $10^{-3}$. The BER performance severely deteriorates for higher values of DGD. The
reason for the degradation is DGD causing fading ("spectral hole burning") which reduces the SNR of several sub-carriers.

![Figure 2: BER performance for different values of differential group delay.](image)

**Polarization Diversity Receiver**

For the purpose of introducing DGD tolerance the OFDM setup can be extended by use of a polarization diversity receiver (see Figure 3) at the expense of a polarization beam splitter and a second receive path. Such kind of receiver provides two signals \( r_x(t) \) and \( r_y(t) \) which both have to be sampled and transformed to the frequency domain resulting in two versions of received symbols \( Y_{k,l,x} \) and \( Y_{k,l,y} \). The estimated TX symbol is obtained by diversity combining.

![Figure 3: Architecture of polarization diversity direct detection.](image)

For both receive branches channel estimation has to be performed. We observe that for all sub-carriers the received power is split between the orthogonal states of polarization. Assuming independent noise of same variance in both receive branches along with perfect knowledge of the channel coefficients, it can be shown that diversity combining according to

\[
\hat{X}_{k,l,x} = Y_{k,l,x} \cdot \hat{H}_{k,l,x}^* + Y_{k,l,y} \cdot \hat{H}_{k,l,y}^* \tag{2}
\]

leads to AWGN-channel performance. Ideally the system is now able to compensate for DGD up to the length of the cyclic prefix without penalty [2]. Figure 4 depicts the BER performance for DGD values up to 500 ps. We observe just marginal penalty compared to the back-to-back case.

However, with respect to the CO-OFDM setup [2] there is an additional constraint regarding the state of polarization of the incoming optical signal at the carrier frequency. One has to ensure that the PBS splits the signal in such a way that the power of the carrier is equally distributed to both branches. Otherwise the “self-coherent” down-conversion generates sub-optimum SNR in one branch. The worst case would be total loss of the carrier in one branch, as then the corresponding sub-carriers are not down-converted to the desired frequency band. Consequently, polarization control before the PBS is required.

![Figure 4: BER performance of the SSB polarization diversity system.](image)

**Conclusions**

This paper investigates the DGD robustness of an optical OFDM system which is based on SSB transmission and direct detection. Simulations verify that DGD causes fading which severely impairs the BER performance. DGD tolerance can be achieved by extending the system by a polarization diversity receiver. In this case the system is able to compensate for DGD up to the length of the cyclic extension. However, this gain comes at the expense of a PBS, a second receive branch, and a polarization control circuit.

On the other hand diversity combining is done on sub-carrier basis which simplifies signal processing requirements compared to an equivalent single-carrier transmission system.

**References**