# High-speed Fading-free Direct Detection for Double-Sideband OFDM Signal via Block-wise Phase Switching

**X. Chen, A. Li, D. Che, Q. Hu, Y. Wang, J. He and W. Shieh**

*Dept. of Electrical and Electronic Engineering, the University of Melbourne, Parkville, Vic 3010, Australia*

*e-mail: xc@unimelb.edu.au*

**Abstract:** We employ phase switching of either main-carrier or subcarriers of two consecutive signal blocks for double-sideband fading-free direct-detection (DD). In so doing, 40-Gb/s DD-OOFDM is successfully received over 80-km SSMF with single polarization and detector.

**OCIS codes:** (060.2330) Fiber optics communications; (060.4080) Modulation

## 1. Introduction

The Internet traffic continues to grow unabated and the demand for high-speed transport at 40 Gb/s and beyond are across every level of optical network, from core, to metro, to access network. Coherent detection has achieved dramatic success in the past few years due to adoption of powerful electronic digital signal processing [ 1 - 4 ]. However, the optical gears for coherent detection are rather sophisticated, involving polarization multiplexing/de-multiplexing, double IQ modulators and balanced receivers. The high cost of the coherent systems constrains coherent communication for long-haul transport for the time being. At the other extreme of the spectrum is direct modulation (DM) and direction detection (DD) for cost-sensitive short-reach high-speed communication [5,6], such as inter-cabinet communication. However there is a fundamental limitation for DM/DD for 40 Gb/s and beyond communication due to serve dispersion-induced fading occurring when the electrical spectrum is beyond 15 GHz and reaches is beyond 10 km. There exists an interesting window of applications such as interconnect between data centers about 80 km apart that excludes either coherent detection due to high cost, or DM/DD due to serve dispersion-induced fading. This paper is looking at the prospect of using external modulation (EM) and DD for 40 Gb/s and beyond transmission. DD-OOFDM 120-Gb/s transmission has been reported by using offset OFDM but with receiver complexity closed to that of coherent detection [7]. 40-Gb/s and beyond DD would be ideal to be achieved with single polarization and single detector, and preferably without a need for feedback path to perform pre-distortion. This proposition has placed a high premium on the high electrical spectral efficiency (SE) rather than optical SE for these medium reach systems. As the electrical bandwidth is the dictating factor for the transponder cost – high bandwidth means high modulator and receiver bandwidth, and faster signal processing elements. There is pioneering work for high SE DD using virtual single-sideband (VSSB) demonstrated only at 10 Gb/s [8]. In this work, we propose a novel alternative approach called block-wise phase switching (BPS) where for two similar consecutive signal blocks, the phase of the main carrier or subcarriers are switched by 90 or180 degrees, achieving complete separation of double sideband signals. We also propose modification of the conventional optical IQ modulation by including a path for supplying main carrier, enhancing modulation efficiency of IQ modulation. With such a scheme, we have achieved the first single-polarization DD of 40 Gb/s over 80 km SSMF. BPS may offer an effective means to achieve DD-based 100G Ethernet with high electrical SE for medium reaches.

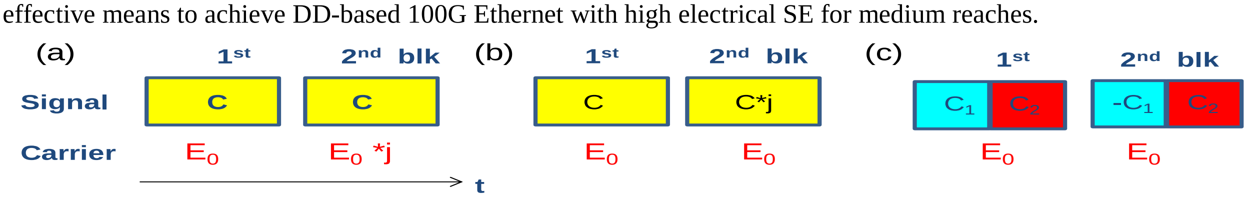


Fig. 1. Conceptual diagram of three schemes of block-wise phase switching (BPS) for fading-free double-side band direct detection: (a) carrier phase switching (CPS) where carrier phase is switched by 90 degree between 1st and 2nd blocks, (b) signal phase switching (SPS) where signal phase is switched by 90 degree, and (c) (signal) set phase reversal (SPR) where the phase of lower sideband is changed by 180 degree while upper sideband is unchanged. C is signal, $E_0$ is main carrier, C1 (C2) is lower (upper) sideband. blk: Block.

## 2. Principle of BPS

The main idea to achieve high electrical SE is to use double sideband modulation. The conventional double side band suffers from dispersion-induced fading at moderate distance of 80 km. The three schemes of BPS are depicted in Fig. 1, including (i) carrier-phase-switching where the main carrier phase is switched 90 degree for two consecutive blocks while the subcarriers remain the same, (ii) signal(subcarrier)-phase-switching where the signal subcarrier phase is switched by 90 degree while the main carrier phase remains the same, and (iii) (signal) set phase reversal (SPR) where the entire subcarriers are partitioned into two sets of $C_1$ and $C_2$. $C_1$ (or $C_2$) has no overlapping with their mirror image (over the main carrier). In the two consecutive blocks, one of the set, for instance, $C_1$ is switched 180 degree. The simplest set partition is $C_1$ for upper sideband and $C_2$ for lower sideband as shown in Fig. 1(c). All the three schemes can be shown to achieve fading-free detection. However, in this work, only the scheme I is reported and the theory is provided next.

In scheme I, the photo currents for the first and second blocks, $I_1$ and $I_2$ are given by

$$I_1 = \left|E_0 + E_s\right|^2 = \left|E_0\right|^2 + 2\,\mathrm{Re}\left\{E_s E_0^*\right\} + \left|E_s\right|^2 \tag{1}$$

$$I_2 = \left|E_0 j + E_s\right|^2 = \left|E_0\right|^2 + 2\,\mathrm{Im}\left\{E_s E_0^*\right\} + \left|E_s\right|^2 \tag{2}$$

where $E_0$ and $E_s$ are respectively the main carrier and the signal. Combining Eqs. (1) and (2), we construct a complex variable as

$$\tilde{I} = I_1 + I_2 j = \left(1+j\right)\left|E_0\right|^2 + 2E_s E_0^* + \left(1+j\right)\left|E_s\right|^2 \tag{3}$$

The first term is DC that can be ignored. The second term is proportional to the fading-free complex signal, and the third terms represent the signal-to-signal beating noise (SSBN). Assuming we start with sufficient high carrier to signal ratio (CSR) so that the second term is dominant over the third term, an iteration detection can be used to remove the nonlinear term [8]. The preliminary symbol decision can be made and the estimated signal is reconstructed and subtracted from (3); the second iteration of the symbol decision can be made based on the new signal after removing nonlinear term. In this report, we find that we only need one iteration. For scheme I, we already have the time-domain signal as shown in (3) and the first iteration cancellation can be made without symbol decision, reducing computation complexity and error propagation.

The principle of scheme II is the same as scheme I. For scheme III, the operation of subtraction and summation between $I_1$ and $I_2$ will recover lower and upper subbands. BPS approach has twice of the electrical SE of offset OFDM [7] requiring half of the spectrum as the guard band. The signal block of BPS could comprise one OFDM symbol for multicarrier, or many symbols for single carrier, or narrow band signals for RF over fiber (RoF).

In medium reach systems, optical spectral efficiency is not as an important factor as long haul systems. Because it is relatively easy to introduce a pair of optical amplifiers at the two sides to light a new fiber. The cost of OAs is shared by 10 or 20 WDM channels per fiber. The channel spacing can be 100 GHz and even 200 GHz such that the cross-channel nonlinearity is not a critical factor.

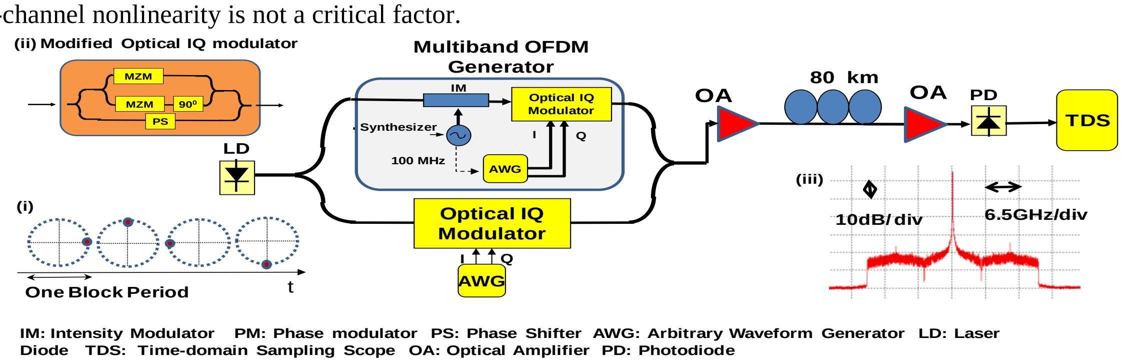


Fig. 2. The experimental set up for DD-OFDM transmission using block-wise phase switching. The insets: (i) main carrier constellation versus time, (ii) modified optical IQ modulator, and (iii) optical spectrum of the combined optical DD-OOFDM signal.

## 3. Experimental setup

Although the signal can be of single-carrier or multicarrier, for this proof-of-concept demonstration of BPS, the signal used is a multiband OFDM consisting 3 orthogonal bands. As shown in Fig.2, an ECL laser is split into two branches, one fed into a multiband OFDM generator, the other to an optical IQ modulator for main carrier phase switching. The OFDM generator consists of an intensity modulator for tone generations, and an optical IQ modulator driven by an arbitrary waveform generator (AWG) at 20 GSa/s. Each OFDM band consists of 1124 subcarriers; the tones spacing of 11.09375 GHz is multiple of subcarrier spacing, satisfying orthogonal band multiplexing (OBM) condition [9] and enabling direct detecting the three bands simultaneously. The main carrier phase is rotated between $0^0$, $90^0$, $180^0$, and $270^0$ (inset (i) of Fig. 2) aligned with OFDM frames by driving the IQ modulator with complex IQ values of (1,i, -1,i) supplied by an AWG on corresponding OFDM frames. The main carrier only needs to switch the phase at frequency of ~10 MHz, and therefore its cost should be insignificant compared to with the signal optical IQ modulator requiring about 15-20 GHz bandwidth. In practice, the main carrier phase switching and OFDM generation can be achieved using a modified optical IQ modulator as shown in the inset (ii) of Fig. 2, where an additional path is provided for the main carrier. The phase switching can be accomplished by a phase shifter (PS). For schemes II and III, the PS is not needed. The separation of the main carrier and signal generation is ideal for DD that provides a strong main carrier and a large linear dynamic range for the signals. The OFDM signal and the main carrier are combined, amplified to 6 dBm before launching into an 80-km fiber. At the receiving end, the signal is re-amplified and filtered with 100-GHz WDM filter, and fed into a photo-detector, the output of which is sampled with a real time oscilloscope at 50 GSa/s. The combined receiver bandwidth of the photodiode and the sampling scope is about 15 GHz. 16 training symbols with only odd subcarriers filled are used for channel estimation to avoid SSBN [8]. The training symbols in practice will be only used at acquisition stage and the subsequent channel estimation can be recovered via the data, and therefore should not be considered in overhead computation for the proof-of-concept demonstration. The OFDM signal processing involves (1) FFT window synchronization using Schmidl format to identify the start of the OFDM symbol, (2) channel estimation in terms of Jones Matrix H, (3) phase estimation for each OFDM symbol, and (5) constellation construction for each carrier and BER computation. About 4 millions bits are collected for BER computation.

## 4. Experimental results and discussion

The spectra of the photocurrents $I_1$ and $I_2$ , and $I_1 + I_2 j$ (with 10 dB offset) after 80-km transmission are shown in Fig. 3 to illustrate the effectiveness of BPS. It can be seen for either $I_1$ or $I_2$, severe fading took places at some frequencies, making conventional SSB signal extremely sensitive to dispersion. However, after combining $I_1$ and $I_2$, the complex current $\tilde{I}$ shows fading free spectrum, signifying that the BPS format is immune to dispersion fading. Fig. 4 shows the BER performance versus OSNR after 80-km transmission for 4-QAM and 8-QAM. It can be seen that both of the modulation formats can achieve error-free performance with 20% FEC threshold for a raw data rate of 32.9 Gb/s for 4-QAM and 49.4 Gb/s 8-QAM. We also test the effectiveness of the iteration cancellation at 80-km for 1-band and 3-band OFDM signal. We find that the method is effective for narrow 1 band of 10.97 GHz that improves the Q by 3 dB, but is moderate successful for 33 GHz bandwidth. We deduce that for such large bandwidth, the phase response of the photodetector can no longer be ignored as in this work. Although the net effective data rate of 40 Gb/s at 8-QAM is modest for the first proof-of-concept experiment, it is mainly due to the limitation of the equipments used such as AWG that has 3 dB bandwidth of 4 GHz and the receiver that has 15 GHz bandwidth. With a better access to high performance DAC and ADC at 20 GHz bandwidth, we anticipate the fast progress of demonstration over 100 Gb/s using BPS method. Nevertheless, to the best of our knowledge, this is the first demonstration of 40-Gb/s signal over 80-km SSMF with single detector and single polarization without optical dispersion compensation.

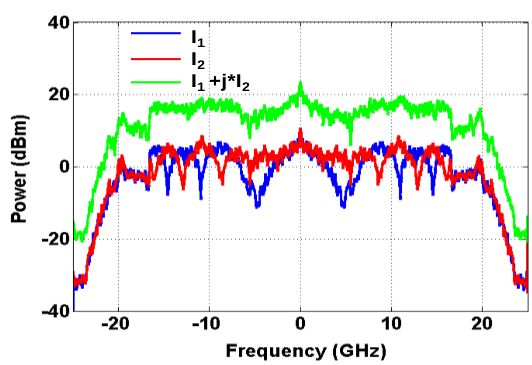


Fig. 3. Detected photocurrents showing fading-free complex current

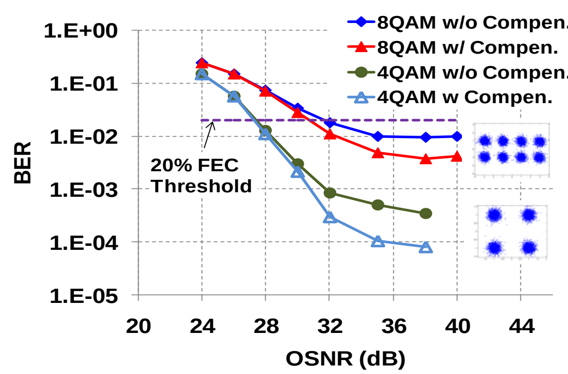


Fig. 4. BER performance at 80-km for 3-band 4- and 8-QAM signals

## 5. Conclusion

We have demonstrated the first 40-Gb/s transmission over 80-km SSMF with single polarization and single detector. BPS may offer an effective means to achieve DD-based 100G Ethernet with high electrical SE for medium reaches.

## References

[1] S. J. Savory, et al., Opt. Express 15, 2120-2126 ,2007.
[2] C. R. S. Fludger, et al., J. Light. Technol. 26, 64 -72 (2008).
[3] W. Shieh, et al., Electron. Lett., 42, 587-589 (2006).
[4] X. Liu, et al., JLT, vol. 27, pp. 3632-3640, 2009.
[5] J. Lee, et al., OFC, Paper PDP6, 2007.
[6] J. L. Wei, et al., ECOC, Paper P6.05, 2012.
[7] B. Schmidt, et al., JLT, vol. 28, pp. 328-335, 2010.
[8] W. Peng, et al., JLT, vol. 27, pp. 5723-5735, 2009.
[9] Q. Yang, et al., JLT, vol. 27, 168-176, 2009.