# 112 Gb/s/λ WDM Direct-Detection Nyquist-SCM Transmission at 3.15 (b/s)/Hz Over 240 km SSMF Enabled by Novel Beating Interference Compensation

**Z. Li, M.S. Erkılınç, K. Shi, E. Sillekens, L. Galdino, B.C. Thomsen, P. Bayvel, and R.I. Killey**
*Optical Networks Group, Department of Electronic & Electrical Engineering, UCL (University College London), London, WC1E 7JE, UK*
*Author e-mail address: zhe.li@ee.ucl.ac.uk*

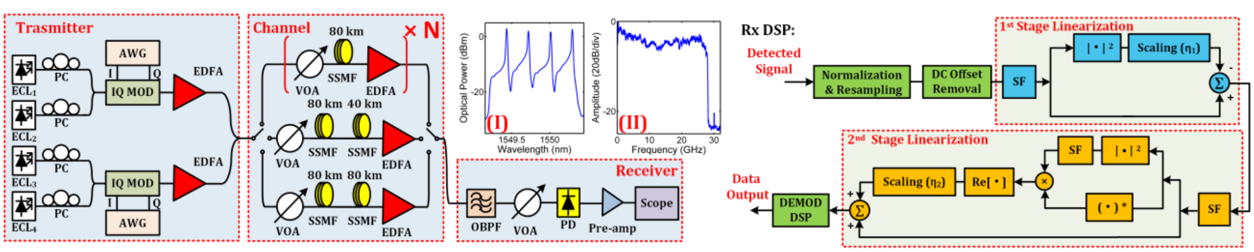
**Abstract:** We experimentally demonstrate 112Gb/s/channel 35GHz-spaced WDM direct-detection SSB Nyquist-SCM transmission over a record distance of 240km SSMF using a novel beating interference compensation method, which offers a 7.6dB required OSNR improvement, and 200% reach enhancement.
**OCIS codes:** (060.0060) Fiber optics and optical communications; (060.2360) Fiber optics links and subsystems

## 1. Introduction

The total data traffic in short- and medium-haul optical links/networks is continuously increasing, mainly driven by data-intensive applications such as high definition video-on-demand and data centers/cloud applications. Recent studies have reported that the metro traffic is growing almost twice as rapidly as the traffic traversing the backbone networks, and that the majority of the traffic is terminated within metro networks. Due to their cost-effective and simple structure, single-polarization direct-detection (DD) wavelength division multiplexing (WDM) transceivers may be a good solution for such applications. In DD applications, single-sideband (SSB) QAM Nyquist subcarrier modulation (Nyquist-SCM) [1-3] can be used to achieve high information spectral density (ISD) and at the same time exhibits lower peak-to-average power ratio (PAPR in the range of 7 dB) than OFDM. It has been demonstrated to enable 100 Gb/s per channel WDM DD transmission up to 80 km [4, 5]. However, it would be challenging to utilize such transceivers in 100 Gb/s per channel WDM metro-ring scenarios (transmission distances up to 300 km) because square-law detection results in signal-signal beating interference (SSBI) which causes a significant increase in the required carrier-to-signal power ratio (CSPR). The distortion due to SSBI and the increase in the required optical carrier power limits the achievable reach in such systems.

In this paper, we present experimental back-to-back and transmission results with a spectrally-efficient 4×112Gb/s WDM dispersion pre-compensated SSB 16-QAM Nyquist-SCM DD system utilizing different beating interference cancellation techniques and found the two-stage linearization filter which we have recently proposed and experimentally demonstrated at 25 Gb/s in [6], provides the maximum compensation gain. The required OSNR at the pre-FEC BER of $3.8\times10^{-3}$ is decreased by 7.6 dB using this compensation scheme. Such reduction in the required OSNR enables to triple the transmission distance, leading to a record 240 km multiple span link, and 160 km repeater-less fiber link transmission.

## 2. Experimental Setup and Beating Interference Cancellation DSP




(a) (b)

Fig. 1: (a) Optical transmission experimental test-bed. Insets: (I) experimental WDM spectrum, (II) detected digital spectrum. ECL: External cavity laser. PC: Polarization controller. AWG: Arbitrary waveform generator. EDFA: Erbium-doped fiber amplifier. VOA: Variable optical attenuator. SSMF: standard single-mode fiber. OBPF: Optical band-pass filter. PD: Photodiode. (b) Receiver DSP with two-stage linearization filter. MOD & DEMOD DSP: Modulation and demodulation DSP for SSB Nyquist-SCM signal. SF: sideband filter.

The experimental setup is shown in Fig. 1(a). Two IQ-modulators seeded by four external cavity lasers (ECLs) were used to generate the odd and even channels. The modulators were driven by two AWGs operating at a 92 GSa/s sampling rate and with 33 GHz 3-dB bandwidth. In the modulation DSP, a SSB 16-QAM Nyquist-SCM signal operating at a symbol rate of 28 GBaud (112 Gb/s) was generated using root-raised cosine (RRC with 0.01 roll-off) filters, frequency up-conversion to a subcarrier frequency of 14.28 GHz (0.51 × symbol rate), and following this, lower frequency sideband removal using a digital sideband filter. Digital pre-distortion was carried out to compensate the accumulated chromatic dispersion during transmission. Finally, the modulated odd and even channels were multiplexed to generate a 4×112 Gb/s WDM signal, and the optimum optical carrier-to-signal power ratio (CSPR) value, which is OSNR-dependent, was used.

Two transmission scenarios were considered: firstly, a straight-line multiple span fiber link, consisting of spans of 80 km standard single-mode fiber followed by erbium-doped fiber amplifiers (EDFAs) with a 5 dB noise figure, and, secondly, repeater-less fiber links, with extended spans of 120 km and 160 km with no mid-span amplification.

At the receiver, a 30 GHz 3-dB bandwidth optical band-pass filter (OBPF) was utilized to demultiplex the channel of interest. A single-ended PIN photodiode followed by a single ADC at 80 GSa/s were used for signal detection and digitization. The receiver DSP (Rx DSP) is depicted in Fig. 1(b). Following the normalization, resampling and DC offset removal, a two-stage linearization filter, recently proposed and tested at 25 Gb/s subcarrier modulation system [6], was utilized to mitigate the beating interference caused by square-law detection. The two-stage linearization filter consists of two stages: The first stage improves the system performance by compensating the signal-signal beat interference (SSBI), whereas the second stage removes the majority of the unwanted beating interference (signal-SSBI beating) introduced by the first stage, and thus, further increases the compensation gain. In contrast to the other proposed beating interference mitigation techniques [7, 8], this technique does not introduce significant unwanted beating interference by the technique itself [7]. Therefore, it can achieve a higher compensation gain, whilst significantly reducing the DSP complexity by avoiding the need to perform symbol decision-based SSBI reconstruction, which requires multiple FFT/IFFT pairs [8]. The system performance using the two-stage linearization filter was compared to the single-stage linearization filter and the symbol-decision based SSBI estimation and cancellation schemes proposed in [7] and [8], respectively.

### 3. Experimental Results

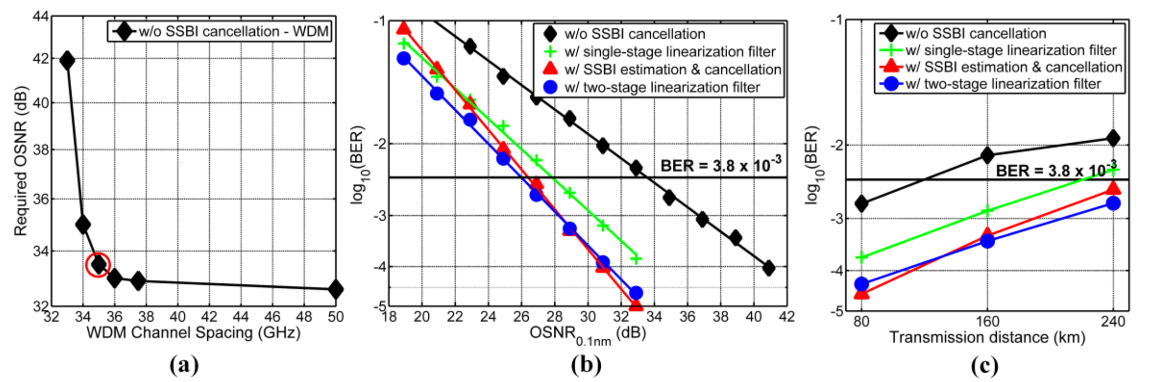
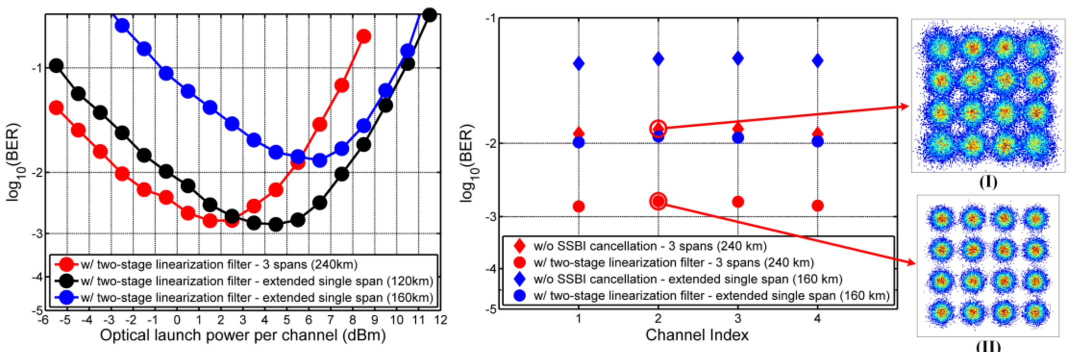



Fig. 2: (a) Required OSNR at BER = $3.8 \times 10^{-3}$ vs WDM channel spacing. (b) BER vs OSNR. (c) BER vs transmission distance.

Initially, the optical back-to-back performance was evaluated by ASE-noise loading at the receiver. In order to determine the minimum WDM channel spacing to achieve the highest possible ISD, the channel spacing was varied from 33 to 50 GHz and the required OSNR at BER = $3.8 \times 10^{-3}$ was monitored without using beating interference cancellation, as shown in Fig. 2(a). The WDM channel spacing was set to 35 GHz, yielding a gross ISD of 3.2 (b/s)/Hz, in order to keep the OSNR penalty due to linear crosstalk caused by neighboring channels within 1 dB. Moreover, the BER versus OSNR at 35 GHz WDM channel spacing is plotted in Fig. 2(b) in back-to-back operation for the cases without and with three different beating interference compensation methods, namely single-stage [7], two-stage [6] linearization filters and SSBI estimation and cancellation [8]. The optimum performance was achieved by sweeping the CSPR value from 4 dB to 14 dB and setting it at the optimum value for each OSNR level. It can be observed that the required OSNR at the HD-FEC threshold (BER = $3.8\times10^{-3}$) was found to be 33.5 dB without using beating interference compensation, with an improvement by 7.6 dB to 25.9 dB for the case with the two-stage linearization filter, which is higher than the 5.4 dB and 6.9 dB gains achieved using the single-stage linearization filter and SSBI estimation and cancellation schemes, respectively. Following this, the system was further assessed through WDM transmission experiments over distances from 80 km to 240 km multiple span ($N$ = 1, 2 and 3) fiber links without and with beating interference mitigation schemes. The CSPR value was swept from 9 dB to 12 dB and adjusted at each transmission distance for the optimum system performance. The BER (at the optimum optical launch power and CSPR) with respect to the transmission distance is plotted in Fig. 2 (c). It can be observed that the WDM transmission performance is significantly improved at all distances, and the BER at 240 km transmission was reduced from $1.2\times10^{-2}$ to $1.8\times10^{-3}$ by implementing the two-stage linearization filter, which performs the best amongst all the utilized beating interference compensation schemes. The transmission reach was enhanced by 200% (from 80 km to 240 km).

The WDM transmission performance was next investigated for extended reach single span fiber links. The BER versus optical launch power per WDM channel using the two-stage linearization filtering scheme is plotted in Fig. 3(a) for the cases of 3 spans (240 km), and extended reach single span (120 km and 160 km) transmission scenarios. Since extending the reach of a single span significantly degrades the OSNR, it can be observed that the minimum BERs at the optimum launch power were $1.5\times10^{-3}$ and $1.4\times10^{-2}$ for 120 km and 160 km extended reach single span transmissions, respectively. The optimum optical launch power per WDM channel was increased to 4.5 dBm and 6.5 dBm and the optimum CSPR values were found to be 9 dB and 6 dB for 120 km and 160 km extended reach single span fiber transmission, respectively. Finally, the performance of all 4 WDM channels are shown in Fig. 3(b) at the distances of 240 km (3 spans) and 160 km (extended reach single span). The average BER for all the channels was decreased by one order of magnitude (from $1.1\times10^{-2}$ to $1.6\times10^{-3}$) for 240 km multiple span transmission whereas a half-order of magnitude reduction (from $5.5\times10^{-2}$ to $1.3\times10^{-2}$) was observed for 160 km extended reach single span transmission. Based on the theoretical hard-decision decoding bound for the binary symmetric channel at the $1.6\times10^{-3}$ and $1.3\times10^{-2}$ BERs, the achieved net optical ISDs were found to be 3.15 (b/s)/Hz and 2.88 (b/s)/Hz respectively.




**(a)** **(b)**

Fig. 3: (a) BER vs optical launch power per channel. (b) BERs for each WDM channel. Insets: Received constellations without beating interference mitigation (EVM = 21.4%) and with two-stage linearization filter (EVM = 15.6%) at 240 km transmission.

## 4. Conclusions

We reported the experimental demonstration of a 35 GHz-spaced 4×112 Gb/s WDM SSB 16-QAM Nyquist-SCM DD signal transmission at up to 3.15 (b/s)/Hz net optical ISD, utilizing a novel signal-signal beating interference compensation technique combining low complexity with high compensation gain. Record transmission distances over a 240 km multiple span link and a 160 km extended reach single span link were achieved. To the best of our knowledge, this is the first experimental demonstration of the utilization of single-polarization direct-detection transceivers achieving beyond 100 Gb/s per channel spectrally-efficient (> 3 (b/s)/Hz) WDM transmission. Such technology is a potential solution for metro-ring (200-300 km) applications, and for 400G (4×112 Gb/s) links over metro distances.

*This work has been supported by the UK EPSRC UNLOC project, EU FP7 ASTRON project and Semtech Corporation.*

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