Extended Reach 40km Transmission of C-Band Real-Time 53.125 Gbps PAM-4 Enabled with a Photonic Integrated Tunable Lattice Filter Dispersion Compensator

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Abstract: Reach-extended C-band transmission of real-time 53.125Gbps PAM-4 data over 40km SSMF is enabled using a dispersion compensating photonic-integrated programmable lattice filter. Transmission of 100GHz spaced channels error-free below the FEC threshold is demonstrated.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (060.2340) Fiber Optic Components

1. Introduction

Low-cost high-capacity data center interconnects (DCIs) for connecting over inter-campus and metro region scales are becoming increasingly important with as much as 50% in the 10 - 40km distance range for certain deployments. Extension of low cost interface technologies developed for shorter reaches to this application space is of great interest. The penetration of PAM-4 as a solution for today's DCIs has increased dramatically and the push to apply this interface beyond the original dispersion limited reach of 5km is of great interest.

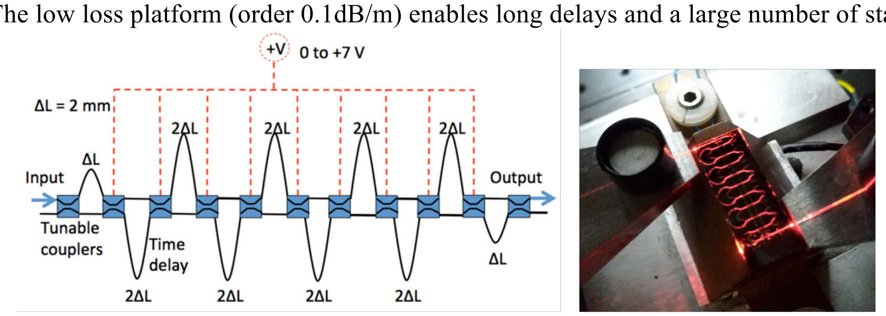
Reach extension beyond the dispersion limited tolerance of 5km SMF28 for direct detection was focused on using the low dispersion window at 1310nm [1-3]. However, due to fiber scarcity in these applications, there has been increased interest to move PAM-4 to the 1550nm C-band in order to increase the link capacity. A tradeoff in moving to C-band has been a need for discrete dispersion compensation technologies like dispersion compensating fibers (DCFs) or fiber Bragg gratings (FBGs), and demonstration of real-time 28GBd WDM C-Band to 80km and 100km has been demonstrated [4-6]. However, in order to address cost, size, weight, and form factor, compact photonic integrated technologies are critical. These integrated solutions will need to mitigate PAM-4 dispersion for multiple WDM channels while at the same time satisfying the strict OSNR requirements.

In this paper, we report the first demonstration of C-band transmission of real-time 53.125 Gbps PAM-4 over 40km SSMF using a monolithically integrated programmable lattice filter for dispersion compensation. The 10-stage lattice filter [7], capable of tuning +/-500 ps/nm, was fabricated in a low loss silicon nitride platform compensating different channels on a 100GHz channel spacing. Pre-FEC BER curves demonstrate error-free performance below the FEC threshold for up to four different WDM channels, over fiber lengths of 40km, 35km and 25km. While the lattice filter used here is designed to operate on multiple WDM channels on a 100GHz grid simultaneously, we describe the design in this platform to operate on a 50GHz grid and to lower the overall chip loss to under 4dB.

2. Dispersion Compensation Photonic Integrated Tunable Lattice Filter

The filter, shown in Fig. 1a, incorporates a 10-stage cascaded lattice filter constructed with unbalanced Mach-Zehnder interferometers (MZIs) fabricated in a low-loss silicon nitride platform with heater controlled dispersion tuning as reported in [7]. The device size is 22.5 mm x 9.89 mm and was designed to operate on simultaneous WDM channels on a 100GHz channel spacing grid, with maximum dispersion tuning of +/-500 ps/nm over a 15GHz bandwidth per channel. For PAM-4 over 40km in the C-band we expect the required dispersion compensation to be +/- 550 ps/nm assuming the receiver can handle +/- 170ps/nm residual dispersion [5]. Optical backscatter reflectometry (OBR) measurements of wavelength dependent group transmission, group delay, and corresponding dispersion are reported in [7].

Dispersion is continuously tuned by adjusting the phase of the couplers. The current device has a total through loss of 20dB due to absence of fiber coupler tapers and close proximity of the thermal tuners to the waveguides. As discussed in the summary, these design points are readily changed to realize a filter with under 4dB loss. The current loss was not a limiting factor in this demonstration, as the link was dispersion limited with the OSNR maintained above 40dB. Critical filter design parameters include the unit optical delay (2mm for this design) and number of filter stages, which determine the maximum tunable dispersion, FSR and bandwidth. With a longer unit optical delay, a smaller filter free spectral range (FSR) and increased dispersion tuning maximum is achievable, enabling 50GHz WDM. The low loss platform (order 0.1dB/m) enables long delays and a large number of stages.



(a) (b)

Fig. 1. (a) Integrated programmable lattice filter architecture with DL = 2mm for 100GHz channel spacing. (b) Photograph of tunable 10-stage dispersion compensating lattice filter (red light used for coupling).

3. Experimental setup

The transmission experimental setup is shown in Fig. 2. Inphi PAM-4 Phy IC transmitter and receiver boards were used to generate and detect real-time PAM-4 PRBS31 patterns as well as generate histograms and counting BER. The real time PAM-4 boards were interfaced to a C-band 40Gbps Mach-Zehnder modulator based transmitter and a 32GHz linear receiver. Transmission booster and receiver optical amplifiers and optical filters were used to set the OSNR with the integrated dispersion compensation chip in place to > 40dB. The transmitter electrical block consists of an Inphi PAM-4 PHY IC board generating at KR4 (25.78125GBd) and KP4 (26.5625GBd) standard IEEE baud rates [2]. The PAM-4 IC board outputs differential signals that drive a single ended Sumitomo MZM intensity modulator using a differential to single-ended linear amplifier (IN3214). A C-band tunable laser and booster EDFA were input to the modulator at a power level of +7dBm to transmit 53.125Gbps data channels onto a 100GHz C-band ITU grid. A single-ended optical to differential electrical output linear receiver (Picometrix PT-28E) suitable for 28GBd direct detection enabled measurements with received power as low as -16dBm. Receiver side DSP and signal recovery was performed on-board the PHY-IC PAM-4 unit, with built-in pre-FEC BER and SNR analytics.

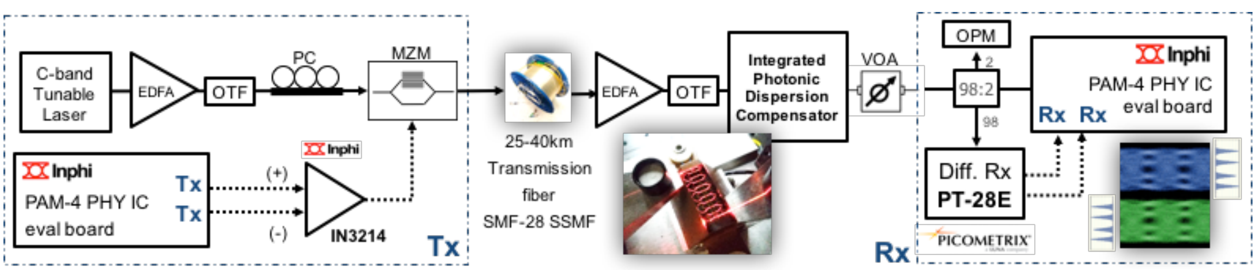
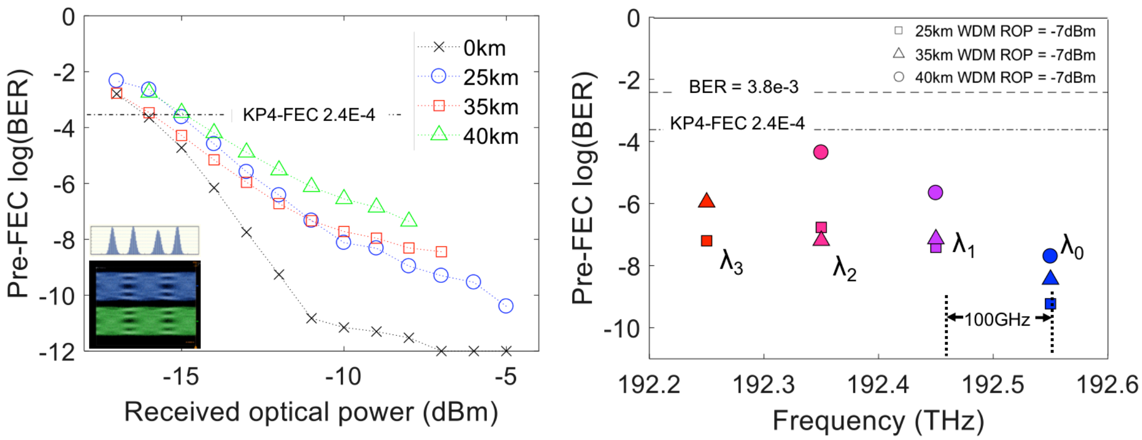


Fig. 2. Experimental setup for transmission of real time C-band 53.125 Gbps PAM-4 transmission using 10-stage photonic integrated programmable lattice-filter dispersion compensator.

For each real-time pre-FEC BER measurement only the laser frequency and EDFA filter center frequencies were changed, in increments of 100GHz. For each BER measurement all other transmission components were kept constant including the booster EDFA, the MZM and PAM-4 drive electronics, the receiver EDFA, the linear receiver gain and bandwidth, and the PAM-4 receiver board equalization settings. All BER measurement are pre-FEC and shown relative to FEC threshold. Back to back optical pre-FEC BER measurements using the experimental setup in Fig. 2, were made with no transmission fiber in place at 1560nm, and baseline error detection better than the FEC threshold limit is shown in Fig. 3a. Transmission measurements were performed using SMF-28 standard single mode fiber (SSMF) with approximate dispersion of 18 ps/nm•km at 1560nm and loss of ~0.2dB/km.

Fiber lengths of 40km, 35km and 25km were used for transmission measurements with resulting pre-FEC BER for channel 1560nm shown in Fig. 3a below the KP4-FEC error threshold of 2.4×10^{-4} BER. Also shown is a sample eye diagram at the receiver differential output and a post-DSP 4-level histogram. The 40km length corresponds to dispersion of ~720ps/nm. An EDFA was incorporated before the photonic chip to overcome device loss and enable transmission measurements up to -5dBm received optical power (ROP). Optical signal-to-noise ratio (OSNR) was maintained >40dB for all measurements to ensure link performance was not limited by the OSNR margin for PAM4 optical transmission. Measurement of the real-time pre-FEC BER multiple channels at 100GHz spacing for the three fiber lengths at four wavelengths is shown in Fig. 3b. Channel λ_3 for the 40km case was not plotted due to the accumulated dispersion of 720ps/nm and the combination of 170ps/nm residual dispersion tolerance at the PAM-4 receiver board with the 500ps/nm integrated photonic circuit compensation falling just short of the required compensation at that wavelength. The photonic circuit was operated at 80mA and 5.9V = 470mW.



(a) (b)

Fig. 3. Measured Pre-FEC BER for (a) λ_0 back-to-back and over 25km, 35km and 40km of SMF-28 SSMF with the KP4-FEC 2.4E-4 threshold indicated and (b) four 100 GHz spaced channels λ_0 - λ_3 with received optical power (ROP) = -7dBm also showing performance well below the KP4-FEC 2.4E-4 threshold (channel λ_3 was not recovered for 40km due to total dispersion exceeding compensated + residual).

4. Discussion and Summary

We have presented the first demonstration of real-time transmission of 53.125 Gbps PAM-4 over 40km SSMF using a photonic integrated 10-stage tunable lattice filter for dispersion compensation. Test results show 100GHz spaced C-band channels to be transmitted error-free below the KP4-FEC 2.4E-4 threshold. The integrated compensator tunable dispersion range of +/-500 ps/nm supported transmission of three channels over 40km and four channels over 35km and 25km. The dispersion for the fourth channel at 40km was just under the receiver dispersion tolerance combined with the compensator maximum and therefore was not able to be recovered while keeping all transmission components constant while only the transmission wavelength was changed. It should be noted that this fourth channel was recoverable by adjusting its transmission frequency slightly, however we left the data point off to show only true 100GHz grid spaced channels. All measurements were made with dispersion limited transmission and OSNR >40dB. The integrated photonic lattice filter had an insertion loss of 20dB, which did not limit the link OSNR, but in next generation filters can be lowered to <4dB using fiber taper couplers on-chip [8] and thicker upper cladding moving the thermal tuning metal further away from the optical mode. Tuning using PZT is also under investigation to further lower loss and greatly lower the power consumption.

5. References

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