Electronic equalization and FEC enable bidirectional CWDM capacities of 9.6 Tb/s-km

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Abstract: Using electronic equalization to combat chromatic dispersion and forward error correction (FEC) to increase robustness to in-band crosstalk, we demonstrate CWDM capacities of 32x10 Gb/s (2x16, full-duplex) over >30 km of low-water-peak standard single-mode fiber.

OCIS codes: 060.2330 Fiber optics communications , 060.2360 Fiber optics links and subsystems

1. Introduction

Coarse wavelength division multiplexed (CWDM) systems are becoming increasingly important for fiber-exhaust optical access applications, such as metro-feeders, central-office interconnects, or potentially WDM passive optical networks (WDM-PONs), where they allow for the low-cost deployment of short-reach links with appreciable capacity. By using inexpensive components, e.g., uncooled directly modulated lasers (DMLs), full-spectrum CWDM systems presently offer up to 18 wavelength channels, 20-nm spaced between 1270 nm and 1610 nm, with per-channel bit rates up to 2.5 Gb/s and reach up to 80 km over low-water-peak fiber (LWPF). Recent research has pushed bit rates of uncooled DMLs to 10 Gb/s [1,2] and beyond [3]. However, due to the high chirp inherent to DMLs, and the dispersion properties of standard LWPF (λ_0 at 1310 nm, 17 ps/(nm km) at 1550 nm), such an increase in bit rate comes at the expense of significantly reduced system reach, unless low-water-peak non-zero dispersion-shifted fiber (NZDF) is used [2,4]. Recent work on minimizing the impact of 10-Gb/s DML chirp for DWDM metro applications at 1550 nm has used negative dispersion fiber [5] or electronic equalization [6]. Regarding full-duplex systems to efficiently use the fiber plant, in-band crosstalk from connector reflections and Rayleigh backscatter places severe limits on the systems' loss budgets [7], so far preventing economical deployment.

In this paper, we demonstrate record CWDM transmission capacities based on potentially low-cost and highly integrated electronic equalization in combination with forward error correction (FEC), using 16 uncooled DMLs (1310 nm to 1610 nm) and standard LWPF (AllWave™). Electronic equalization combats chromatic dispersion (CD) for the longer wavelength channels, while FEC both establishes higher margins and enables bidirectional transmission due to increased in-band crosstalk tolerance at FEC error rates.

2. Two CWDM system setups

The two CWDM systems demonstrated in this work are depicted in Fig.1: Both employed 16 uncooled DMLs, driven with an FEC-precoded pseudo-random bit sequence of length 2^{31}-1 using non-return-to-zero modulation at 10.664 Gb/s (9.953-Gb/s information bit rate). All DMLs were rated for 2.5-Gb/s operation [3,4], with extinction ratios of ~3 dB at 10 Gb/s. As is typical for non-selected DMLs, our sources had widely varying thresholds (8-17 mA), slope efficiencies (0.06-0.2mW/mA), output powers (5-10dBm), and chirp characteristics. Thin-film multiplexers with channel-dependent insertion losses between 1 and 4 dB were used to combine the CWDM sources. In the setup sketched in Fig.1(a), the 16 channels were partitioned to let 8 propagate in each direction along a standard LWPF, whose characteristics are given in Fig.2(c). In the 2x16 channel system of Fig.1(b) all 16 channels propagated in each direction. To test the system of Fig.1(b) we used the setup of Fig.2(a). Choice of appropriate optical power splitters to generate

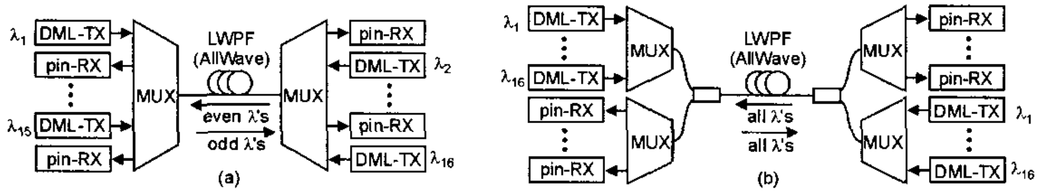

Fig. 1 : (a) 16-channel CWDM system: 8 channels East, 8 channels West. (b) 32-channel CWDM system: 16 channels each direction.

the backward traffic ensured the launch of approximately equal channel powers into the fiber span from both directions. The CWDM spectrum is shown in Fig.2(b). Various types of angled and straight fiber connectors were used. The dominant source of in-band crosstalk in the 32-channel system was Rayleigh backscatter from backward traffic. We adjusted the backward traffic's polarization for worst-case interference with the detected signal, and compared a state-of the art 10-Gb/s *pin*-receiver (with FEC) to the same *pin*-front-end using electronic equalization and FEC.

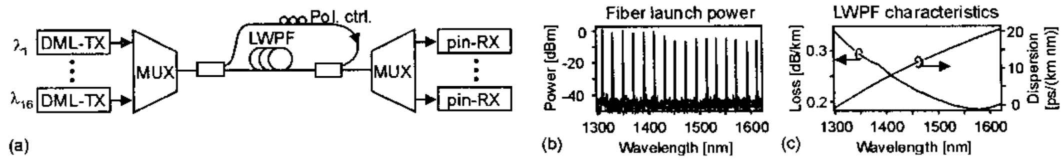

Fig. 2 : (a): Experimental setup for bidirectional CWDM transmission. (b): CWDM spectrum launched bidirectionally into fiber. (c): Loss and dispersion of LWPF.

The *electronic equalization* chipset for dispersion compensation consisted of a CMOS FEC device (7.14% bit rate overhead, including framing, to correct raw error ratios of $< 2\cdot10^{-3}$ to values $< 10^{-15}$) and a SiGe device for equalization, variable high-frequency peaking, clock and data recovery. A parallel sub-rate feedback channel between the SiGe receiver and the FEC provides rapid automatic equalizer adaptation over a broad range of signal conditions. While previous work has investigated the benefits of various compensation techniques such as adaptive thresholding, feed forward equalization (FFE), decision feedback equalization (DFE), and maximum likelihood sequence estimation (MLSE) [8], the electronic equalization used in the receiver chip incorporates elements of each of these techniques. After passing adaptive DFE and FFE elements, the signal undergoes multiple adaptive thresholding, which provides the quantization for subsequent soft decision decoding by simple, MLSE-like processing and FEC feedback.

3. CWDM system benefits from electronic equalization and FEC

Fig. 3(a) shows, as a typical example, the receiver sensitivity as a function of transmission distance for the 1550-nm CWDM channel without (circles) and with (squares) electronic equalization. Both solid curves were taken at BER = 10^{-3} and with enabled FEC to ensure block error correctability. The dotted curve shows sensitivities at BER = $6\cdot10^{-5}$. All curves used the same laser driving conditions, optimized for maximum reach. The improvement in receiver performance beyond 20 km reflects the effect of self-steepening, caused by the interplay of CD and adiabatic laser chirp, and leading to pulse recompression [9]. The effect of equalization, visualized by the hatched area in Fig.3(a) is twofold: firstly, equalization provides a back-to-back sensitivity improvement of almost 4 dB, which compensates for the limited 10-Gb/s performance of our 2.5Gb/s DMLs. For the compressed pulses at around 50 km we find an equalization gain of 2-3-dB. Secondly, at distances where the pulses are broadened by CD (~ 20 km and > 60 km), the equalizer gain is > 7 dB. Thus, equalization reduces strong variations in CD penalty over distance, enhancing design flexibility. With equalization, error-free transmission over 85 km was achieved.

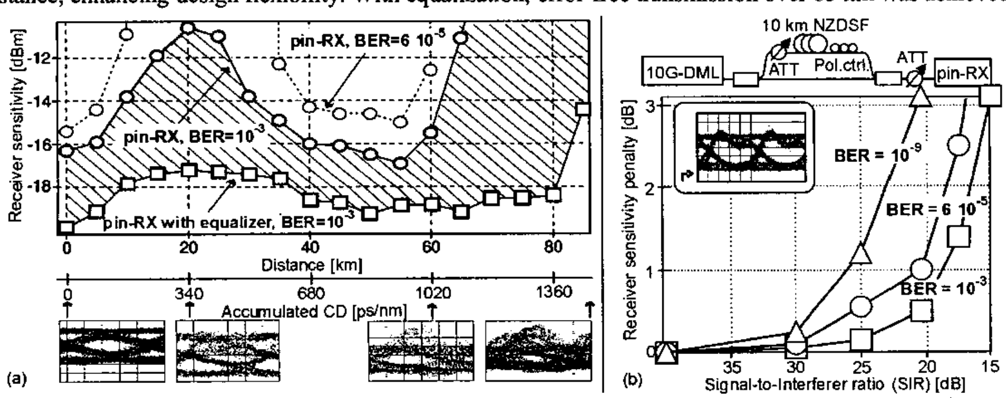

Fig. 3 : (a) Receiver sensitivity (solid: BER=10^{-3}, dashed: BER=$6\cdot10^{-5}$) vs. transmission distance for the 1550-nm CWDM laser. Circles: Unequalized receiver. Squares: Equalized receiver. Hatched area: Equalization gain. Optical eye diagrams shown at various distances. (b) Sensitivity penalty for the unequalized receiver and the 1550-nm channel vs. SIR at BER = 10^{-3}, $6\cdot10^{-5}$, and 10^{-9}.

Fig.3(b) shows the sensitivity penalty due to in-band crosstalk at various raw BERs for a 1550-nm DML, rated for 10 Gb/s to achieve 7.6 dB extinction, more representative for deployable 10-Gb/s systems than our 2.5-Gb/s-rated sources. Here, we used the unequalized pin-receiver, but with enabled FEC. During our measurements (setup of Fig.3(b)), we adjusted the polarization of the interferer for worst performance. Signal and interferer were decorrelated using 10 km of NZDSF. At BER = 10^{-9} we find a 1.5-dB sensitivity penalty at SIR = 24 dB, while at BER = 10^{-3}, the 1.5-dB penalty shifts to SIR = 17 dB, proving that FEC can substantially relax SIR requirements [10]. This ~7-dB reduced SIR requirement significantly boosts the attractiveness of bidirectional systems: the received SIR in a full-duplex system is given by Eq. (10) of [7]: $SIR_{[dB]} = R_{[dB]} - L_{[dB]} - \Delta P_{[dB]}$, where R is the near-end reflection, L is the span loss, and ΔP is the power divergence between same-wavelength transmitters. Reductions in SIR requirements can thus be traded for system loss (i.e., reach): At $R_{[dB]} = 33$ dB and $\Delta P_{[dB]} = 5$ dB, the requirement SIR > 24 dB (no FEC) translates into a maximum tolerable span loss of 4 dB, while 11 dB can be supported using FEC.

4. CWDM transmission results

Fig.4 summarizes the results of the CWDM experiments (*circles:* unequalized receiver, Fig.1(b); *squares:* equalized receiver, Fig.1(b); *triangles:* equalized receiver, Fig.1(a)). Fig.4(a) shows the maximum transmission distance for each CWDM channel. The significant variations among channels are typical for DMLs [4]. In the high-wavelength region (high dispersion but low loss), the equalizer proves particularly valuable, boosting transmission distances from 10 km up to 65 km in the 32-channel system, and up to 80 km in the 16-channel system, where the absence of optical couplers generating the backward traffic helps the loss budget, and no degradations due to in-band crosstalk can occur. Fig.4(b) shows the CD at maximum transmission distance for each CWDM channel. While the unequalized receiver only supports ~ 300 ps/nm of CD, the equalizer allows up to 1600 ps/nm. Finally, Fig.4(c) gives the total CWDM system capacity as a function of transmission distance. Electronic equalization and FEC enable a bidirectional capacity of 32x10 Gb/s over 30 km (9.6 Tb/s-km) and a 16-channel capacity of 16x10 Gb/s over 40 km (6.4 Tb/s-km), with more than 50% of all channels going beyond 50 km (32-channel setup) and 65 km (16-channel setup).

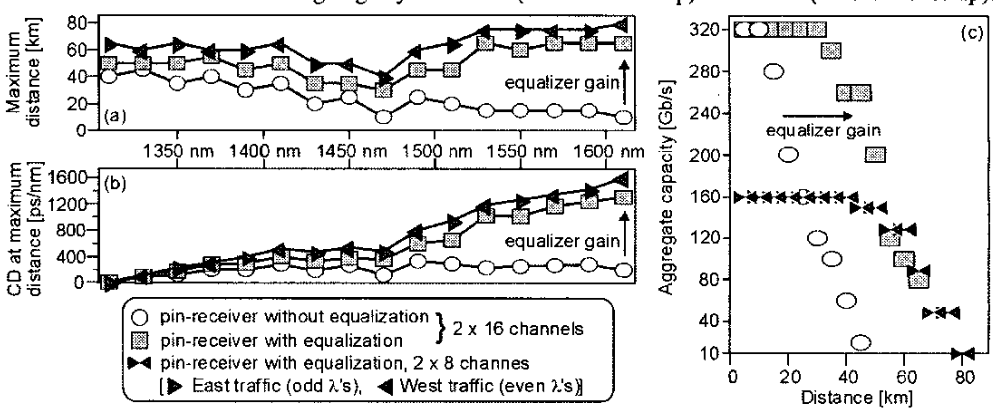

Fig. 4 : (a): Maximum transmission distance for all CWDM channels. (b): Accumulated chromatic dispersion (CD) at maximum distance for each channel. (c): Total system capacity as a function of distance.

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