A novel symmetric 10 Gbit/s architecture with a single feeder fiber for WDM-PON based on chirp-managed laser*

Aftab Hussain[1], XIN Xiang-jun(忻向军)[1], Abdul Latif[1], Ashiq Hussain[2], YU Chong-xiu(余重秀)[1], Abid Munir[1], Yousaf Khan[1], and Muhammad Idrees Afridi[1]**

1. *State Key Laboratory of Information Photonics and Optical Communications, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876, China*
2. *Processing and Communication Systems Research Group, Heavy Industries Taxila Education City University, Islamabad 47070, Pakistan*

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We propose the single feeder fiber architecture for wavelength division multiplexing passive optical network (WDM-PON) based on directly modulated chirp managed laser (CML). The downlink (DL) signal output from the laser is converted to return-to-zero (RZ) differential phase shift signal using a pulse carver. The downstream signal is reused as a carrier for the upstream using intensity modulation technique. Simulation results show the error-free performance at symmetric data rate of 10 Gbit/s per channel with negligible power penalty and improved receiver sensitivity for the uplink (UL), over 25 km standard single-mode fiber (SSMF). A low-cost and reduced circuitry network design is implemented on a single feeder fiber with the elimination of differential encoder and one external modulator.

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The demands of bandwidth in access network show a surging growth due to the video content based services and emerging data-centric applications[1,2]. It is quite evident that in the near future, access network bandwidth requirements will be symmetric, and will reach the range of multi-gigabit per second per subscriber[3,4]. Therefore, the next generation access technology for last mile is required to provide higher bandwidth at low cost. To reduce the network cost, several factors can be considered. Firstly, the provision of higher data rate of 10 Gbit/s or above per channel should be taken into account. Secondly, the remodulation of downstream signal to generate upstream signal is an attractive solution for low-cost realization of WDM-PON[5-7]. Thirdly, at higher data rate of 10 Gbit/s or above, increasing transmission distance (>10 km) can enhance the dispersion and magnify the bit error rate (BER) over a single-mode fiber. Therefore, the dispersion tolerant transmitters are deployed in an optical access network. Moreover, dispersion compensation modules should be eliminated from the system[8]. Last but not least, the single feeder fiber network design should be implemented between optical network unit (ONU) and optical line terminal (OLT). But the performance of single feeder fiber colorless WDM-PON systems suffers from the transmission impairments due to Rayleigh backscattering (RBS) and reflections along the fiber because of the RBS of the downstream continuous wave (CW). It causes the degradation in upstream signal and deterioration of receiver bit-error-rate (BER) at OLT. But reducing modulation depth of downstream differential phase shift keying (DPSK) signal can make the upstream signal more robust to RBS noise[8]. Chirp-managed laser (CML) based transmitters are inexpensive, compact in size, tolerant to both negative and positive dispersions and provide high optical output power and long transmission distance in single-mode fiber[9-12]. CML is considered as a better choice for single fiber based WDM-PON architecture, as it is efficient and tolerant to dispersion and RBS.

In this paper, we demonstrate a single feeder fiber based low-cost and colorless WDM-PON driven by a CML trans-

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** E-mail: aftabhusein@gmail.com

mitter. Only a single Mach-Zehnder modulator (MZM) as a pulse carver is required for producing RZ-DPSK shaped downlink signal. The inverse-return-to-zero (IRZ) shaped data through an NAND gate with the clock signal is used to drive the CML transmitter. The output signal from the laser is then converted to an RZ-DPSK shaped downlink signal using a pulse carver. The downstream signal can be subsequently remodulated at the ONU for on-off keying (OOK) upstream signal at symmetric rate of 10 Gbit/s. The proposed scheme can reduce deployment cost and network circuitry for future WDM-PON.

CML transmitter is a simple combination of directly modulated lasers (DMLs) and an optical filter called optical spectrum reshaper (OSR). DMLs are used for optical communication at low BER and have some short distance applications due to high inherent chirp[9]. DML frequency chirp has two major components of the transient chirp and the adiabatic chirp at high data rates (⩾2.5 Gbit/s). Currently, DMLs get more interest, and their intrinsic chirp is exploited by CML to increase the transmission distances[2]. In CML transmitter, a wavelength locker is formed at the OSR in conjunction with two photodiodes of PD1 and PD2 which monitor the optical power from the distributed feedback (DFB) and the reflection from the OSR, respectively. The locking circuit adjusts the laser temperature and wavelength to keep the ratio of PD2/PD1 constant[12]. It follows a phase rule that “1” bits separated by odd number of “0” bits are π out of phase. Normally, dispersion spreads the energy of the “1” bits into adjacent “0” bits, and closes the eye. However, this π phase shift in the CML causes the destructive interference in the middle of the “0” bits, and keeps the eye open even in the presence of fiber dispersion[9,13]. Fig.1 shows the principle of operation of CML. When DML is biased near threshold and modulated to achieve the extinction ratio (ER) from 8 dB to 10 dB, the transient chirp is enhanced, which spreads the optical pulse[9]. A standard DFB laser in CML is therefore biased at ~ 5 × threshold and directly modulated by digital data. It results in low extinction ratio (~1−2 dB) intensity modulation, high output power, wide modulation bandwidth,

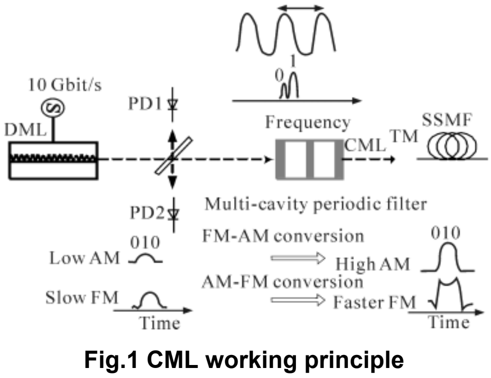


Fig.1 CML working principle

low timing jitter and suppression of transient chirp.

For a 10 Gbit/s data rate, the pulse width is 100 ps. To get the phase shift, adiabatic chirp needs to be equal to π/ (2π× 100 ps)=5 GHz. It means that the “1” bit has 5 GHz blue shift relative to entire “0” bit[2]. The laser wavelength is aligned with the transmission edge of the OSR, so as to pass the “1” bits, attenuate the “0” bits, and simultaneously suppress the transient chirp and shape it into the top-flatted chirp. The frequency modulation (FM) to amplitude modulation (AM) conversion increases extinction ratio (ER) at the output of the OSR to above 10 dB[9,10,13]. The frequency profile reshaping in the OSR is caused by the action of slope of the filter. Consider an optical electric field with amplitude envelope $A(t)$, and adiabatic chirp passes through an OSR with a linear transmission edge function as

$$T(\omega) = a + b(\omega - \omega_0) \ , \tag{1}$$

where b is the slope, and a is the transmission at center frequency. According to Fourier theory, linear filter adds the time derivative of the input signal to itself with a π/2 phase shift. The frequency profile of the output field $\Delta\omega_{\text{out}}$ is modified because of the π/2 phase shift, and can be measured approximately as

$$\Delta\omega_{\text{out}}(t) = \Delta\omega_{\text{AD}}(t) - \frac{\mathrm{d}}{\mathrm{d}t}\tan^{-1}\left\{\frac{bA'(t)}{A(t)[a + b\Delta\omega_{\text{AD}}(t)]}\right\} \ , \tag{2}$$

where $\Delta\omega_{\text{AD}}$ is the input adiabatic chirp. The OSR performs weighted derivatives of the input amplitude, and symmetrically adds the blue shifted peaks to the adiabatic chirp at both the “1” to “0” and “0” to “1” bit transitions. This addition of chirp, which scales with the slope of the OSR b, significantly reduces the rise and fall times, and creates the flat-top chirp profile across each pulse[9].

Fig.2 shows the proposed scheme of 10 Gbit/s RZ-DPSK transmission system using CML. The transmitter includes an IRZ driver, a CML and a pulse carver. The IRZ shaped data with 33% duty cycle is generated via a logic NAND gate which is used to directly modulate the CML. The driving voltage V_{pp} is adjusted to induce adiabatic chirp with $\Delta f = 1/T$. The adiabatic chirp generates phase shift during low level with the period of[15,16]

$$\Delta\varphi = 2\pi\int_0^{T/2}\Delta f(t)\,\mathrm{d}t = 2\pi \times 1/T \times T/2 = \pi \ . \tag{3}$$

Here, the chirp value required for 10 Gbit/s RZ-DPSK is 5 GHz. The output of the filter is an IRZ-DPSK signal, in which both the intensity and differentially encoded phase carry the same information. Hence, no differential encoder and phase modulator (PM) are needed. Fig.3 shows the simulation setup using CML for the proposed single feeder fiber based WDM-

PON system with a centralized light source for downlink (DL) and uplink (UL). The transmission performance of the proposed WDM-PON with four 10 Gbit/s downlink channels and four 10 Gbit/s uplink channels over 25 km-long standard single-mode fiber (SSMF) is evaluated by this simulation. Four continuous light waves with launch power of 5 dBm and an ER of 20 dB are generated by four DFB DMLs at wavelengths of 1552.52 nm (λ_1), 1552.04 nm (λ_2), 1551.56 nm (λ_3) and 1551.08 nm (λ_4) for four different channels respectively on a 60 GHz channel grid. 2nd-order Gaussian optical filters with a bandwidth of 25 GHz and a depth of 100 dB are used as OSR. For each channel, 10 Gbit/s pseudorandom binary sequence (PRBS) data is through NAND gate with 10 Gbit/s clock signal to generate an IRZ format signal to directly modulate CML. The output is then fed to a pulse carver. The pulse carver consists of an MZM driven by a 5 GHz clock pulse, generating RZ pulses with duty cycle of ~33%.

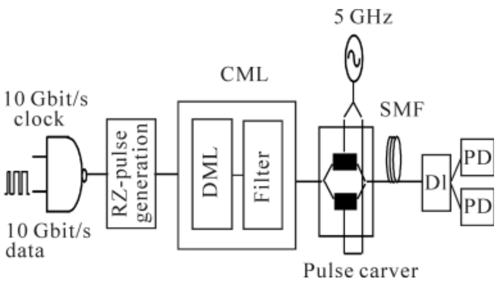


Fig.2 Simulated scheme of 10 Gbit/s RZ-DPSK transmission system using CML

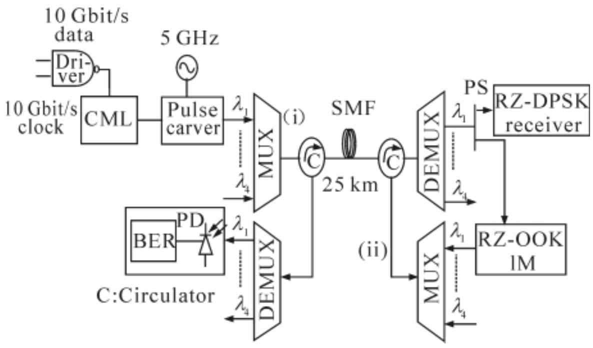


Fig.3 Proposed CML based single fiber 10 Gbit/s RZ-DPSK DL and OOK UL WDM-PON

The four produced RZ-DPSK signals are multiplexed by a 4 × 1 multiplexer (MUX) on a 60 GHz channel spacing and transmitted over a 25 km single-mode feeder fiber. The downlink multiplexed signal is first demultiplexed using a 1 × 4 demultiplexer (DEMUX) and then transmitted to the corresponding ONU. At the receiving ONU, a 3 dB optical power splitter (PS) is used for the downstream receiver. A Mach-Zehnder delay interferometric (MZDI) demodulator is used to convert the phase-modulated DPSK signal to an intensity-modulated signal before being received by a regular direct detection PIN receiver. The other half of the DPSK signal is injected into a Mach-Zehnder intensity modulator (IM) driven by 10 Gbit/s upstream data with RZ modulation format. The remodulated RZ OOK upstream signal is transmitted back to the OLT through the same 25 km of SMF-28 before being received by a direct detection avalanche photodiode (APD) receiver. The PRBS length of the upstream data is set to 2^7-1. A 4th-order Bessel low-pass electrical filter (LPF) with 3 dB bandwidth of 7.5 GHz is used at RZ OOK receiver for retrieving 10 Gbit/s upstream data.

The ER of uplink transmitter is set to 100 dB, which is greater than that of the downlink transmitter in order to cope with the RBS of the fiber[8]. Fig.4 shows the multiplexed signals for RZ-DPSK downlink and OOK uplink, respectively.

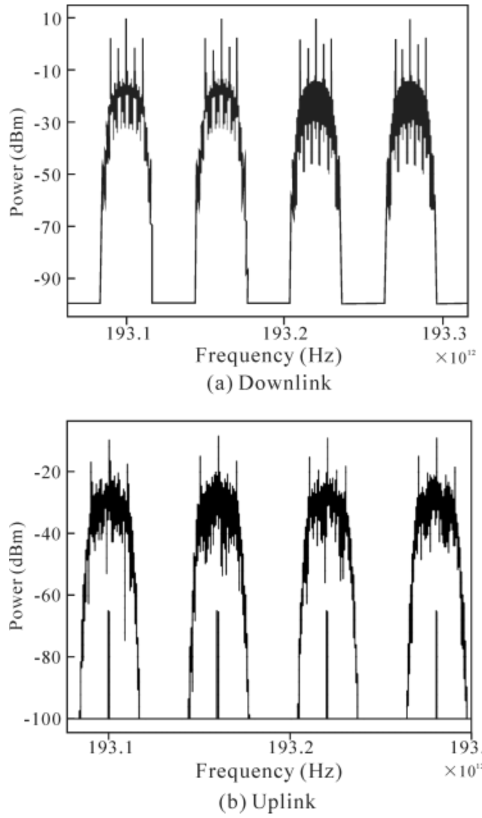


Fig.4 Multiplexed spectra for downlink and uplink channels

CML is dispersion tolerant compared with other transmitters using external modulators. To verify it, receiver sensitivity is measured at BER=10^{-9} after various lengths of SSMF transmission for CML and phase modulator (PM) as shown in Fig.5. The insets of Fig.5 show that CML based RZ-DPSK signal has much clearer eye than PM based RZ-DPSK signal after 70 km SSMF transmission.

BER as a function of received optical power for RZ DPSK downlink and OOK uplink channel-1 and channel-3 before and after 25 km transmission is illustrated in Fig.6. The individual power penalties measured at 10^{-9} BER for DPSK downlink channels (1 and 3) are 0.3 dB and 0.7 dB, respectively.

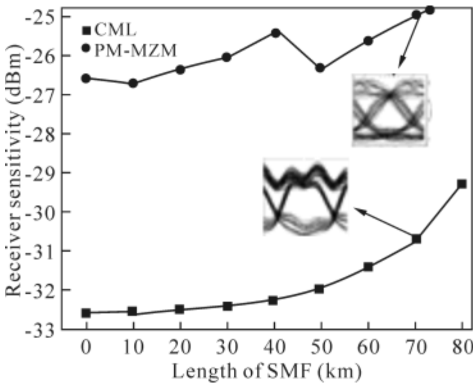


Fig.5 Chromatic dispersion tolerances for CML and PM-based RZ-DPSK signals

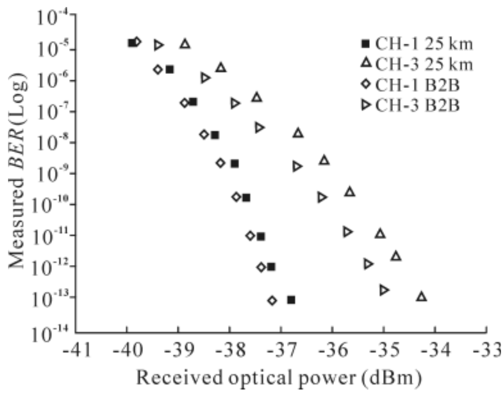


Fig.6 BERs for downlink channel-1 and channel-3 for 25 km and B2B transmissions

In the uplink transmission, due to a single feeder fiber structure, the measurement of back-to-back (B2B) BER for uplink is impossible. The BERs over 25 km distance for uplink channels 1 and 3 are measured as -35.697 dBm and -36.497 dBm, respectively, as shown in Fig.7.

At 10^{-9} BER, the average power penalty of all four multiplexed DPSK downstream signals is about 0.9 dB after transmission of 25 km SMF without any signal amplification or dispersion compensation module. On the other hand, at 10^{-9} BER, the average received power for four multiplexed OOK upstream signals is -35.065 dBm over the transmission of 25 km SMF without any signal amplification or dispersion compensation. From Fig.8, it is also evident that this scheme improves the upstream power penalty significantly relative to downstream signal as reported in our previous work[5].

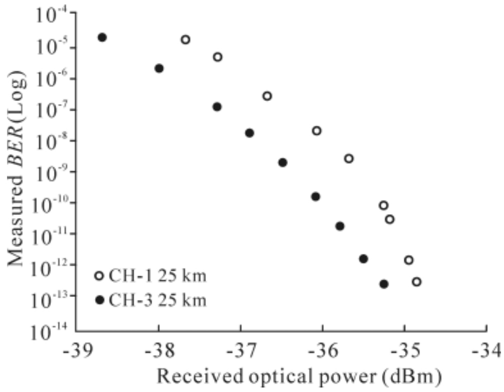


Fig.7 BERs for uplink channel-1 and channel-3 for 25 km transmission

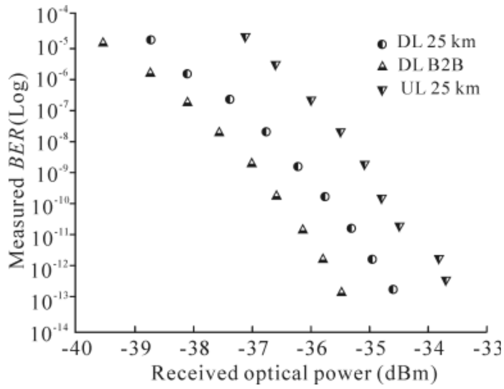
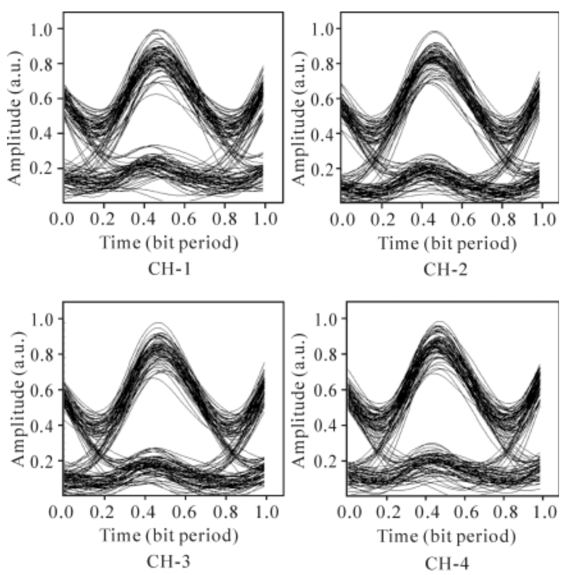


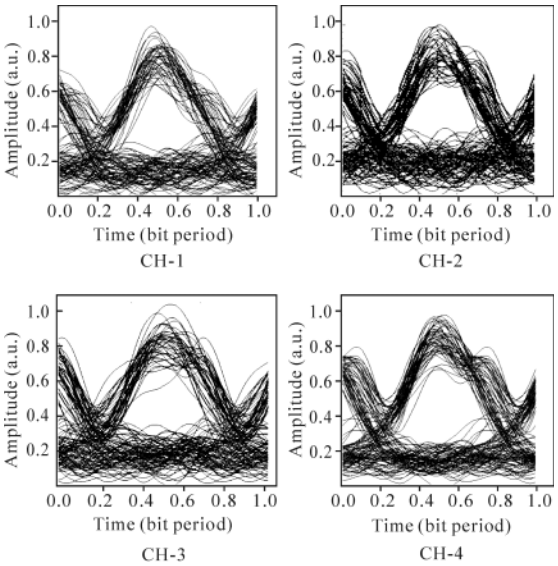
Fig.8 Average BERs for DL 25 km, DL B2B and UL 25 km transmissions

Fig.9 shows the eye diagrams for all the four multiplexed RZ-DPSK downlink and OOK uplink channels at a BER of 10^{-9}. The eyes are very wide and open.

A 10 Gbit/s full duplex wavelength division multiplexed passive optical network (WDM-PON) system is simulated



(a) Downlink 25 km RZ-DPSK channels



(b) Uplink 25 km OOK channels

Fig.9 Eye diagrams of all four multiplexed downlink RZ-DPSK and uplink OOK channels

and analyzed in this paper. A CML along with RZ-DPSK modulation format is used for downlink. In the ONU, the downlink signal is remodulated for the uplink with symmetric data rate of 10 Gbit/s per channel. An error-free colorless transmission over a distance of 25 km with lower BER is achieved. Hence a cost-efficient and reduced-circuitry network design is implemented on a single feeder fiber with elimination of differential encoder and one external modulator. The scheme also shows improved receiver sensitivity for upstream transmission relative to downstream.

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