An AWG-based 10 Gbit/s colorless WDM-PON system using a chirp-managed directly modulated laser*

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We propose an arrayed waveguide grating (AWG)-based 10 Gbit/s per channel full duplex wavelength division multiplexing passive optical network (WDM-PON). A chirp managed directly modulated laser with return-to-zero (RZ) differential phase shift keying (DPSK) modulation technique is utilized for downlink (DL) direction, and then the downlink signal is re-modulated for the uplink (UL) direction using intensity modulation technique with the data rate of 10 Gbit/s per channel. A successful WDM-PON transmission operation with the data rate of 10 Gbit/s per channel over a distance of 25 km without any optical amplification or dispersion compensation is demonstrated with low power penalty.

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In the near future, the requirement of bandwidth may reach gigabit per second per subscriber in multimedia, graphic-rich services, etc[1-5]. The next generation of access technology for last mile section is required to provide higher bandwidth at lower cost. The access network architectures based on centralized light source at optical line terminal (OLT) and re-modulation of downstream wavelength received at optical network unit (ONU) are considered as the optimum solutions[6-8].

One method for the cost reduction is the elimination of dispersion compensating modules (DCM)[9]. By increasing transmission distances, the dispersion of single-mode fiber (SMF) is enhanced, and bit error rates (BERs) are magnified. Therefore, dispersion tolerant transmitters are also important for metro and regional networks.

To further reduce the cost in the access network, chirp-managed lasers (CMLs) are considered as efficient alternatives compared with the transmitters with external modulators, because the external modulators are expensive and have larger size (>45 mm) and higher power consumption (⩾5 V)[10-12].

CML is a kind of inexpensive and dispersion-tolerant transmitter. The most important feature of CML is its large tolerance to fiber dispersion. The CMLs can realize transmission without dispersion compensation over 200 km[10]. It provides high optical output power and long transmission distances in SMF[12]. It has characteristics of lower cost, compact size, lower power consumption and higher output power compared with other external transmitters, such as electro-absorption modulator (EAM) and Mach-Zehnder modulator (MZM)[2]. Therefore, CML is a better choice for wavelength division multiplexing passive optical network (WDM-PON).

In this paper, we use CML as a transmitter in arrayed waveguide gratings (AWG)-based 10 Gbit/s colorless WDM-PON using the re-modulation and establish fault-free communication without any power amplifier or dispersion compensation management.

The CML is a simple combination of directly modulated laser (DML) and optical filter, also called as optical spectrum reshaper (OSR). A wavelength locker is formed at the OSR in conjunction with two photodiodes of PD1 and PD2,

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which can monitor the optical power from the distributed feedback (DFB) and the reflection from the OSR, respectively. A locking circuit adjusts the laser temperature, hence its wavelength, to keep the ratio of PD2/PD1constant[13].

Fig.1 shows the principle of CML. When DML is biased near threshold and modulated to achieve the extinction ratio (ER) of 8−10 dB, the transient chirp is enhanced[10]. A standard DFB laser in CML is therefore biased at threshold of ~5×, and directly modulated by the digital data. It results in the intensity modulation with low ER (~ 1−2 dB), high output power, wider modulation bandwidth, low timing jitter and suppression of transient chirp.

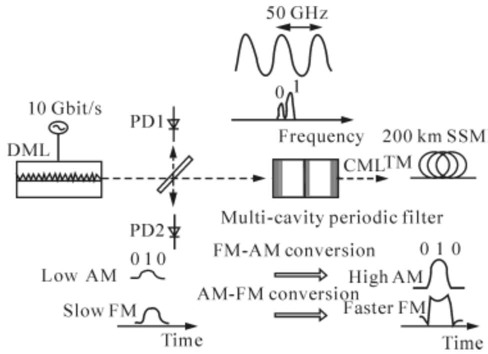

Fig.1 Working principle of CML

For a data rate of 10 Gbit/s, 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 the blue shift of 5 GHz 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, simultaneously suppress the transient chirp, and shape it into the top-flatted chirp. The frequency modulation (FM) to amplitude modulation (AM) conversion increases ER to more than 10 dB at the output of the OSR[9,10-13] .

The frequency profile reshaping in the OSR is caused by the action of filter slope. Consider an optical electric field with amplitude envelope of $A(t)$ and adiabatic chirp passing through an OSR with a linear transmission edge function of $T(\omega) = a + b(\omega - \omega_0)$, where b is the slope, and a is transmission at center frequency. According to Fourier theory, the time derivative of the input signal induced by linear filter is added to itself with a π/2 phase shift. The frequency profile of the output field $\Delta\omega_{out}$ is modified because of the π/2 phase shift, and can be measured approximately as

$$\Delta\omega_{out}(t) = \Delta\omega_{AD}(t) - \frac{d}{dt}\tan^{-1}\left(\frac{bA'(t)}{A(t)(a + b\Delta\omega_{AD}(t))}\right), \quad (1)$$

where $\Delta\omega_{AD}$ is 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 changes with the slope of the OSR b, significantly reduces the rise and fall times, and creates the flat-topped chirp profile across each pulse [10].

The proposed scheme of 10 Gbit/s return-to-zero (RZ)-DPSK transmission system using CML is shown in Fig.2. The transmitter consists of an inverse-return-to-zero (IRZ) driver, a CML, and a pulse carver. The IRZ shaped data shown in Fig.2 with a duty cycle of 33% is generated via a simulated logic NAND gate, before being used to directly modulate the CML. The driving voltage V_{pp} is adjusted to induce adiabatic chirp of $\Delta f = 1/T$. The adiabatic chirp generates the phase shift during low level period[14,15], which can be written as

$$\Delta\varphi = 2\pi\int_0^{T/2}\Delta f(t)\,dt = 2\pi\times 1/T\times T/2 = \pi\,. \quad (2)$$

Here, the chirp 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 or PM is needed.

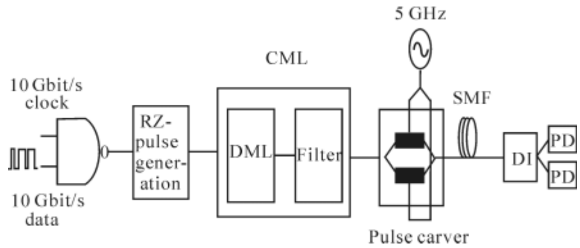

Fig.2 Simulated scheme of 10 Gbit/s RZ-DPSK transmission system using CML

Fig.3 shows the simulation setup using CML for the proposed AWG-based WDM-PON system with a centralized light source for downlink (DL) and uplink (UL) directions. The transmission performance of the proposed WDM-PON with four 10 Gbit/s DL channels and four 10 Gbit/s UL channels over 25 km (feeder + distribution) fiber is evaluated by this simulation. Four continuous light waves with launch power of 0 dBm 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, keeping the channel spacing of 60 Hz. Bessel optical filters are used as OSRs. For each channel, 10 Gbit/s (2^7-1) pseudo random binary sequence (PRBS) data and 10 Gbit/s clock signal are operated by an NAND gate for giving IRZ data to modulate CML. The output is then fed to the Mach-Zehnder modulator (MZM), driven by a 5 GHz clock pulse for generating RZ pulses with duty cycle of ~33%.

The four produced RZ-DPSK signals are then multiplexed by a 4 × 1 AWG multiplexer (MUX) on 60 GHz channel grid, and transmitted over a 25 km single-mode feeder fiber. The DL multiplexed signal is first de-multiplexed using a 1×4 AWG de-multiplexer (DEMUX), and then transmitted to the corresponding ONU. At the receiving ONU, a 3 dB optical splitter is used for tapping half of the optical power for the downstream receiver. A Mach-Zehnder delay interferometer (MZDI) is used for converting the phase-modulated DPSK signal to an intensity-modulated signal before it is received by a regular direct detection PIN receiver. The other half of the DPSK signal is injected into the Mach-Zehnder intensity modulator (IM) driven by 10 Gbit/s UL data with RZ modulation format. The re-modulated RZ on-off keying (OOK) UL signal is transmitted back to the OLT through another 25 km SMF-28 before being received by a direct detection PIN receiver. The PRBS length of the UL data is set to 2^7-1. The 4th order Bessel low-pass electrical filter (LPF) with 3 dB bandwidth of 7.5 GHz is used at RZ OOK receiver for 10 Gbit/s UL data.

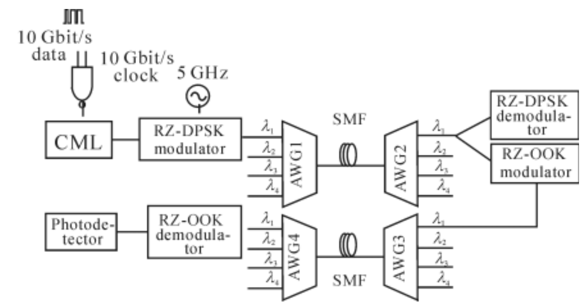

Fig.3 Simulated scheme of the proposed AWG-based 10 Gbit/s RZ-DPSK DL & OOK-based UL WDM-PON system using CML

The same wavelengths are used for DL and UL transmission, and a dual fiber transmission structure between OLT and ONU is used to prevent transmission performance limited because of Rayleigh back scattering reflections. In the simulation, PIN photodetector receivers are used at DL side, and avalanche photodiode (APD) at UL side.

CMLs are dispersion tolerant compared with the other transmitters using external modulators. The sensitivities of receiver are measured at BER of 10^{-9} after various lengths of standard SMF (SSMF) transmission for CML and phase modulator (PM-MZM), which is shown in Fig.4.

The BERs as a function of received optical power for RZ-DPSK downlink and OOK uplink channels before and after 25 km transmission are illustrated in Figs.5 and 6, respectively.

The individual power penalties measured at BER of 10^{-9} for DPSK downlink channels (1, 2, 3 and 4) are 0.16 dB, 0.66 dB, 0.7 dB and 1.3 dB, respectively for the distance of 25

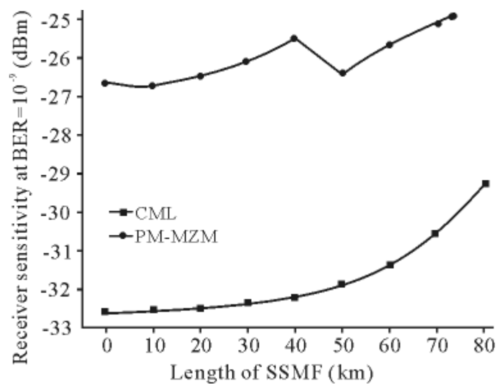

Fig.4 Measured sensitivities of receiver for CML and PM-based RZ-DPSK signals

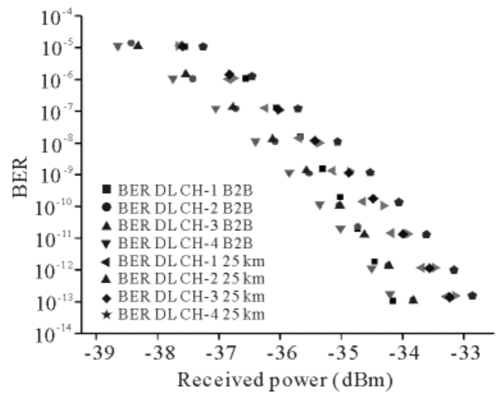

Fig.5 BER as a function of received optical power for four channels of DPSK downlink data

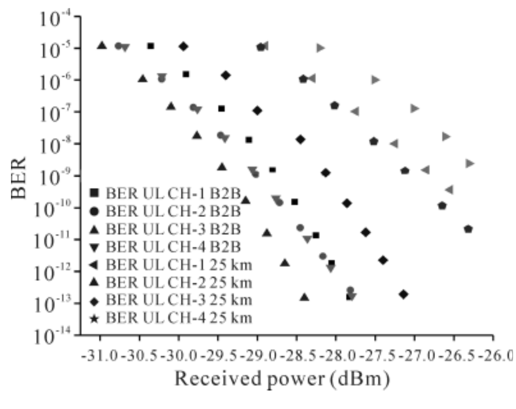

Fig.6 BER as a function of received optical power for four channels of OOK uplink data

km. Similarly, for the same distance, the measured power penalties at BER of 10^{-9} for the OOK uplink channels (1, 2, 3 and 4) are 1.95 dB, 2.7 dB, 1.3 dB and 1.94 dB, respectively.

At the BER of 10^{-9}, the average power penalty of all the four multiplexed DPSK downstream signals is about 0.7 dB after the transmission of 25 km in an SMF without any signal amplification or dispersion compensation. On the other hand, at the BER of 10^{-9}, the average power penalty of the four multiplexed OOK upstream signals is less than 2 dB after the corresponding upstream transmitted over a 25 km SMF without any signal amplification or dispersion compensation.

An AWG-based 10 Gbit/s full duplex WDM-PON system is simulated and analyzed by utilizing a CML for RZ-DPSK modulation technique at downlink direction. In the ONU, the downlink signal is re-modulated by IM for the uplink direction with a data rate of 10 Gbit/s per channel. A fault-free and low-cost colorless WDM-PON full duplex transmission operation for a data rate of 10 Gbit/s per channel over a distance of 25 km is achieved without any signal amplification on the fiber or dispersion compensation.

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