20-Gbps low cost WDM-OFDM-PON downstream transmission with tunable filter and linear APD module

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This letter presents a low cost solution for wavelength division multiplexed orthogonal frequency division multiplexed passive optical network (WDM-OFDM-PON) with widely tunable optical filter and linear small form-factor pluggable (SFP) module. With 9-nm tunable range from 1551 to 1560 nm, the tunable filter can support up to 10-channel 100-GHz spacing WDM PON system. A linear avalanche photodiode (APD) based SFP+ module is designed for optical OFDM signal demodulation, which can provide better receiver performance compared with limiting APD module. Experimental results show that ∼34 dB power budget can be achieved in 4×5-Gbps WDM-OFDM-PON system, which can satisfy the transmission requirements of next generation PON system.

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Fronthaul is the connectivity segment between the multiple distributed remote radio heads (RRHs) and the centralized base band unit (BBU) in long term evolution/long term evolution advanced (LTE/LTE-A) cloud radio access network (C-RAN). With the rapid growth of mobile traffic, fronthaul need an optical fiber infrastructure with high bit rate and long reach capability[1]. Passive optical network (PON) is considered as a promising solution for the fronthaul network.

Unlike long-haul optical communication system,optical access network is cost sensitive. For example, intensity modulation and direct-detection (IMDD) other than external modulation and coherent detection is widely adopted in optical access network due to its simplicity and low cost.

Wavelength division multiplexed (WDM) technology, which uses multiple optical wavelengths to simultaneously transmit broadband digital signal via one single optical fiber, is a possible enabling solution to meet high speed requirement in access network[2−6]. In WDM-based PON system with N wavelengths, every optical wavelength carries $1/N$ of data and optical components occupies $1/N$ bandwidth compared with PON system with a single wavelength. However, colorless optical network unit (ONU) is preferred in WDM-based PON system. It adopts the same physical unit irrespective of the downstream wavelength, which benefits from massive production and makes maintenance easier.

Recently, other studies are considering new architectures of PONs based on orthogonal frequency division multiplexing (OFDM) modulation[6−8]. By using high order quadrature amplitude modulation (QAM),OFDM signals can effectively achieve high spectral efficiency and ultimately lower the bandwidth requirement of optical components, which is beneficial in reducing cost in optical access network. However, OFDM signal is very sensitive to nonlinearity in transmission system. Traditional optical moduleforon-off keying (OOK) based PON system need to be modified to meet the requirement of OFDM signal and improve whole system capacity and performance.

In this letter, we present a low cost solution for WDM-OFDM-PON with widely tunable filter and linear avalanche photodiode (APD) module as follows. Firstly, we introduces theWDM-OFDM-PON architecture and discusses key technologies to meet system requirements. Secondly, we demonstrates 4×5-Gb/s WDM-OFDM-PON downstream transmission with 34 dB power budget.

Figure 1 illustrates the proposed WDM-OFDM-PON system. At the downstream side, electrical OFDM signals are generated in optical line terminal (OLT) by arbitrary waveform generator (AWG; AWG7122 Tektronix, USA) using the Matlab programs. Then, OFDM signals are fed to directly modulate multiple 2.7 GHz

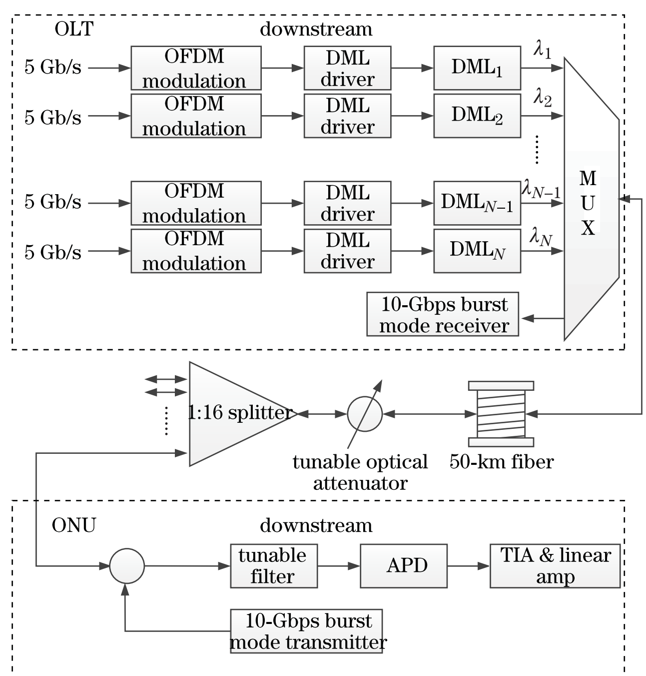

Fig. 1. Proposed WDM-OFDM-PON system architecture.

distributed feedback laser (DFB) lasers with 100-GHz spacing. After the WDM multiplexer, the downstream optical OFDM signals are distributed to ONUs through the optical distribution network (ODN) which consists of 50 km single mode fiber and one or more power splitter. A tunable attenuator is also included to evaluate sensitivity of ONU. At each ONU, an electric controlling tunable filter in the optical receiver is used as the downstream wavelength selection. Then, each ONU can select a single wavelength to demodulate the data from OLT, which greatly reduces the optical receiver bandwidth and lowers the ONU cost. At the upstream side, commercial 10 G burst-mode OOK transmitter and receiver are adopted in ONUs and OLT respectively to meet colorless requirement in WDM-based PON system. So, the proposed WDM-OFDM-PON can support $N\times 5$ Gbps downstream and 10-Gbps upstream capacity, while N means the number of wavelengths used for downstream transmission.

Due to the transmission performance of 10-Gbps burst-mode OOK transceiver is verified in 10 G symmetrical ethernet passive optical network (EPON) system, this letter focuses on studying downstream transmission performance of the proposed WDM-OFDM-PON.

As mentioned before, colorless ONU is preferred in WDM-based PON system. At the ONU side, we designed a widely tunable optical filter with a single thin film filter. A thin film bandpass filter with center wavelength λ_0 is designed for normal light incidence condition. Changing the angle of incoming light incidence from zero to θ, the central wavelength of the filter will decrease, which results in partial tunability. Considering the center wavelength of the thin film filter at normal incidence is λ_0, and then the center wavelength of the tunable filter at incidence angle θ_0 is

$$\lambda_c = \lambda_0\sqrt{1-\frac{\sin^2\theta}{n^2}}, \tag{1}$$

where n is the filter effective index of refraction. In our designed widely tunable optical filter, we integrated a thin film filter with a stepping motor, which is electrical controlled to rotate the thin film filter to alter injection angle of light entering the filter, resulting in center wavelength shift of optical filter. Furthermore, we designed a protocol to control the stepping motor, which is possible to be implemented in media access control (MAC) layer to allow OLT adjust ONU receiver's center wavelength.

Figure 2 shows the superposed optical spectrum of tunable filter injected by erbium doped fiber amplifier (EDFA) amplified spontaneous emission (ASE) noise. It is clear shown that the tunable optical filter is a Gaussian shaping bandpass filter with 3-dB bandwidth of 0.5 nm and center wavelength of tunable optical filter can be shifted from 1551 to 1560 nm with about 4–5 dB insert loss.

Figure 3 shows OLT transmitter spectrum and ONU filtered spectrum. Injected by multiple 100 GHz spacing DFB lasers, it is clearly shown that adjacent channel isolation of the optical filter is greater than 40 dB. Using this tunable optical filter, ONU can be adjusted electrically to select a single downstream wavelength.

OFDM signal can effectively achieve high spectral efficiency and ultimately lower the bandwidth requirement of optical components due to its adoption to high order QAM and the orthogonal properties among its sub-carriers. For example, 10-Gbps OFDM baseband signal with 16-QAM only occupy 10 G/4=2.5 GHz electrical bandwidth. With the advance in digital-signal-processing (DSP) technology, OFDM modulation and demodulation can be implemented in commercial digital integrated circuits, such as Xilinx Virtex series field programmable gate array (FPGA)[9]. However, OFDM signal performance can be greatly deteriorated by nonlinearity in transmission system. In transmitter, OFDM signal suffers much nonlinearity when using discrete mode lasers, which can be reduced by optical injection[10]. While using single mode laser to carry OFDM signal, the nonlinearity is mainly attributed to laser chirp effect. In our experiment, single mode lasers are adopted and the laser chirp effect is weak due to low bandwidth of OFDM signal.Meanwhile, optical receivers adopted in ONU side may introduce great nonlinearity to OFDM signal. Generally, optical modules in ONU are composed with APD, transimpedance amplifier and limiting amplifier. Limiting amplifier can amplify OOK signal efficiently with high nonlinearity, which is not suited for amplifying OFDM signal. In our designed linear APD SFP+ module, a linear amplifier is used to replace limiting amplifier to construct linear optical module.

A single tone test shows that linear APD module and limiting APD module has 40 and 30 dB linear amplification range respectively. Tow tone test shows that linear APD module can achieve more than 25-dB third-order intermodulation distortion (IMD3) while limiting APD module by Finisar have less than 10-dB

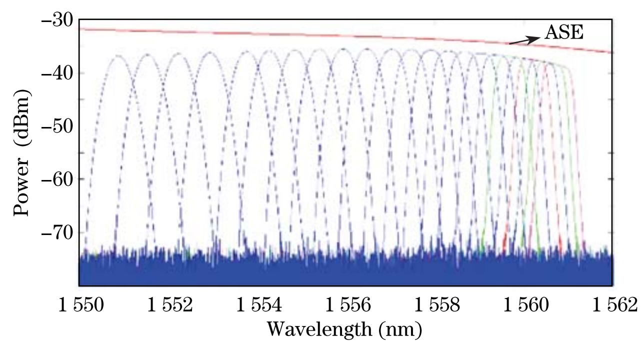

Fig. 2. (Color online) Superposed optical spectrum of tunable filter injected by EDFA ASE noise.

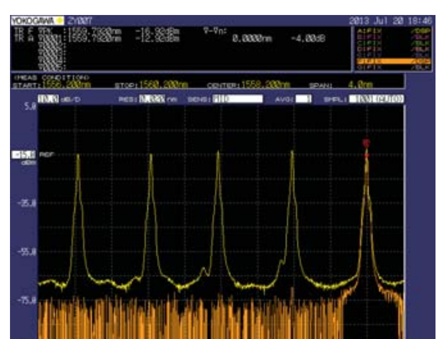

Fig. 3. (Color online) OLT transmitter spectrum and ONU filtered spectrum.

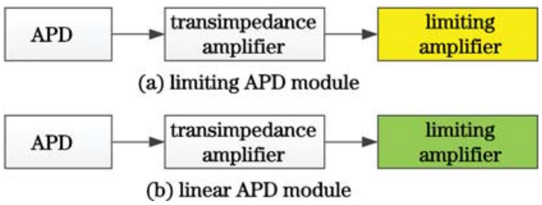

Fig. 4. (Color online)Architecture of limiting APD module and linear APD module.

Fig. 5. (Color online) WDM-OFDM-PON system test bed.

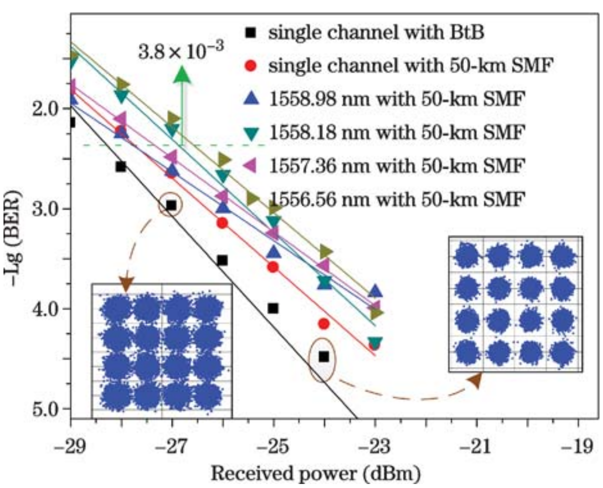

Fig. 6. (Color online) Transmission performance of downstream at 5 Gb/s.

Table 1. Performance of Linear APD Module and Limiting APD Module

Module	Linear Amplification Range	IMD3
Linear APD Module	40	> 25
Limiting APD Module	30	< 15

IMD3. Considering 16-QAM need 16-dB signal-to-noise ratio (SNR) to guarantee bit error rate (BER) of 10^{-3}[11], our proposed linear APD module is more suitable to receive OFDM signal with 16-QAM than limiting APD module.

In our experiment test bed illustrated in Fig. 5, we uses four 2.7 GHz bandwidth DFB laser with 100 GHz spacing to demonstrate proposed WDM-OFDM-PON system.

In the OLT side, electrical OFDM signals, which use the 16-QAM modulation with a fast Fourier transform (FFT) size of 512 and cyclic prefix (CP) size of 32, are generated by arbitrary waveform generator (AWG; AWG7122, Tektronix, USA) using the Matlab programs. The sampling rate and digital to analog converter (DAC) resolution of AWG are 10 GS/s and 8 bits respectively. Then, four same OFDM signals are fed to directly modulate four 2.7-GHz DFB lasers with 100-GHz spacing respectively. Each DFB laser has more than 7-dB output power. After the WDM multiplexer, the downstream optical OFDM signals are distributed to ONUs through the ODN which consists of 50-km single mode fiber and a 1:16 power splitter. A tunable attenuator is also included to evaluate sensitivity of ONU. At each ONU, our designed tunable filter is placed before the linear APD module to select a single wavelength to demodulate the data from OLT. Figure 6 shows the downstream BERs for all the channels in the back-to-back, 50-km single mode fiber conditions. Experimental results show that 34-dB power budget can be achieved at forward error correction (FEC) threshold (BER=3.8×10^{-3})[12], each channel can achieve about 34-dB power budget.

In this letter, we only demonstrate a 4×5-Gbps WDM-OFDM-PON system due to channel limitation of signal generator. For optical filter has more than 40-dB adjacent channel isolation,the system can be easily extended to 8×5-Gbps WDM-OFDM-PON system without any system performance degradation.

In conclusion, we investigate WDM-OFDM-PON system downstream transmission performance using widely tunable optical filter and linear APD module. ONU uses a tunable optical filter to select a specific wavelength to demodulate signal, and then uses linear APD module other than limiting APD module to extend OFDM signal receiver's dynamic range. An experiment using our proposed tunable optical filter and linear APD module is performed to verify its feasibility, experiment results show that ∼34 dB power budget can be achieved in proposed WDM-OFDM-PON system, which can satisfy the fronthaul requirements.

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