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300 Gb/s IM/DD based SDM-WDM-PON with laserless ONUs

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Abstract: A low-cost, high-speed SDM-WDM-PON architecture is proposed by using a multi-core fiber (MCF) and intensity modulation/directly detection (IM/DD). One of the MCF cores is used for sending laser sources from optical line terminal (OLT) to optical network unit (ONU), thus facilitating laserless and colorless ONUs, and providing ease of network management and maintenance. In addition, the wavelengths of the ONUs are controlled on the OLT side, which also enables flexible optical networks. Thanks to the low inter-core crosstalk of a MCF, downstream (DS) and upstream (US) signals are transmitted independently in different cores of the MCF, not only increasing the aggregated capacity but also avoiding the Rayleigh backscattering noise. Finally, a proof-of-principle experiment is performed by using a 7-core fiber, achieving 300 /120 Gb/s aggregated capacity for DS and US (3 × cores, 4 × wavelengths, 25/10 Gb/s per wavelength), respectively.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications; (060.4230) Multiplexing.

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1. Introduction

With the advent of a variety of broad-band internet services such as cloud computing, high-definition (HD)/4K TV, business IP traffic and social networking, there has been an exponential increase of bandwidth demand in access networks [1,2]. Researchers are investigating on high-speed passive optical networks (PONs), and standards of PONs have been updated by both Full Service Access Network (FSAN) and IEEE in recent years [3, 4]. Various kinds of PON technologies have been demonstrated for increasing the bandwidth of access networks. Time-division multiplexing PON (TDM-PON) is initially proposed and has been extensively deployed worldwide, but it has a limited number of end users and transmission reach due to the low power budget. By using wavelength-division multiplexing (WDM), a hybrid WDM-TDM-PON has been demonstrated, which can stack multiple TDM-PONs [5,6]. In addition, many other techniques have also been proposed for a PON system, such as orthogonal frequency division multiplexing (OFDM), ultra-dense WDM and coherent detection [7–11]. In order to further increase the capacity of a PON system, space-division multiplexing (SDM) has been introduced to utilize multiple spatial channels for data transmission through a single fiber [12–17]. On the other hand, optical network unit (ONU) remains highly cost-sensitive in the whole access network, since it directly serves end users who need to pay installation and maintenance cost [18, 19], and a cost-effective ONU is of high importance in the access networks.

In this paper, we propose a cost-effective, high-speed SDM-WDM-PON scheme using intensity modulation and direct detection (IM/DD) with a low-crosstalk multi-core fiber (MCF) without any digital signal processing (DSP). A 7-core fiber is used for the proof-of-concept demonstration, where three outer cores are used for upstream (US) and the other three outer cores are used for downstream (DS). The inner core in the center is used to transmit light source originated from optical line terminal (OLT) to ONU, thus achieving laserless and colorless ONUs. Finally, an aggregated capacity of 300 Gb/s for DS and 120 Gb/s for US are achieved in the SDM-WDM-PON, which may be a good candidate for future broad-band access networks and mobile backhauls such as 5G mobile networks.

2. Proposed SDM-WDM-PON architecture

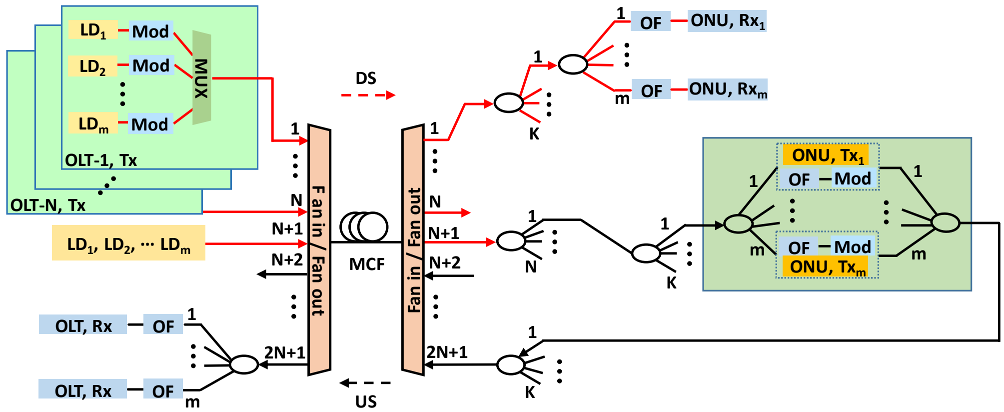

Fig. 1. Proposed SDM-WDM-PON architecture. (LD: laser diode, Mod: modulator, MCF: multi-core fiber, OF: optical filter, Mux: multiplexer, OLT: optical line terminal, ONU: optical network unit, Tx: transmitter, Rx: receiver, DS: downstream, US: upstream.)

The proposed SDM-WDM-PON architecture is shown in Fig. 1. In each subset OLT, there are m transmitters at different wavelengths (λ_1 to λ_m), which send signals to one of the MCF cores. There are totally N OLTs (from OLT-1 to OLT-N), which represents the number of cores for the DS transmission and can share the laser sources. Only m lasers are needed and each laser output is split into N times for each OLT. By sharing the laser source, the cost on the OLT side will be reduced. The signals from the OLTs are multiplexed in wavelength by WDM multiplexers (MUXs) and then launched into the MCF through a fan-in device. After the MCF transmission, the signals are first SDM demultiplexed to N single mode fibers (SMFs) by a fan-out device and the signals in each SMF are split by a factor of K and sent to the ONUs. In each ONU, there are N SMFs for the DS link, which could be packed as a fiber ribbon for ease of management. In each SMF, there are m signals at the wavelengths from λ_1 to λ_m, which are WDM demultiplexed by a coupler and filters and then detected by photo-detectors. Since the WDM light sources are transmitted through one of the MCF, no lasers are needed on the ONU side, which can facilitate laserless and colorless ONUs and ease of network management and maintenance. It will also make the whole networks more flexible since the wavelengths of the ONUs can be controlled on the OLT side. On the other hand, the WDM light sources pass through the 1 × K power splitter and the 1 × N power splitter in order to be distributed for ONUs, so that the increased splitting loss will reduce the power budget. In order to support more ONUs and have enough power budget, an optical amplifier is needed to compensate the splitting loss. Actually, a multi-core fiber amplifier would be desirable solution since it can amplify not only the transmitted light sources but also DS and US signals, resulting in improved power budget with shared cost for all the ONUs [20]. Since the DS and US signals are transmitted through different cores of the MCF with negligible inter-core crosstalk, Rayleigh backscattering noise can be avoided making it easier to split DS and US signals.

3. Experimental setup

In order to verify the feasibility of the proposed SDM-WDM-PON scheme, a proof-of-concept experiment is performed and the experimental setup is shown in Fig. 2. The WDM source consists of four wavelengths (from 1547.88 nm to 1552.68 nm) with a 200 GHz channel spacing, which are emitted from distributed feedback (DFB) lasers and split into two parts. One part is on-off keying (OOK) modulated using an intensity modulator with 25 Gb/s pseudo-random binary sequence (PRBS, 2^{31}-1). The generated DS signals are amplified, split

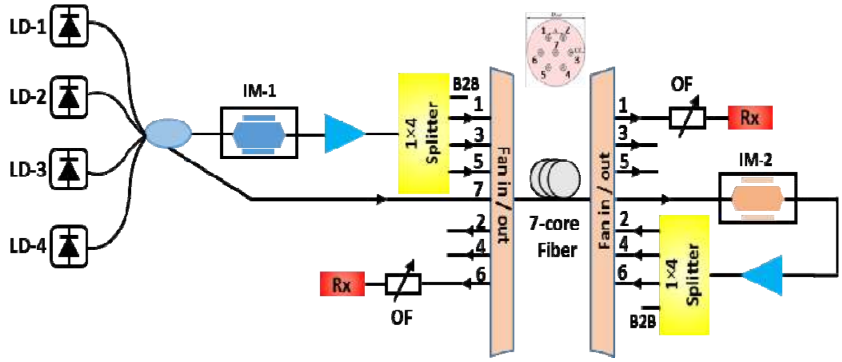

Fig. 2. Experimental setup for SDM-WDM-PON system. (IM: intensity modulator, B2B: back to back.)

and then launched into three outer cores (core 1, core 3 and core 5) of the 7-core fiber through the fan-in device. After the 7-core fiber transmission, the signals are SDM demultiplexed by the fan-out device and launched into three individual SMFs. The DS signals are filtered by an optical filter (OF) and finally detected by a receiver. The receiver consists of a tunable attenuator, an optical pre-amplifier and a 25 Gb/s photo-detector. The parameters of the 7-core fiber used in the experiment are as follows: the diameter and pitch of the core are 9 μm, 46.8 μm respectively, and the cladding diameter is 186.5 μm. For each core at 1550 nm, the dispersion and dispersion slope are around 16.5 ps/km-nm and 0.06 ps/km-nm^2, respectively [21]. The inter-core crosstalk has been measured by launching the light in the central core and measuring the optical power for each of the 6 outer cores. The range of the crosstalk values for 6 outer cores is in between –40 and –50 dB. The core-averaged inter-core crosstalk is ~-45 dB over 2-km at 1550 nm [21]. Fan-in/ Fan-out devices based on a fiber are designed to match the core spacing and mode field of the 7-core fiber [22]. The measured insertion losses of the fan-in/fan-out are 1.45 dB, 2.25 dB, 2.5 dB, 3.05 dB, 1.7 dB, 2.85 dB and 2.3 dB, respectively, for core 1 to core 7. Note that by using free-space device, the fan-in/fan-out loss can be reduced to be ~1dB. Therefore, the combining loss is significantly reduced compared to the existing TDM- PONs that combine signals from the ONUs using couplers. Although the MCF in the experiment has a limited length of 2 km, it's expected to achieve much longer transmission distance using the proposed scheme, since the MCF exhibits very low inter-core crosstalk. The main limitation for long-distance transmission is the dispersion. Since the dispersion of the MCF is similar as that of a standard single mode fiber (SSMF), the expected transmission distance and the solutions are also similar as that of the SSMF, such as using dispersion compensation or using more advanced modulation formats.

The other part of the WDM source is launched into the inner core (core 7) of the 7-core fiber through the fan-in device. After the 7-core fiber transmission, the WDM source is OOK modulated by an intensity modulator with 10 Gb/s PRBS of 2^{31}-1, amplified by an EDFA, combined by a coupler and finally sent back to the OLT through the other three outer cores (core 2, core 4, core 6) of the 7-core fiber as US signals. The spectra of both DS and US signals after transmission are shown in Fig. 3. On the OLT side, the US signals are filtered by OFs, and detected by a receiver.

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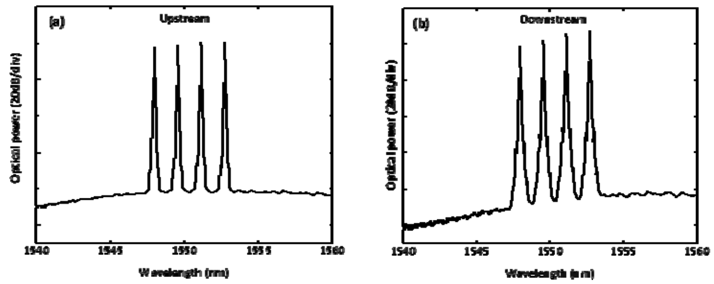

Fig. 3. Optical spectra after transmission for (a) US signals, (b) DS signals.

4. Experimental results

We first evaluate the DS transmission performance with 25 Gb/s signals per wavelength per core, as shown in Fig. 4. We can see that after the 2-km 7-core fiber transmission, the BER performance is almost same as the back-to-back (B2B) case and error-free performance (BER<10^{-9}) is achieved with a receiver sensitivity of around −33 dBm for all the signals of four wavelengths in three cores, indicating similar performances for all these channels. When the launched power is increased to 2 dBm per wavelength per core, no obvious BER degradation has been observed. Therefore, the power budget of ~32 dB is achieved taking into account ~3 dB maximum insertion loss of the fan-in/fan-out device.

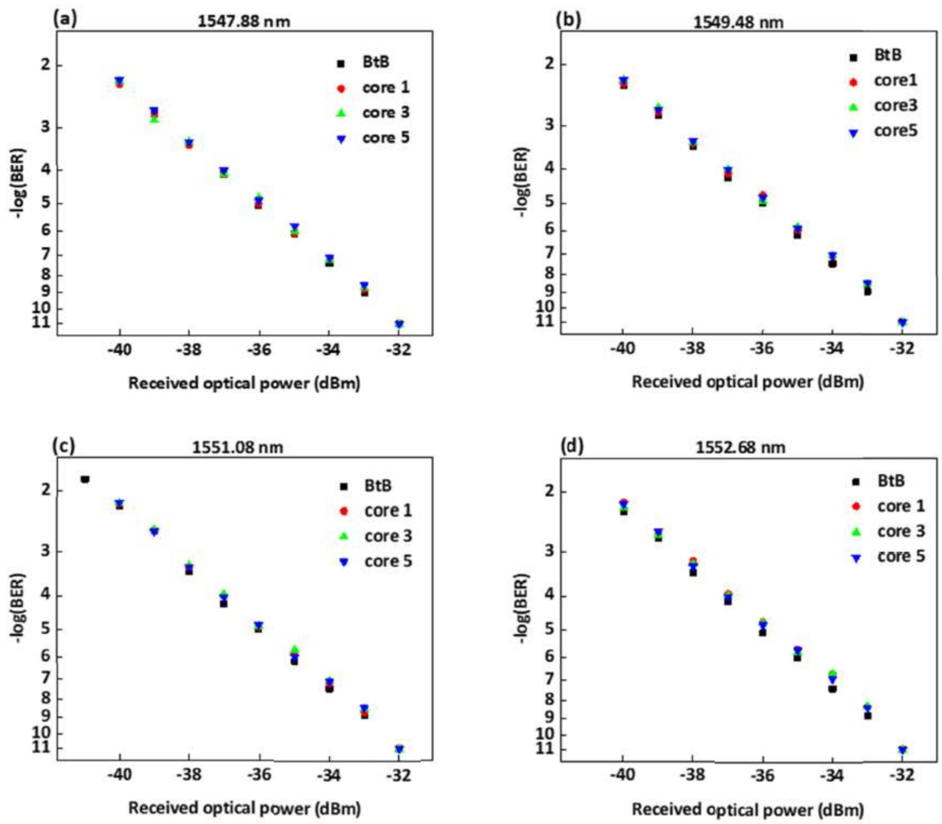

Fig. 4. Measured BER of the DS signals in 3 different cores (core 1, core 3, core 5) at the wavelength of (a) 1547.88 nm, (b) 1549.48 nm, (c) 1551.08 nm, (d) 1552.68 nm.

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Having confirmed that the performance for different wavelengths is almost same, only one wavelength at 1552.68 nm is measured for the 10 Gb/s US signals in order to evaluate the uplink transmission performance. Similar to the DS transmission, the BERs are measured after the 7-core fiber transmission and the results are plotted in Fig. 5. After the 2-km 7-core fiber transmission, the BER performance is almost same as the B2B case, which also confirms the good transmission performance for the US signals.

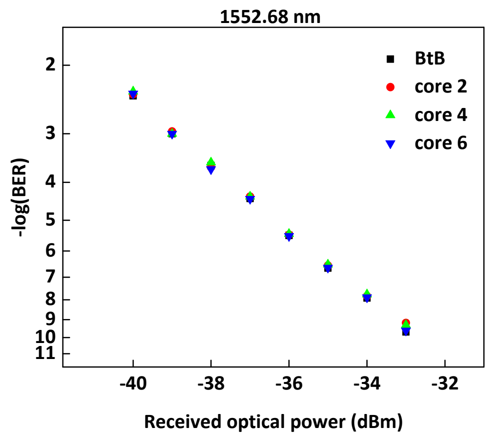

Fig. 5. Measured BER of the US signal in 3 different cores (core 2, core 4, core 6) at the wavelength of 1552.68 nm.

5. Conclusion

An SDM-WDM-PON scheme has been proposed and experimentally verified using a 7-core fiber and IM/DD without DSP. The DS and US signals are distributed in different outer cores of the 7-core fiber, resulting in bidirectional operation. The laser sources originated from OLT are transmitted to ONU through the inner core of the 7-core fiber, thus achieving a laserless and colorless ONU and facilitating cost reduction and ease of wavelength management. Transmission capacity of 300/120 Gb/s for DS/US (4 wavelengths, 3 cores, 25/10 Gb/s per wavelength) has been successfully achieved, which could be a promising candidate for future large-capacity access networks.

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