IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 9, Number 2, April 2017

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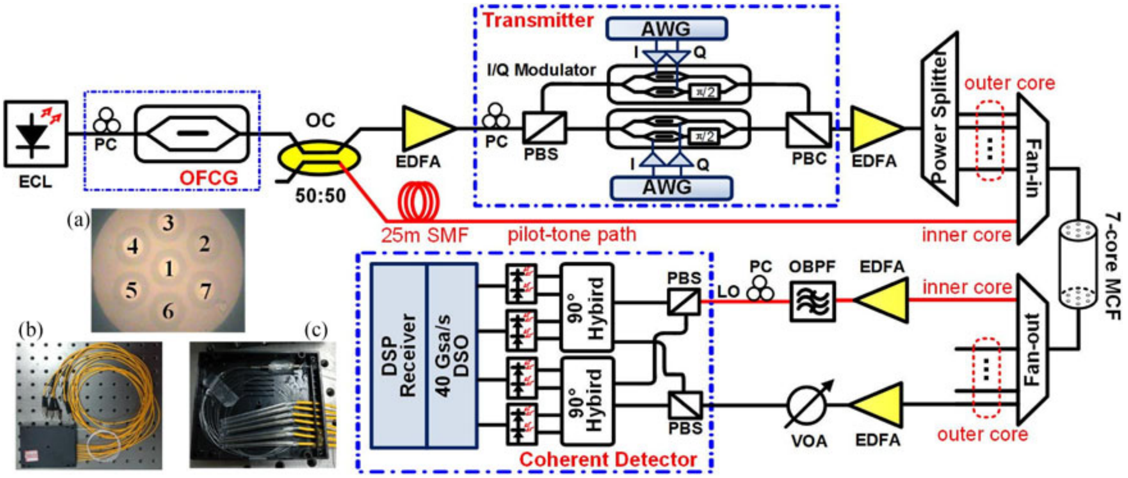

DOI: 10.1109/JPHOT.2017.2677503
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Experimental Demonstration of Ultra-Dense WDM-PON With Seven-Core MCF-Enabled Self-Homodyne Coherent Detection

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DOI:10.1109/JPHOT.2017.2677503

Manuscript received January 18, 2017; revised February 17, 2017; accepted February 28, 2017. Date of publication April 7, 2017; date of current version April 18, 2017. This work was supported in part by the National Natural Science Foundation of China under Grant 61331010, in part by the 863 High Technology Plan of China (2015AA016904), and in part by the Program for New Century Excellent Talents in University (NCET-13-0235). Corresponding author: M. Tang (e-mail: tangming@mail.hust.edu.cn).

Abstract: We demonstrate an ultra-dense wavelength-division-multiplexing (UDWDM) passive optical network (PON) in a spatial-division-multiplexing system utilizing our home-made seven-core multicore fiber (MCF) with a self-homodyne coherent detection (SHCD) scheme. In the SHCD system, we transmit 12 channels of 40-Gb/s UDWDM-PON signals using polarization-division-multiplexing quadrature phase-shift keying (PDM-QPSK) with a 12-GHz grid through the six outer cores of the seven-core MCF with the central core used to transmit the pilot tone. An optical frequency comb generator is employed to supply the multi-carriers for cost saving. After 37-km low-crosstalk seven-core MCF long-reach transmission with compact fan-in/fan-out multiplexers, a large transmission capacity of 2.88 Tb/s and a power budget of 26 dB are obtained. At the optical network unit side, a narrow linewidth local oscillator laser is no longer necessary since SHCD is adopted in our system. The complexity of the digital signal processing procedure at the coherent receiver is also greatly reduced as the carrier phase recovery and carrier frequency offset estimation are not needed.

Index Terms: Multicore fiber, ultra-dense wavelength division multiplexing (UDWDM), passive optical network (PON), coherent detection, spatial division multiplexing, self-homodyne detection.

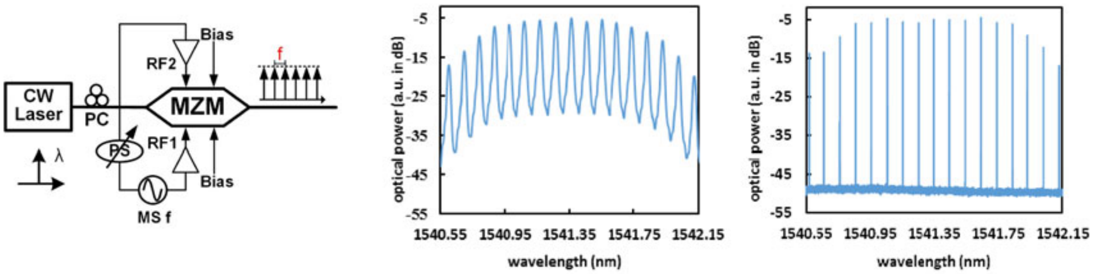
1. Introduction

With the ever-increasing demand for access capacity, ultra-dense wavelength division multiplexing (UDWDM) passive optical networks (PONs) have been intensively investigated in recent years [1]. UDWDM PON is envisioned to offer wavelength resource to each end user with higher and flexible data rates, better spectral efficiency and compatible with heterogeneous services [2], [3]. The optical coherent detection is employed in UDWDM PON system to ensure the high wavelength selectivity from a mass of wavelengths with close spacing. Additionally, the sufficient power budget afforded by optical coherent technologies with high receiver sensitivity enables the long-reach passive optical network (LR-PON) system without an optical amplifier. Optical coherent technologies have been used in UDWDM PON systems with different settings and frameworks [4]–[6]. A 10 Gbit/s LR-UDWDM-PON with 5 GHz channel spacing was investigated in [7]. As digital coherent receiver is employed, the system has a loss budget of 48.6 dB and the signal is transmitted through 120 km standard single mode fibers (SSMFs) without midspan repeaters. In [8], a 2.8 GHz channel spacing coherent UDWDM-PON with a loss budget of 50 dB is demonstrated. Intradyne coherent detection schemes have been used in these demonstrations of coherent UDWDM PONs, where a narrow linewidth laser is needed for the receiver as local oscillator (LO) and digital signal processing (DSP) is required for carrier phase recovery (CPR) and carrier frequency offset (CFO) estimation [9]. A major shortcoming of this architecture is the need for cost narrow linewidth LOs and complex DSP. Fiber nonlinearity and phase noise cancellation should also be considered for system performance.

One feasible way to mitigate the stringent requirement of narrow linewidth LO and complex DSP is to adopt self-homodyne coherent detection (SHCD) scheme. In SHCD system, since the signal and the LO for the receiver originate from the same laser, the CFO is no longer needed to be tracked. The inherent characteristic for phase noise cancellation in SHCD can also reduce the complexity of the DSP and power consumption compared to intradyne coherent detection. Previously, SHCD as one orthogonal polarization is used to transmit the signal and the other is used to transmit the pilot-tone has been demonstrated [10], [11], but one disadvantage of this architecture is that it halves the spectral efficiency (SE) compared to polarization division multiplexing (PDM) systems. Recent investigations in space division multiplexing (SDM) [12] have shown some advantages for SHCD system. First, only one SDM channel is embezzled to transmit the pilot-tone and the others can still be used for signals, so the SE penalty by using SHCD will be negligible with large count number of SDM channels. Second, in a SDM system, all the channels experience the same transmission condition and this is beneficial to reduce the path length variation between signal channels and the pilot-tone in SHCD system for eliminating the phase noise.

Recently, the SDM based SHCD optical communication has been proposed by using multicore fibers (MCFs) [13] and few mode fibers (FMFs) [14] as the physical media. In [15], a FMF based SHCD transmission system is experimentally demonstrated and one spatial mode is used to transmit the pilot-tone. In FMF transmission systems, it is difficult to control the modal interference and modal dispersion varies among the individual spatial modes. As an alternative, MCF has the advantage of the well-controlled inter-core crosstalk and the transmission property is almost the same as SSMF. The feasibility of SHCD in MCF based SDM system has been investigated. A SHCD system utilizing 19-core MCF and 16 WDM channels with 100 GHz channel spacing is proposed in [16]. One core is used to transmit the pilot-tone, while the other 18 cores are used to transmit the signals. Nevertheless, the transmission distance is quite limited (10.1 km) and the system performance is constrained by the large inter-core crosstalk in the 19-core MCF. Furthermore, the feasibility of UDWDM-PON transmission through MCF has yet to be proven.

In this paper, we propose to combine the advantages of SDM-based SHCD and UDWDM technologies together and demonstrate a 7-core low-crosstalk MCF based SDM-UDWDM PON with SHCD. To save the cost of the SDM-UDWDM system, the 12 UDWDM channels with 12 GHz channel spacing are provided by an optical frequency comb (OFC) generator rather than a mass of tunable lasers. The OFC generator is described in detail in the next section. After 37 km 7-core MCF transmission, we accomplish a capacity of 2.88 Tb/s (6 × 12 × 40 Gb/s) through the SDM-UDWDM system. The central core of the 7-core MCF is used to transmit the pilot-tone and the other six outer cores are used to transmit the 12 40 Gb/s UDWDM signals on a 12 GHz grid which use PDM quadrature phase-shift keying (PDM-QPSK) modulation format. It is equivalent to achieve an extremely ultra-dense wavelength spacing of 2 GHz in a single fiber with our OFC and SDM setup.



(a) (b) (c)

Fig. 1. (a) Experimental setup for OFC generator, (b) optical spectrum of the generated OFC with 0.02 nm spectrum resolution, and (c) with 0.2 pm spectrum resolution.

2. Generation of Optical Frequency Comb

OFC which can provide a variety of applications has been researched widely. Owing to its good properties of high stability, low cost, simplicity, and flexible tunability, it has been widely used as multicarrier light source, precision optical reference source, and arbitrary waveform generation [17]. A lot of methods have been presented for generating OFC such as using a mode-locked laser [18], electro-optical modulator based OFC [19]–[22], optical fiber nonlinear effects/four-wave mixing effect [23], and microresonator-based OFC [24].

For the system simplicity and cost-effectiveness, we adopt the technique proposed in [20] to generate an OFC. In this scheme, only a conventional single-stage dual-drive electro-optic LiNbO3 Mach-Zehnder modulator (MZM) is required. Fig. 1(a) plots the experimental setup of the OFC generator. The upper and lower arms of the MZM are driven by two sinusoidal RF signals with same frequency and phase, RF1 and RF2 in Fig. 1(a). Theoretically, under a driving condition, which is summarized in the following equation:

$$\Delta \mathrm{A} \pm \Delta\theta = \pi/2 \tag{1}$$

the generated OFC will have a flat optical spectrum. In (1), ΔA represents the amplitude difference between two RF signals (RF1 and RF2) which is normalized by the half-wave voltage ($V\pi$) of the MZM. $\Delta\theta$ is the normalized phase shift induced by the bias difference between two arms.

In our experiment, we use a dual-drive electro-optic MZM (FTM7937) with the modulation speed up to 43 Gb/s and the RF $V\pi$ at 1.8 V under the push-pull condition. A monitor PD chip and coupler function are integrated inside the modulator for automatic bias control (ABC) which is used to compensate the DC-drift in the system. Therefore, it is easy to keep a stable working state for a long time. The microwave source (MS) generates a 12 GHz sinusoidal RF signal. A RF power splitter is used to provide the two RF signals, RF1 and RF2. To make sure the two RF signals are in-phase, a phase shifter (PS) is inserted into one RF path to align the phase. Then, the two RF signals are amplified by RF driving amplifiers (OA4SMM4). By simply adjusting the drain bias voltage alone, we can control its gain and change the amplitude difference between two arms. The normalized optical spectrum as shown in Fig. 1(b) has good flatness when the flat-spectrum driving condition as described in Eq. (1) is satisfied. The frequency spacing is 12 GHz, respectively. We can get 12 frequency components with less than 1.5 dB spectral ripple. The envelope of the generated OFC is nearly rectangle and the extinction ratio is almost 25 dB measured with an optical spectrum analyzer (OSA, AQ6370C, 0.02 nm spectrum resolution). In fact, the poor spectrum resolution restricts the extinction ratio measurement accuracy. In Fig. 1(c), we can see the actual extinction ratio is larger than 40 dB measured with a high spectrum resolution (0.2 pm) OSA.

3. SDM-UDWDM-SHCD Transmission Experiments and Results

We conduct an experiment to validate the feasibility of our proposed SDM-UDWDM system with SHCD. The experimental setup is given in Fig. 2. We utilize 37 km low-crosstalk 7-core fibers and

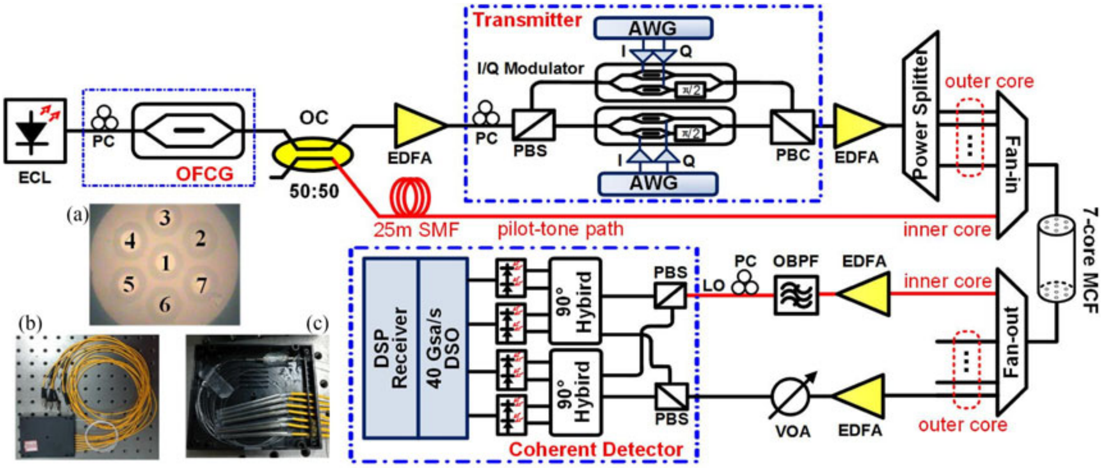
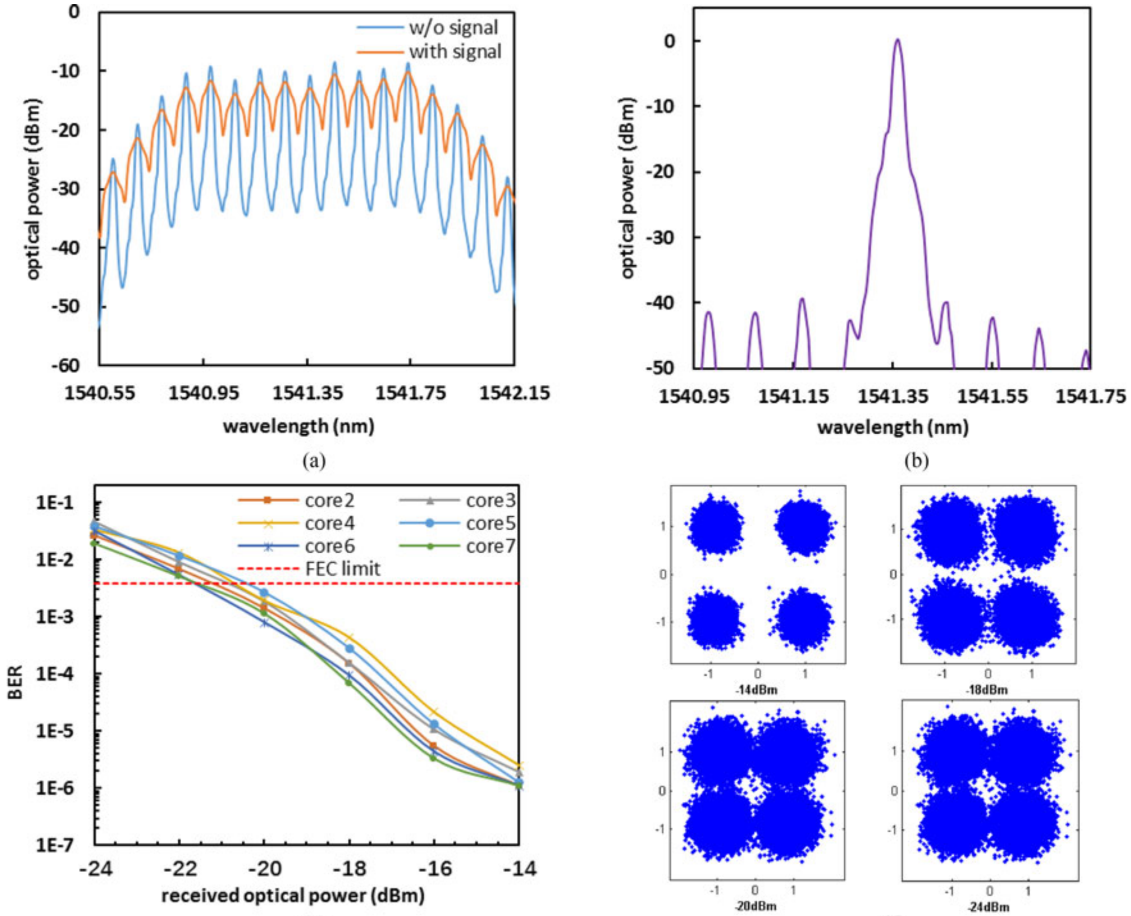


Fig. 2. Experimental setup for the SDM-UDWDM system with SHCD. (a) Cross section view of the fabricated seven-core fiber. (b) and (c) Overall fan-in/fan-out multiplexers with single mode fiber pigtails.

compact low-loss fan-in/fan-out multiplexers to implement the access network architecture. The seven cores of the low-crosstalk MCF are arranged in a hexagon, as shown in the inset Fig. 2(a). The compact low-loss fan-in/fan-out multiplexers as given in insets Fig. 2(b) and (c) are fabricated by chemical etching process and fiber bundles technique. The detail descriptions can be found in our previous works [25], [26]. With improved operation platform and optimized manufacturing process, the performance of our fabricated 7-core fiber and fan-in/fan-out devices have been improved a lot. The insertion loss of a pair of fan-in/fan-out multiplexers is reduced to about 2 dB per core. The end-to-end inter-core crosstalk and the entire loss of the transmission link including 37 km MCFs and a pair of fan-in/fan-out multiplexers can be as low as -60 dB and 10 dB, respectively.

In the experiment, an external cavity laser (ECL) is adopted as the light source in the system. The center wavelength is 1541.35 nm and the output optical power is set to 14 dBm. An OFC generator as introduced in previous section is developed to generate twelve wavelengths with 12 GHz channel spacing. Then, the 12 CWs are split into two parts with an optical coupler (OC). One part is transmitted as the pilot-tone to provide LOs for the coherent receiver. The pilot-tone is then injected into the central core (core 1) of the MCF through the fan-in multiplexer. The other part is used to transmit the signals. In the signal path, an Erbium-doped-fiber-amplifier (EDFA) is employed to amplify the amplitude and the polarization state is regulated by a polarization controller (PC) to obtain the maximum modulation efficiency. Then, the 12 tones are divided into two independent polarizations by a polarization beam splitter (PBS). Two polarizations are modulated respectively by two separate I/Q modulators with 10 GBaud single carrier QPSK signal, and recombined together again by a polarization beam combiner (PBC). An arbitrary waveform generator (AWG) with four channels is adopted to convert the time domain QPSK signal to drive the optical I/Q modulator. The optical PDM-QPSK signals is amplified by an EDFA and imported into a 1:8 power coupler to split the signals for six outer core input fibers of the fan-in multiplexer. The spectra of the amplified optical PDM-QPSK signals are given in Fig. 3(a), together with the signal before modulation. During the experiment, the input power of every single wavelength is set to 6 dBm by adjusting the gain of the EDFA. After 37 km transmission over the 7-core MCF, the fan-out multiplexer is used to separate the signals and pilot-tone into seven single mode fibers. Before injected into the coherent receiver, the signal of every single mode fiber (SMF) is amplified by an EDFA and a variable optical attenuator (VOA) is inserted for the purpose of analyzing the system performance under different received optical power (ROP). In the pilot-tone path, a tunable 0.1 nm optical band pass filter (OBPF) is used to separate the required wavelength from the 12 tones after amplified with an EDFA, which works as LO for the receiver. Since matching the path length between signal channels and the pilot-tone is significant in SHCD system for eliminating the phase noise, a section of SMF of about 25 m in the



(a) (b) (c) (d)

Fig. 3. (a) Optical spectra of 12 tones with/without the PDM-QPSK signal. (b) Optical spectrum of the LO at the receiver. (c) BER curve for the transmission with 40 Gb/s PDM-QPSK. (d) Constellation diagrams of ROP at −14 dBm, −18 dBm, −20 dBm, and −24 dBm.

pilot-tone path is inserted to match the optical path length due to the transmission link differences, such as the pilot-tone path contains one EDFA while the signal channels have three, etc. The optical spectrum of LO is given in Fig. 3(b). The received LO optical power is maintained at 1 dBm for all measurements. It is necessary to clarify that there is an additional 7.78 dB loss in the pilot-tone path as the LO optical power should be equally allocated to each signal core in a practical system. If required, a second EDFA should be inserted into the pilot path before the allocation to decrease the OSNR degradation on the LO. A typical digital coherent receiver is adopted to detect the optical signal and the electrical waveform is sampled by four 40 GS/s digital sampled oscilloscope (DSO). A typical PDM-QPSK algorithm [27] is carried out offline for demodulation and bit error (BER) counting. As SHCD is adopted, requirement of the narrow linewidth LO laser is canceled. CFO estimation and CPR are not needed which greatly decrease the complexity of DSP at the receiver.

First, we studied the performance difference among six out cores with the same LO wavelength centered at 1541.35 nm. The BER curves of the PDM-QPSK signals at different ROP are given in Fig. 3(c). The constellation diagrams recovered offline using DSP in MATLAB of ROP at −14 dBm, −18 dBm, −20 dBm, and −24 dBm from core 3 are also shown in Fig. 3(d) at the same time. As we can see, after 37 km MCF transmission, there is no significant transmission performance difference among six spatial channels. Note that, six outer cores present the similar performance differen-

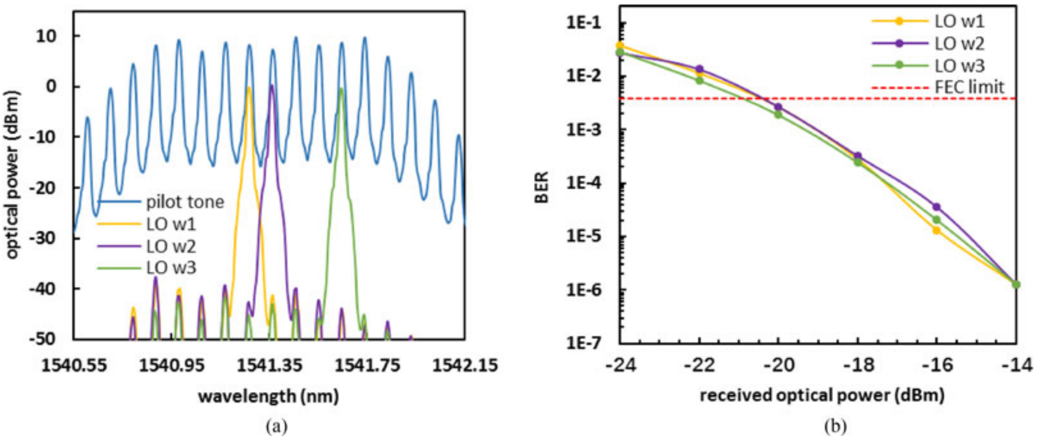


Fig. 4. (a) Optical spectra of three different LO wavelengths and the pilot-tone. (b) BER curve for three different ONUs with individual LO.

ce with different LO wavelength. The system can realize error free transmission with the ROP no less than −20 dBm under 7% forward error correction (FEC) limit (BER $= 3.8 \times 10^{-3}$).

Next, we evaluated the performance of the SHCD system with different LO wavelength in one outer core. For different OUN, the corresponding LO wavelength is separated from the UDWDM comb by tuning the 0.1 nm OPBF and the performance of different channel with individual LO wavelength is investigated. As shown in Fig. 4(a), we choose three wavelengths as the LO for different ONU. The BER performance in core 3 with three different LOs is given in Fig. 4(b). As we can see, with individual LO wavelength, the receiver can receive the corresponding UDWDM channel with almost identical performance after 37 km MCF propagation. The choice of LO wavelength for different ONU reception has a negligible impact on system performance. In the SHCD system, a narrow bandwidth OBPF in the signal path is eliminated which is necessary in direct detection receivers. It is easy to realize the channel selecting through tuning the OBPF in the pilot-tone at the receiver side and a dedicated LO laser source is no more needed at the ONU. Those intrinsic features greatly reduce the system cost and make the system simplified. An adequate power budget is also one of the key parameters in an UDWDM-PON system. In our system, the inserted EDFA at the signal path guarantees the optical power of each channel is 6 dBm before injected into the fan-in multiplexer. As the sensitivity under 7% FEC limit (BER $= 3.8 \times 10^{-3}$) is about −20 dBm, we can get a power budget of 26 dB at the worst cases. Compared with the UDWDM-PON with SHCD in a SSMF proposed in [28], the SDM-UDWDM system with SHCD we proposed shows an even better performance in terms of the transmission distance and the system power budget. Since the optical power of the LO is as low as 1dBm in our system, there is still an opportunity to enlarge the power budget by augmenting the relative power of the pilot-tone. A larger optical power of the LO will provide a higher receiver sensitivity in a SHCD system as in a traditional coherent detection system.

4. Conclusion

We have experimentally demonstrated an UDWDM PON with SHCD in a SDM system utilizing the home-made low-crosstalk 7-core MCF and compact low-loss fan-in/fan-out multiplexers. With advanced manufacturing techniques, the inter-core crosstalk and insertion loss of the MCF and fan-in/fan-out multiplexers are greatly reduced and have a negligible influence on the system performance compared to SSMF transmission system. We perform an access network with the properties of large capacity, long reach transmission and massive count of users, where we transmit the LO in the central core of a 7-core MCF with the other six outer cores adopted to transmit 12 × 40 Gb/s PDM-QPSK signals. An OFC generator using a conventional dual-drive MZM is adopted to generate the 12 GHz channel spacing signal sources for cost saving. Twelve optical combs with a spectral ripple less than 1.5 dB, and an extinction ratio large than 40 dB are obtained. We have realized a capacity of 2.88 Tb/s UDWDM-PON supporting 72 ONUs in the current experiment. After 37 km 7-core MCF transmission, the system shows an acceptable performance. Since a sufficient power budget of 26 dBm is obtained in our proposed system, it can be further power split to raise the amount of the user and expand the feeding area. It is feasible to implement SHCD in a transmission system combining UDWDM with SDM, it provides a compromise and cost efficient scheme between intradyne coherent detection and conventional intensity modulation/direct detection (IM/DD) schemes.

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