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REVIEW ARTICLE

Frontier research of ultra-high-speed ultra-large-capacity and ultra-long-haul optical transmission

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Abstract Ultra-high-speed, ultra-large-capacity and ultra-long-haul (3U) are the forever pursuit of optical communication. As a new mode of optical communication, 3U transmission can greatly promote next generation optical internet and broadband mobile communication network development and technological progress, therefore it has become the focus of international high-tech intellectual property competition ground. This paper introduces the scientific problems, key technologies and important achievements in 3U transmission research.

Keywords ultra-high-speed, ultra-large-capacity, ultra-long-haul, optical transmission, high spectral efficiency, parametric amplification, dispersion management

1 Introduction

Mankind's rapid increase in the demand for information has promoted the continuous progress of information science. As the foundation of the information age, optical communication is continuing to move forward. Light has a very high frequency (about 300 terahertz) which implies that it has a high bandwidth to accommodate huge communication information, therefore using light as the carrier for high speed optical fiber communication has always been the goal of information science. From the initial establishment of US Bell Laboratories in Atlanta to the first practical 45 Mbit/s optical fiber communication line in Washington, the rate of optical fiber communication continues to improve. From the end of the 20th century to the beginning of the 21st century, the rate of optical fiber transmission has increased exponentially from single wavelength of 2.5 and 10 Gbit/s to multi-wavelengths of Tbit/s (1 Tbit/s = 1000 Gbit/s), which greatly promoted the development of information science and industry.

At present, optical communication is moving toward the direction of larger scale and capacity with richer and more flexible applications. To seek a new ultra-high-speed, ultra-large-capacity and ultra-long-haul (hereinafter referred to as 3U) optical transmission mechanism has become a major challenge of future optical communication. As a new mode of optical communication, 3U optical transmission can greatly promote next generation optical internet and broadband mobile communication network development and technological progress, therefore it has become the focus of international high-tech intellectual property competition ground. China's optical communication manufacturing capability and capacity has been at the forefront in the international arena, however her original core technologies and intellectual properties are significantly behind the developed countries, which greatly restricts her sustainable development in the 21st century. The development of 3U optical transmission has great significance in promoting our country's information industry to serve the national economy and establish the international strategic dominance.

In response to this, the 973 project "Frontier Research of Ultra-high-speed Ultra-large-capacity and Ultra-long-haul Optical Transmission" began the research in 2010. It focuses on 3 major scientific problems: 1) methods,

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mechanisms and capacity limit of high spectral efficiency; 2) precise management approach of complex fiber dispersion; 3) dynamic synergy mechanism of fiber nonlinear suppression. It is expected to achieve the following theoretical results through five years in-depth research: 1) establish the theoretical model of 3U optical transmission system; 2) reveal the limit law of spectral efficiency of 3U optical coding and modulation; 3) establish accurate dispersion management mechanism in 3U optical transmission; 4) improve dynamic synergy theory of full-band nonlinear suppression in 3U transmission. The general structure and topics of the project are shown in Fig. 1.

This project is jointly undertaken by Wuhan Institute of Posts and Telecommunications, Huazhong University of Science and Technology, Fudan University, Beijing University of Posts and Telecommunications and Xidian University. It is the first 973 project led by a state-owned enterprise in information field, which has a distinct characteristic of industry, teaching and research integration.

Due to space limitations, this paper only introduces the most important and representative results of the project.

2 Research contents

2.1 High spectral efficiency in 3U transmission

With the further maturation of high speed digital-to-analog converters, super-channels using high spectrum efficiency technologies based on digital signal processing (DSP) at both transmitter and receiver sides has attracted a great deal of interest for the transmission of 100G beyond [1–3]. Technology options for transmission with higher bandwidth efficiency are being intensively studied, which comes in two major categories: reducing the spectrum bandwidth requirement [1–3] or increasing the modulation levels [4–6]. The former uses spectrum shaping technologies based on optical or electrical filtering, known as the Nyquist or super-Nyquist technology; the latter uses multi-level modulation formats, such as 32-QAM, 64-QAM and even higher order QAMs. However, both schemes relies on advanced DSP in transmitter or receiver due to the high sensitivity to the laser frequency offset, phase noise, intra-channel and inter-channel impairments, such as inter-symbol interference and inter-channel crosstalk.

On the other hand, super-Nyquist, also known as Fast-than-Nyquist, signal generation based on optical or electrical spectrum shaping methods has been demonstrated to be an efficient scheme for future high-capacity transmission systems. Super-Nyquist signal demodulations based on maximum a posteriori (MAP) or maximum likelihood sequence estimation (MLSE) on receiver side have been demonstrated in 100G, 200G and 400G systems [1–3,7], which enables polarization division multiplexed quadrature phase shift keying (PDM-QPSK) transmission with 4 bit/s/Hz net spectral efficiency at lower optical signal-to-noise ratio (OSNR) requirement and longer transmission distance. Using algorithms based on fixed or adaptive digital filtering with multi-symbol detection to equalize both Inter Symbol Interference (ISI) and Inter

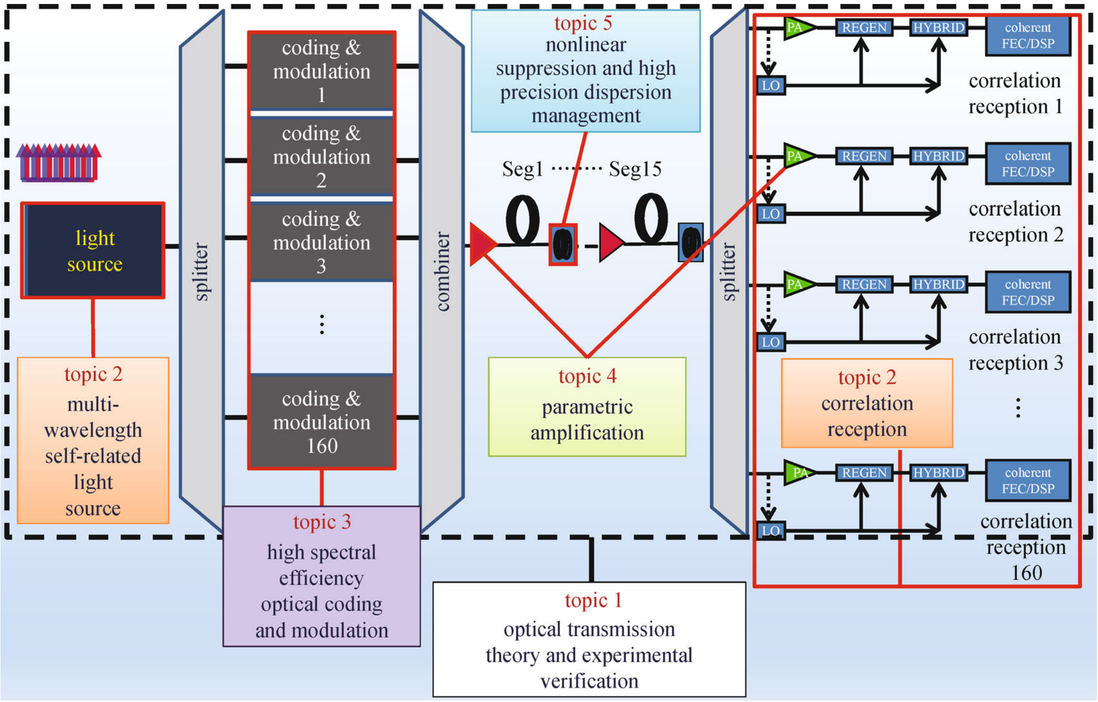


Fig. 1 General structure and topics of the project

Code Interference (ICI) impairments, one can transmit a super-Nyquist (channel occupancy much less than signal baud rate) signal, of which the channel spacing can be smaller than the symbol rate without much penalty. This feature is quite useful for signals transmission under aggressive optical filtering in multiple reconfigurable optical add-drop multiplexers (ROADMs) transmission link [8].

We propose a novel DSP scheme for optical super-Nyquist filtering 9-ary quadrature amplitude modulation (9-QAM) like signals based on multi-modulus equalization (MMEQ) without post filter, which directly recovers the Nyquist filtered QPSK to a 9-QAM like signal. It has improved filtering tolerance and transmission performance for high spectrum efficiency high-speed long-haul transmission system. The details are demonstrated in Section 3.

2.2 Optical parametric amplifier for 3U transmission

Fiber optical parametric amplifiers (FOPAs) based on highly nonlinear fibers (HNLFs) have been regard as the potential technique for amplification in high capacity fiber optical communication systems [9–12]. FOPAs is able to achieve high gain at arbitrary wavelength with arbitrary modulation format and symbol rate. It is polarization independent, and compatible with the wavelength-division multiplexing (WDM) operation over a wide bandwidth range, and also have ultra-low noise and flat-gain with high gain efficiency. In this research, the FOPAs are investigated theoretically and experimentally for 3U transmission. Our results show that theyhave high gain (more than 40 dB), wide bandwidth (>100 nm), high flatness (~1 dB) and ultra-low noise. Additionally, the HNLFs designed and fabricated achieve as high as 46% four-wave mixing (FWM) conversion efficiency. The details are demonstrated in Section 3.

2.3 High precision dispersion management and nonlinear effect suppression in 3U transmission

Chromatic dispersion is a major distortion occurring when optical signals are transmitted over optical fibers, especially for signals with ultra-high-speed data rates. The other major limiting factor on the transmission performance and spectral efficiency is the nonlinear distortion which becomes serious in ultra-high-capacity and ultra-long-haul system with a large number of multiplexed channels and a large amount of accumulated nonlinear interactions. Thus nonlinear effects suppression and highly precision dispersion management are key techniques for 3U transmission systems. Some novel techniques are proposed and the details are demonstrated in Section 3.

3 Important experiments and results

3.1 High spectral efficiency

Figure 2 shows the comparison of different channel multiplexing schemes, including the regular WDM (symbol bandwidth < channel spacing), the Nyquist-WDM (symbol bandwidth = channel spacing) and the super-Nyquist WDM or faster-than-Nyquist WDM signals (symbol bandwidth < channel spacing). The regular WDM scheme with guard-bands between the channels has no inter-channel crosstalk and no ISI. However, this scheme has lowest spectrum efficiency due to the guard-bands. Nyquist-WDM, utilizing the time domain orthogonal pluses, has the subcarriers spectrally shaped so that their occupancy is close or equal to the Nyquist limit for zero inter-channel cross talk and ISI-free transmission. However, when considering the forward error correction (FEC) overhead, the transmission of 100G or 400G channels on existing optical line systems based on an International

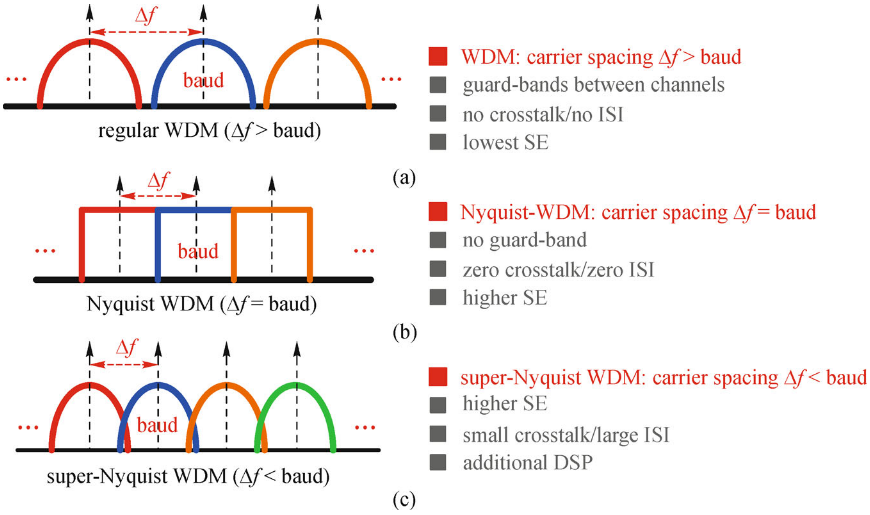


Fig. 2 Comparison of different channel multiplexing schemes

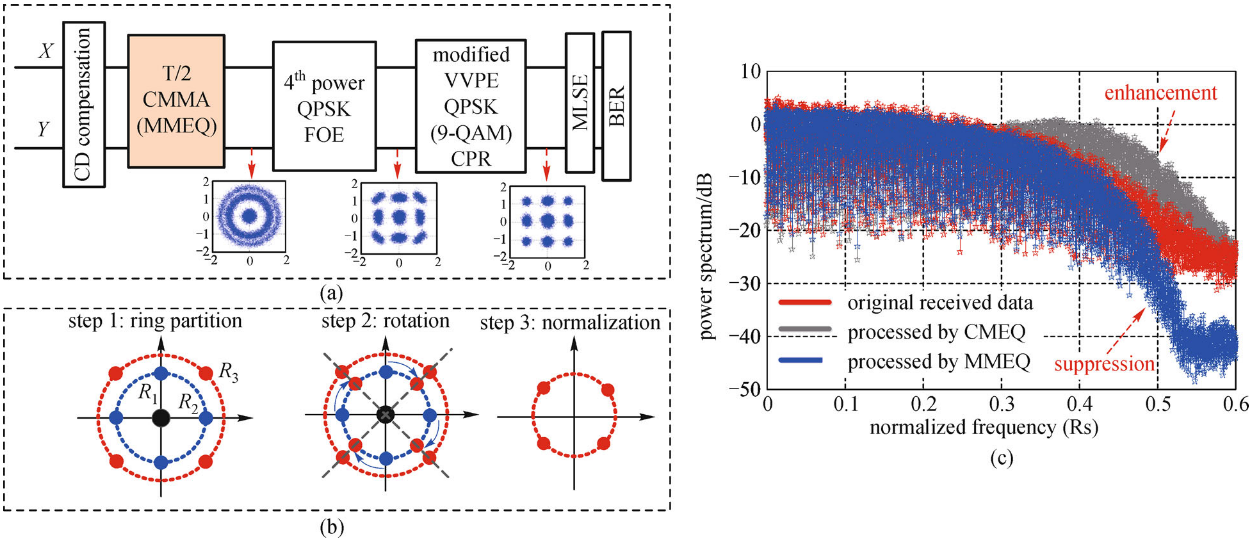
Telecommunications Union (ITU) grid presents a difficult challenge due to the limited bandwidth available for each channel. The excess bandwidth causes severe crosstalk. On the other hand, the super-Nyquist WDM with narrow-band optical filtering or electrical pre-filtering can be used with the symbol bandwidth less than channel spacing. However, due to the filtering effect, the system performance is seriously degraded by noise and inter-channel crosstalk enhancement and ISI. Therefore, additional processing is needed for higher spectrum efficiency to counter the noise and crosstalk enhancement and ISI in order to maintain the reasonable long-haul transmission distance with FEC overhead.

To handle the noise enhancement caused by the linear equalization algorithm such as conventional constant modulus algorithm (CMA), one simple method is the partial response signaling, also called duobinary signaling or correlative coding. It uses digital delay-and-add post filtering before decision to mitigate the enhanced inter-channel crosstalk and intra-channel noise, which turns the constellation of the QPSK signal to that of the 9-QAM [13]. However, it still leaves parts of the DSP blocks such as the carrier recovery process under the impact of enhanced noise and crosstalk. Based on the duobinary signaling, we proposed an improved duobinary DSP scheme using the MMEQ without post filtering, which directly recovers the QPSK data from the 9-QAM like quadrature duobinary (QDB) signals based on the cascaded multi-modulus algorithm (CMMA) [14].

Figure 3 shows the main DSP blocks based on MMEQ using CMMA and modified carrier recovery scheme for the super-Nyquist filtering 9-QAM like QDB signals. The QDB 9-QAM signal is directly recovered by using the MMEQ scheme as shown in Fig. 3(a). The frequency offset estimation and carrier phase recovery are also based on the 9-QAM like constellation. The principle of 9-QAM signal carrier recovery can be found in Fig. 3(b). After phase recovery, the 9-QAM signal is converted back to the QPSK signal by the multi-symbol equalization and detection algorithm maximum likelihood sequence estimation (MLSE). The 1-bit MLSE is applied to equalize ISI impairment. Before the calculation of the bit error rate (BER), the MLSE based on Viterbi algorithm is utilized for symbol decoding and detection to eliminate the ISI impact. Compared with the CMA and poster filter scheme, both simulation and experiment results shows this MMEQ method has better performance for noise and crosstalk suppression, resulting in improved filtering tolerance as shown in Fig. 3(c). Therefore, using algorithms based on adaptive digital QDB signaling with multi-symbol detection to equalize the both ISI and ICI impairments, one can transmit a super-Nyquist signal of which the channel spacing can be smaller than the symbol rate without much penalty.

3.2 Optical parametric amplifier

The experimental FOPA setup [15] is illustrated in Fig. 4. A tunable laser (TL1) serves as the pump. The phase modulator driven by multi-tones radio frequencies (RF) is used to suppress the Stimulated Brillioun Scattering (SBS). Figure 4(b) shows the power refection of different fiber before and after modulator is used. To increase the pump power, an Erbium-doped fiber amplifier (EDFA) is used to boost the pump power. After the pump is amplified by the EDFA, an optical bandpass filter (OBF) with a full-width at



(a)

(b)

(c)

Fig. 3 (a) Main DSP blocks for MMEQ based on CMMA and modified carrier recovery scheme for the super-Nyquist filtering 9-QAM like QDB signal; (b) DSP principle for 9-QAM signal recovery; (c) benefit of proposed MMEQ with better performance of noise and crosstalk suppression [14] half-maximum (FWHM) of 0.9 nm is introduced to filter the amplified spontaneous emission (ASE) noise caused by the EDFA. Another tunable laser (TL2) is used as the signal. The signal is input into the FOPA together with the processed pump. The polarization controllers (PCs) are used to maintain the relative state of polarization (SOP) of the signal and the pump. Optical power meters (OPMs) and optical spectral analyzer (OSA) are used to monitor the FOPA's characteristics. The HNLF is used as the interaction medium where the zerodispersion wavelength (ZDW) is λ_0 = 1553 nm, the effective area is A_{eff} = 9.5 μm^2, the dispersion slope at 1550 nm is about 0.02 ps/km/nm^2, and the attenuation at 1550 nm is about 0.6 dB/km. The wavelength of the pump is set at 1554 nm. The on-off gain measured is shown in Fig. 4(c). By using equalization phase modulation technique, the highest gain is 46 dB and the gain bandwidth of 110 nm (gain>20 dB) can be realized. The experimental platform is shown in Fig. 4(d).

As is known, FOPAs utilize FWM, a nonlinear process depending on dispersion in HNLF, to achieve amplification. We modeled the gain and noise characteristics of the FOPA with higher order of propagation constant, as shown in Fig. 5. The gain and noise of FOPA is seriously affected by the β_2 and β_4 of the HNLF. After optimizing parameters of the β_4 and $\beta_{2,}$ the improvement of the gain flatness was about 3 dB and the noise figure was about 4 dB.

To achieve more efficient parametric amplification, we developed new photonic crystal fiber (PCF) [16–19] as gain medium of parametric amplification as shown in Fig. 6. The structure and the corresponding dispersion of the PCF, hollow PCF and polarization-maintained hollow PCF are shown in Fig. 6(a), Fig. 6(b) and Fig. 6(c) respectively. The simulation results track the experimental results well, as shown in Fig. 6(d). As pump power increases, the output spectra power in PCF gradually increases (Fig. 6(e)). The highest FWM conversion efficiency obtained in PCF is 46% (Fig. 6(f)).

The effect of Raman Effect on the parameters of optical parametric amplification is also analyzed. As a result, the flatness of FOPA is seriously affected by the Raman Effect in HNLF. Therefore, the hybrid low noise parametric amplification system using Raman pre compensation structure is introduced. The diagram of three order distributed Raman assisted FOPA is shown in Fig. 7(a). Genetic algorithm is introduced to optimize the gain flatness as well as low noise as shown in Fig. 7(b). After optimization, the flatness of the hybrid FOPA is as low as 1 dB.

3.3 High precision optical domain dispersion management

The proposed chromatic dispersion (CD) measurement method is based on spectral interferometry using an asymmetric signal loop and broadband optical source [20]. The setup of the system is shown in Fig. 8. An OSA is used to measure the interference pattern, from which the spectral relative phase and the CD of test fiber can be derived.

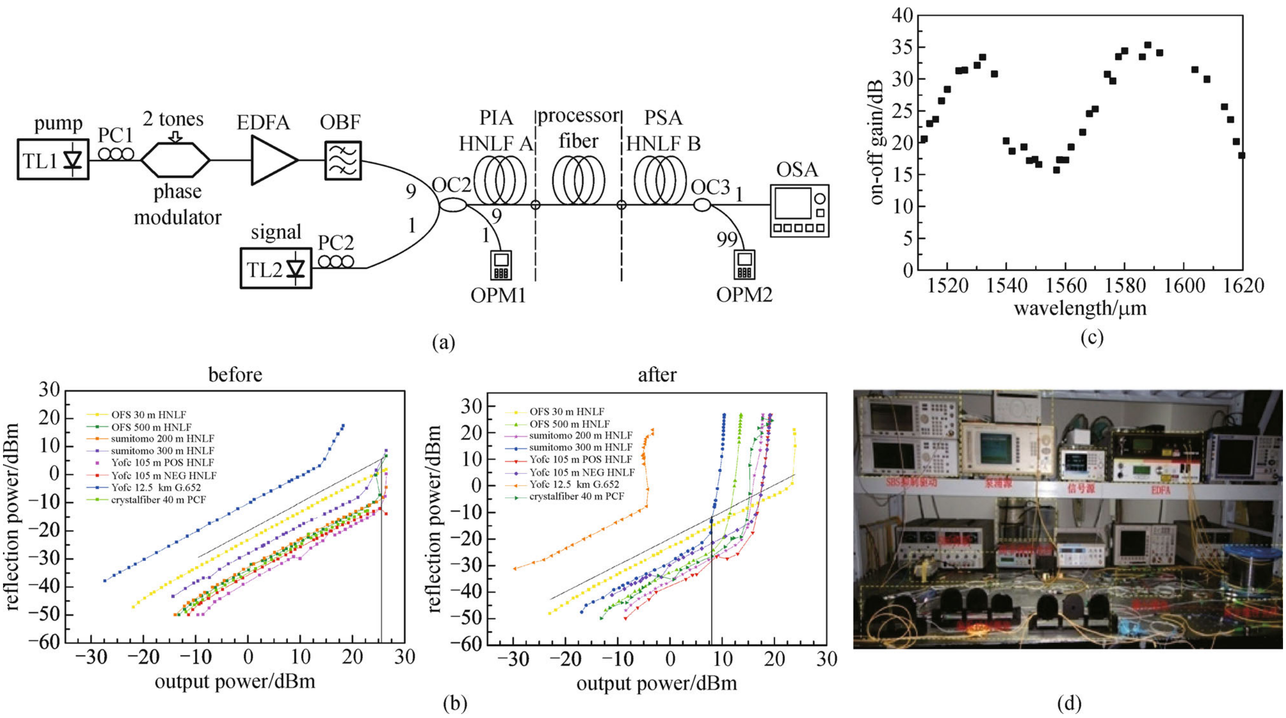


Fig. 4 Experimental setup of the FOPA. (a) FOPA diagram; (b) reflection power of the HNLF before and after suppression technique used; (c) ON-OFF gain of the FOPA; (d) experimental platform [15]

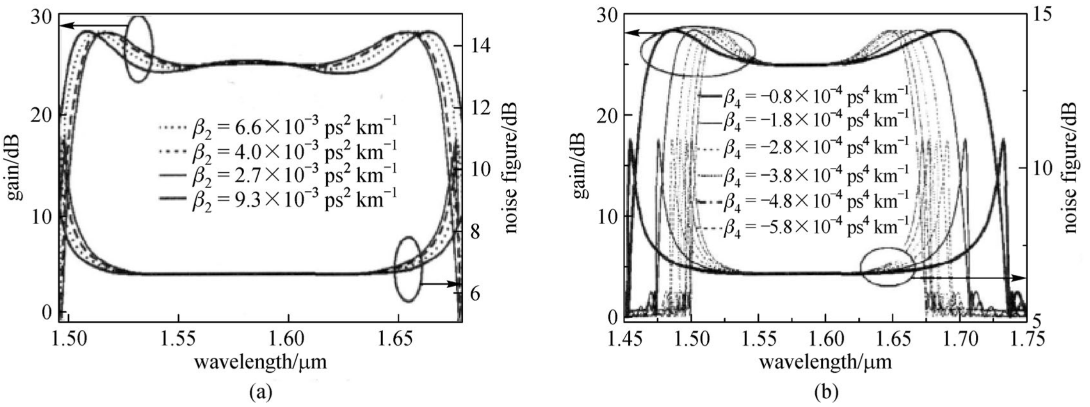


Fig. 5 Gain and noise figure characteristics of the FOPA as β_2 (a) and β_4 (b) considered

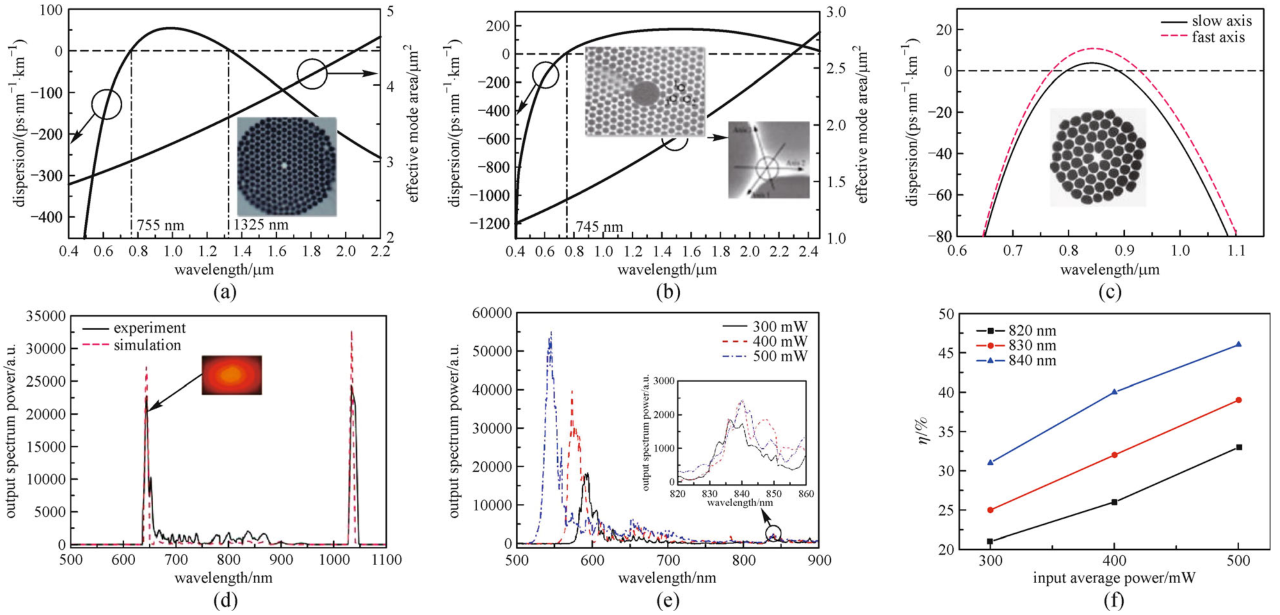


Fig. 6 Characteristics and structure of PCF. (a) Dispersion, effective mode area and structure of PCF; (b) hollow PCF and (c) polarization-maintained hollow PCF; (d) output spectra of PCF obtained by simulation and experiment; (e) output spectra power as various pump power used; (f) FWM conversion efficiency of PCF [16–19]

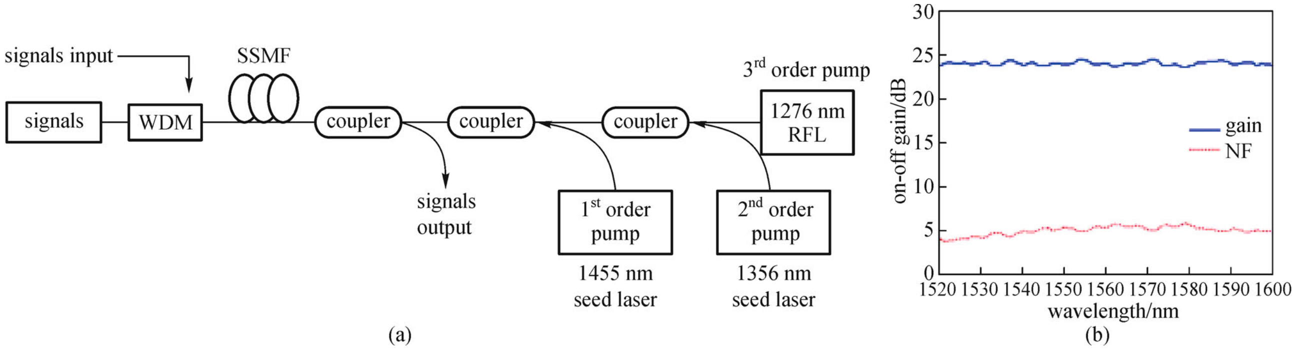


Fig. 7 (a) Diagram of three order distributed Raman assisted FOPA; (b) gain and NF after optimization

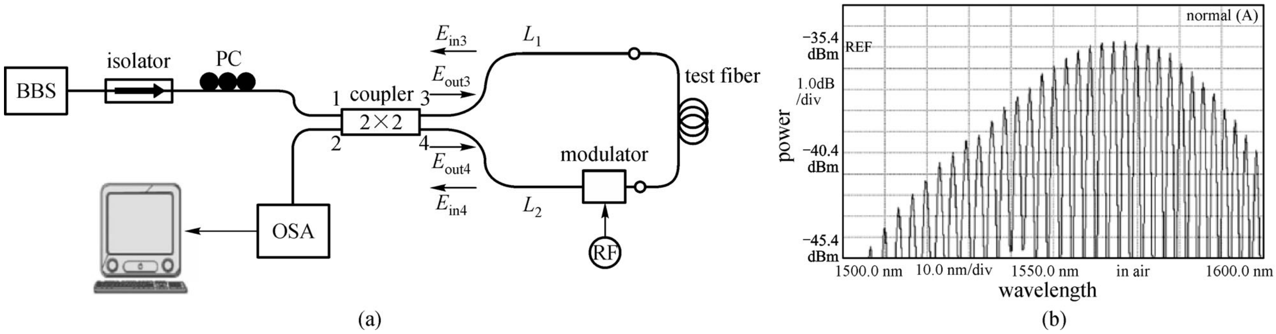


Fig. 8 (a) Experimental setup of the proposed CD measurement; (b) measured optical spectral interferogram in the wavelength range of 1500 to 1600 nm [20]

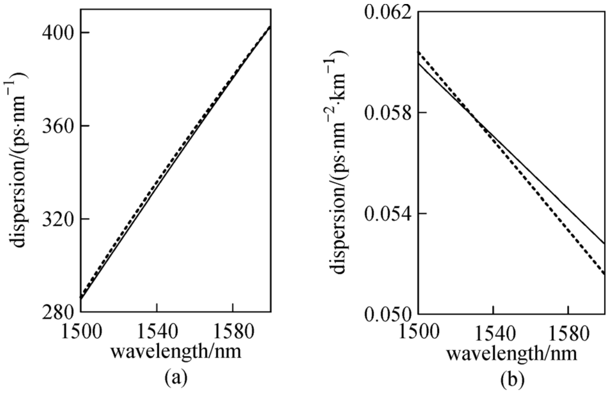


Fig. 9 Experimental results. (a) Measured CD of 20.62 km G.652 fiber by our method (solid curve) and by Agilent 86037C (dashed curve); (b) measured CD slope by our method (solid curve) and by Agilent 86037C (dashed curve) [20]

Results of CD and dispersion slope measurement are shown in Fig. 9. As can be clearly seen, the measured results show excellent agreement with that obtained by a high-precision Agilent 86037C optical dispersion analyzer based on tunable optical source. Therefore the proposed measurement method is rapid (< 1 s, wavelength sweeping is not needed), accurate (0.1% difference), simple and low cost. Experiments show that the method provides the largest dispersion measurement range (0.3 ps/nm to infinity) compared to the spectral interferometry method reported in other papers. On this basis, we proposed a technique to realize a passive dispersion compensation module (DCM) which can achieve fourth-order dispersion compensation [21]. This module is comprised of four parameter optimized dispersion compensation fiber (DCF) segments. Numerical and experimental results show that

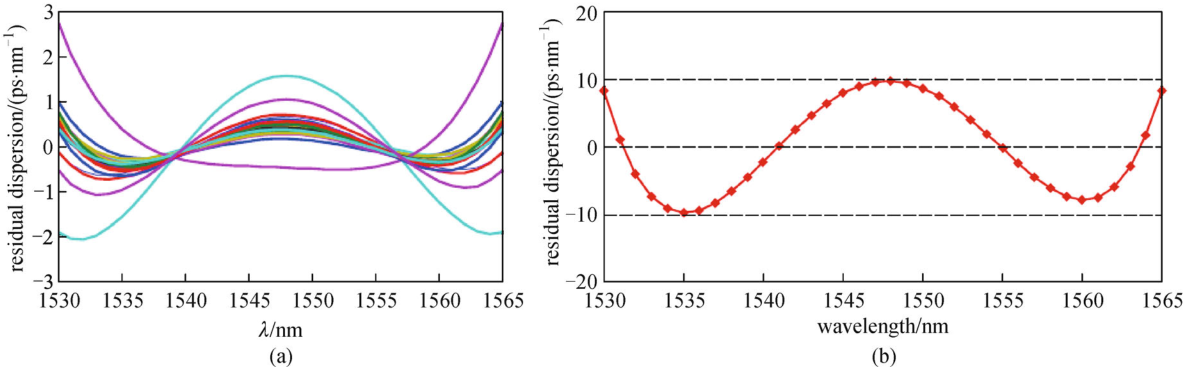


Fig. 10 (a) Residual CD for each G.652 fiber compensation. Twenty segments (out of 261) 100-km G.652 transmission fiber are randomly selected. (b) residual CD after 2000-km optical transmission. A 2000-km lane is linked by 20 random 100-km G.652 fiber and corresponding fourth-order CD compensation module [21]

with DCM the residual dispersion (RD) in the C-band (1530–1565 nm) can be reduced down to ±3 ps/nm for 100-km G.652 compensation and is only ±10 ps/nm for 2000-km transmission system, as shown in Fig. 10. Thus the proposed DCM can support 100 Gbit/s transmission system without any high power consumption electrical devices.

For the environment change induced residual CD variation, a highly accurate and sensitive all-optical CD monitoring based on FWM effect is proposed [22]. The setup of the monitor is shown in Fig. 11 (a). The monitoring ability comes from the exponential FWM gain which provides an exponential power transfer function (PTF) and maps the residual CD experienced by the signals onto the average power of the output idler wave. Therefore, the technique requires only low cost power meter to monitor high speed signals in a bit-rate transparent manner. Figure 11(b) shows the output idler power versus residual CD. The residual CD can be determined from the central power peak. As can be seen, the proposed technique is much more sensitive (enhanced by about 10 dB) compared to other PTF based all-optical monitoring methods proposed before.

3.4 Optical domain nonlinear effect suppression

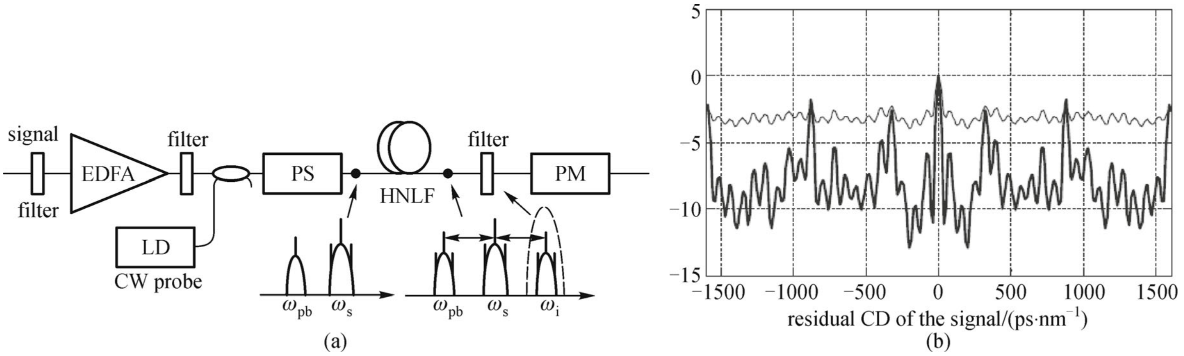
The pre-distortion method capable of suppressing nonlinear effects is based on optical time domain fractional Fourier transform (FRFT) [23]. The FRFT operation which depends on the nonlinear length $L_{\mathrm{NL}} = (\gamma P_0)^{-1}$ (γ and P_0 are fiber nonlinear coefficient and signal power respectively) can be interpreted as an angle of rotation from the time domain plane to the destination domain plane. When the angle is neither 0 nor $\pi/2$, the signal will be transformed into a special domain between time domain and frequency domain, containing both time and frequency components to equalize related fiber impairments and improve system performance. The behavior of CD and Kerr nonlinearities mostly contributes to time and frequency domain respectively. However, they always act on the transmitted signal simultaneously in the fiber links of a DWDM system, resulting in some coupled time-frequency distortion. One can assume that there exist continuous states or domains from time domain to frequency domain. Pulses suffered from fiber impairments are considered to be in a certain intermediate state, which corresponds to some coupled time-frequency distortion, or actually, the combined effect of CD and Kerr nonlinearities in some degree.

The configuration of the optical FRFT module is shown in Fig. 12. It consists of phase modulators (PM) driven by parabolic electric signals and a high dispersive medium. Arbitrary waveform generator (AWG) can be employed to generate periodic parabolic electric signal to drive the PMs. An FRFT module with proper configuration will pre-distort those input optical pulses before they are launched into the fiber and mitigate the CD and nonlinear distortions to the maximum extent. It can always be realized by changing the maximum phase shift of PM to adjust the amount of pre-distortion to combat the fiber nonlinearity.

Figure 13 shows the variation of received BER for the pre-distorted signals with different phase shifts of PM at a launch power of 0 and 3 dBm per channel. The results show that significant performance can be achieved with the optimal pre-distortion configuration through an 860 km transmission link. Although its capability of nonlinearity suppression is limited by the electric driver, the simplicity, flexibility and lower power consumption of the pre-distortion technique still make it a viable candidate for the next-generation green optical network.

3.5 Final result: 168 × 103 Gbit/s 2240 km 3U transmission system

Based on the research conducted above, we established a 3U transmission system platform and successfully implemented 168 × 103 Gb/s coherent optical discrete Fourier transform-spread-orthogonal frequency division multiplexing (DFT-S OFDM)-8PSK C-band transmission over 2240 km SSMF with ITU-T standardized 25 GHz channel



(a) (b)

Fig. 11 (a) Setup of the CD monitor (EDFA: Erbium-doped fiber amplifier. PS: Polarization scrambler. LD: Laser diode. PM: Power meter). (b) output idler wave power versus residual CD of 40 Gb/s 33% return-to-zero on-off keying (RZ OOK) signals (Thick and thin lines are results obtained by our and previous PTF based methods) [22]

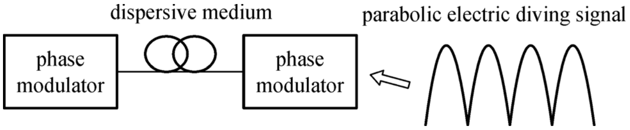
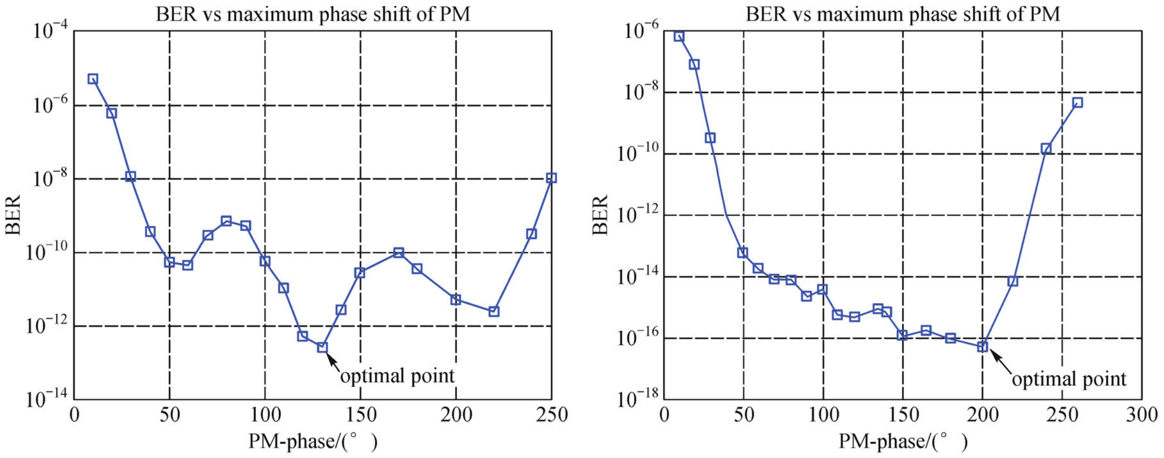


Fig. 12 Configuration of the implementation of FRFT [23]

spacing [24]. When applying 20.5% soft-decision FEC technique, the BER measured for all the sub-channels after transmission is under error threshold of 2×10^{-2}.

Figure 14 shows the experimental setup of the 168 × 103 Gb/s DFT-S OFDM-8PSK transmission system. To emulate 25 GHz C-band carrier sources at the transmitter, eight tunable laser sources are first divided into odd/even pairs, and then fed into the PM based multi-carrier generators. The PMs are driven with strong RF sine waves (~1.5 W) at frequency of 25 GHz. Each laser can generate up to 21 optical carriers. In this fashion, these eight lasers can totally provide $21 \times 8 = 168$ optical carriers. One programmable wavelength selective switch (WSS, Finisar 4000S) is used to combine the PM outputs, which simultaneously performs the function of spectral reshaping and flattening, as shown in Fig. 14(a). The right inserted figure shows the generated multi-carriers in 7th channel. Note that for each measurement at the interest wavelength, the corresponding optical carrier is suppressed and replaced with an individual external cavity laser (ECL). The transmitted signal is generated off-line by MATLAB program with a data sequence of $2^{31}-1$ pseudo-random binary sequence (PRBS) and mapped onto 8PSK constellation. An AWG is used to produce RF signal at 12 GS/s. Then all optical carriers are simultaneously modulated by an optical I/Q modulator. It is worthy to point out that all the modulated sub-bands are correlated. Un-correlated configuration for neighboring bands will further improve the transmission performance. Another optical intensity modulator (IM) driven by a 6.09375 GHz sine wave is used to further duplicate the signal to three copies. The bandwidth of transmitted RF signal for each sub-band is 18.28125 GHz, which is less than the channel spacing (~25 GHz). The modulated optical spectrum is shown in Fig. 14(b). For each sub-band, the payload mapped with 8PSK constellation is partitioned to two sets. Each set is comprised of 64 subcarriers. 2 subcarriers are used to estimate the phase noise. 64-point DFT spreading is first employed by the two sets. When mapping the signal onto frequency domain, the middle 2 subcarriers are unfilled to avoid contamination from DC. By padding zeroes on the higher frequency part, another 256-point IFFT is used to convert the frequency domain signal to time domain. 1/32 of the symbol period is used as the cyclic prefix to compensate the channel dispersion. The optical OFDM signal is then fed into a polarization splitter, with one branch delayed by one OFDM symbol period to emulate the polarization-multiplexing, resulting in a total data rate of 34.36 Gb/s per sub-band. Thus, the data rate for each channel is 3×34.36 Gb/s = 103 Gb/s. The spectral efficiency within each channel is 5.64 bit/s/Hz. The transmission link is constructed by a fiber recirculation loop, which contains four spans of 80 km SSMF with Raman amplifiers only. At the receiver side, an ECL (linewidth ~ 100 kHz) is utilized as the optical local oscillator (LO) and coupled into a polarization-diversity coherent receiver to mix with the signal. The signal is detected by a typical coherent receiver. The four RF signals for the two I/Q components are then fed into a Tektronix oscillator scope of 50 GS/s sampling rate and then processed off-line. The recovered 8PSK constellations in both polarizations are also shown in Fig. 14.

We first conduct a BER versus OSNR performance measurement for a 103 Gb/s (before FEC) CO-OFDM signal in a back-to-back configuration for OFDM-8PSK, OFDM-8QAM and DFT-S OFDM-8PSK, which is shown in Fig. 15. The performance of conventional OFDM-8PSK and DFT-S OFDM-8PSK are very close (OSNR = 18.5 dB for BER = 10^{-3}), while OFDM-8QAM slightly outper-



(a) (b)

Fig. 13 BER as a function of the maximum phase shift of PM after 860 km transmission [23]

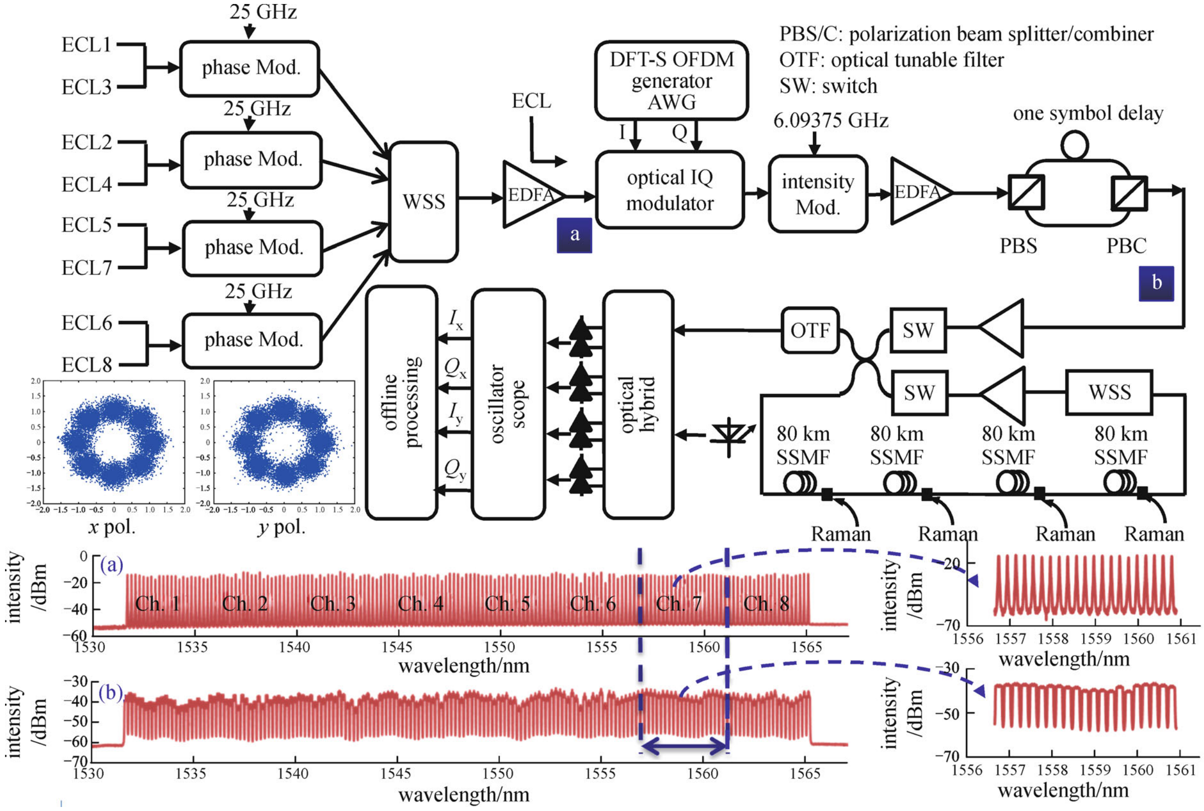


Fig. 14 Experimental setup for 168 × 103 Gb/s DFT-S OFDM-8PSK transmission: (a) 168 carriers generated by the first optical phase modulator; (b) optical spectrum for 168 × 103 Gb/s DFT-S OFDM-8PSK signal. Right inserted figures show the carriers and modulated signal in 7th channel [24]

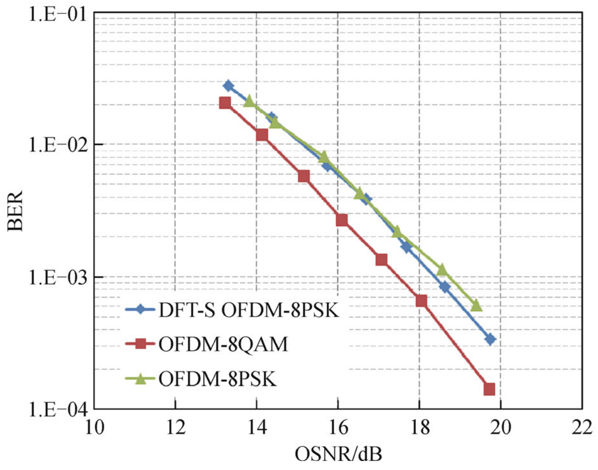


Fig. 15 BER performance against OSNR for DFT-S OFDM-8PSK, OFDM-8QAM, and OFDM-8PSK in a back-to-back configuration [24]

forms (~1 dB) the two 8PSK schemes. To investigate the nonlinearity performance of the three schemes, we then measure the BER as a function of the launch power after 2240 km SSMF transmission (Fig. 16). For the launch power less than −3.2 dBm, with the help of the reduced peak-to-average power ratio (PAPR), DFT-S OFDM-8PSK outperforms OFDM-8PSK, but OFDM-8QAM still shows better performance than DFT-S OFDM-8PSK in this power region. When further increasing the launch power, the nonlinearity effect limits the best BER performance of OFDM-8QAM at ~1 × 10^{-3} (optimum launch power of 0.2 dBm). However, the optimum launch power of DFT-S OFDM-8PSK can further reach 1.4 dBm with BER of 5.17 × 10^{-4}. This experimental result proves that with the help of DFT spread technique, the nonlinearity tolerance can be significantly improved in long haul transmissions.

Figure 17 shows BER versus OSNR for a 103 Gb/s CO-OFDM signal after 2240 km SSMF transmission. Each curve is measured under its corresponding optimum launch power. The required OSNR (BER = 10^{-3}) for OFDM-8QAM is 22 dB. In contrast to the results in back-to-back, the required OSNR for DFT-S OFDM-8PSK is 1.4 dB better than OFDM-8QAM due to the improved nonlinearities caused by the DFT spread during the transmission.

Finally, we carry out the BER measurement for all 168 bands after 2240 SSMF transmission, which is shown in Fig. 18. All the tested BERs are under 20.5% FEC threshold (2 × 10^{-2}). The inset shows the optical spectrum of the entire C-band signal after 2240 km transmission.

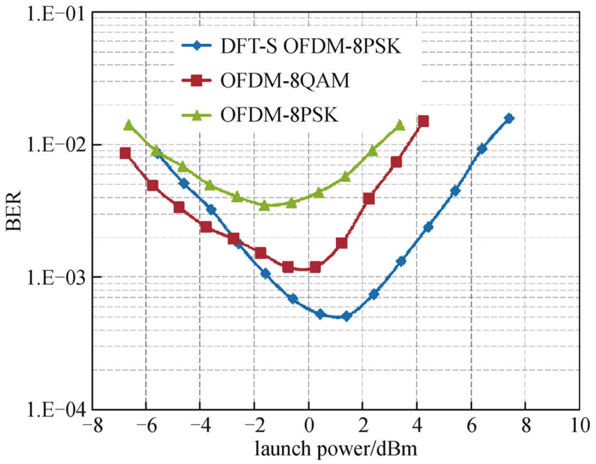


Fig. 16 BER versus launch power for DFT-S OFDM-8PSK, OFDM-8QAM, and OFDM-8PSK after 2240 km transmission [24]

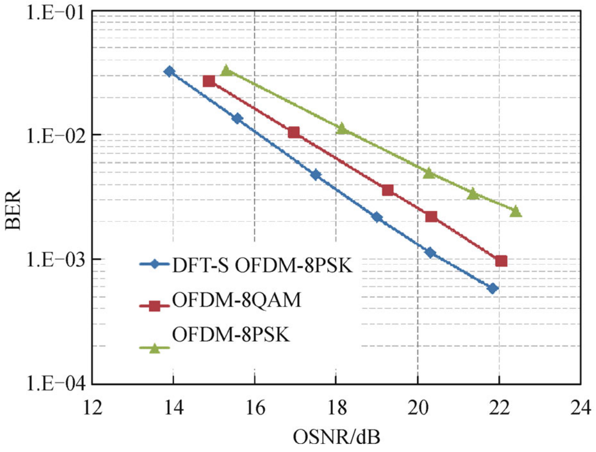


Fig. 17 BER performance against OSNR for DFT-S OFDM-8PSK, OFDM-8QAM, and OFDM-8PSK after 2240 km transmission [24]

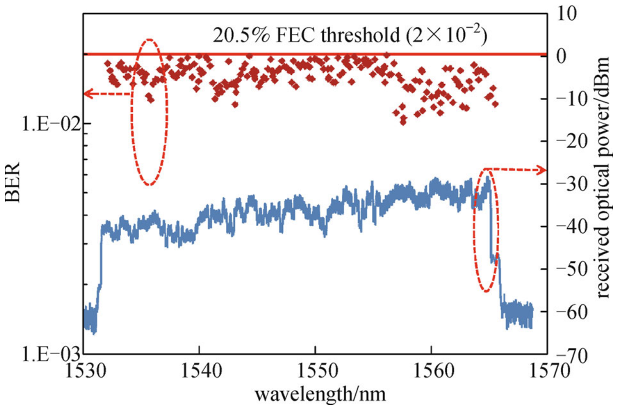


Fig. 18 BER performance for DFT-S OFDM-8PSK after 2240 km transmission [24]

On the same platform, we also conducted a series of 3U transmission experiments, including:

– 1 Tbit/s 1040 km optical transmission [25]

(Identified as “international leading level” by Ministry of Industry and Information)

– 30.7 Tbit/s 80 km optical transmission

– 63 Tbit/s 160 km optical transmission [26]

– 100 Tbit/s 80 km optical transmission [27]

(Selected as one of Ten Major Scientific and Technological Progresses of China in 2014 by academicians)

– 200 Tbit/s 1 km optical transmission [28]

– 1.03 Tbit/s 12160 km optical transmission [29]

– 3.2 Tbit/s 2000 km optical transmission [30]

– 429 Gbit/s 400 km optical transmission [31]

– 2 Gbit/s 440 km ultra-long-haul optical transmission without relay [32]

Through these experiments, we have fully verified the correctness of the theories and methods proposed, which provide core technologies and platform support for the 3U research of our country.

4 Conclusion

Starting from the background and significance of the 3U transmission research, this paper introduces the urgency and importance of the 973 project “Frontier Research of Ultra-high-speed Ultra-large-capacity and Ultra-long-haul Optical Transmission” and presents its three scientific problems and main research tasks, including optical coding and modulation, parametric amplification, nonlinear suppression, dispersion management and experimental verification of 3U transmission. Based on the theories and key technologies acquired through research, we have established the 3U transmission experiment platform and completed a series of important transmission experiments. By the time of its completion, the project has published 345 papers (202 papers included in SCI), applied 90 Chinese patents and 4 US patents, and submitted 6 international standard proposals.

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