Recent progress in an 'ultra-high speed, ultra-large capacity, ultra-long distance' optical transmission system

(Invited Paper)

Shaohua Yu (余少华)[1,2], Ming Luo (罗 鸣)[1,2], Xiang Li (李 响)[2], Rong Hu (胡 荣)[2], Ying Qiu (邱 英)[1,2], Cai Li (黎 偲)[2], Wu Liu (刘 武)[2], Zhixue He (贺志学)[2], Tao Zeng (曾 涛)[2], and Qi Yang (杨 奇)[2,*]

[1]*Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China*

[2]*State Key Laboratory of Optical Communication Technologies and Networks, Wuhan Research Institute of Posts and Telecommunications, Wuhan 430074, China*

**Corresponding author: qyang@wri.com.cn*

Received September 22, 2016; accepted November 11, 2016; posted online December 9, 2016

From 2010 to 2015, the Wuhan Institute of Posts and Telecommunications (WRI) had undertaken the national key basic research development program project 'ultra-high speed, ultra-large capacity, ultra-long distance (3U) optical transmission based research' as the leading agency. Under the support of the project, we have obtained a series of achievements in scientific research and engineering. Some of the results have been widely used in commercial systems. This Review will make a preliminary summary of the achievements during the past 5 years.

OCIS codes: 060.0060, 250.0250, 070.0070.
doi: 10.3788/COL201614.120003.

In 1966, Dr. Charles K. Kao's group showed that it would be possible to purify silica sufficiently to make signal transmission over glass fibers in communication area. Four years later, Corning Inc. successfully fabricated that first ultrapure fiber. Through fifty years of development, hundreds of millions of people or computers exchange information through the Internet which is connected by optic fiber nowadays. If internet technology is the basis of human society nowadays, optical fiber communication technology is the basis of the internet.

In the past forty years, optical fiber communication technology has formed a global industry that is worth hundreds of billions of dollars a year. Chinese manufacturers occupy an increasingly important position in this industry chain. There are three Chinese companies in the top ten of the world's optical communication equipment suppliers. Fiberhome Technology Group (Wuhan Research Institute of Posts and Telecommunications, WRI) is one of the three Chinese companies, and this group is also the only one that has a complete industry chain of optical fiber communication from optoelectronic devices to optical fiber cables and optical communication systems. Specifically, the first optical fiber in China was designed and fabricated by WRI in 1976.

How to improve the transmission capacity, transmission distance, and single-channel transmission rate are the three hot research topics in the optical fiber communication area. The explosive growth of internet data services promote the development of a highspeed dense wavelength division multiplexing (DWDM) transmission system. With the great demands for communication bandwidth by data center, cloud computing, and other emerging industries, the existing backbone networks will not be able to meet the bandwidth demands in the near future. Since 2010, we started to undertake the national key basic research development program project 'ultra-high speed, ultra-large capacity ultra-long distance (3U) optical transmission based research' as the leading agency. Under the support of this project, we have obtained a series of achievements in scientific research. The representative achievements are briefly introduced in this Review below.

In the past ten years, the demand of channel capacity in optical fiber transmission systems has increased dramatically due to ever-increasing data traffic. In order to meet this demand, the most practical solution is to combine the technologies of high spectral efficiency (SE) modulation formats, coherent optical detection, digital signal processing, and wideband low noise optical amplification. Therefore, several optical transport systems with total capacities of 10 to 100 Tb/s have been demonstrated. In 2010, Zhou *et al.* demonstrated a more than 60 Tb/s fiber transmission using a single-carrier polarization-diversity modulation (PDM) 36-QAM format and coherent optical detection, which can achieve an SE of 8 bit/s/Hz[1]. Since then, even more higher-order modulation formats such as 128-QAM, 512-QAM, and 1024-QAM were reported to increase the SE and the transmission capacity[2–5]. Until 2014, 100 Tb/s single-mode fiber (SMF) transmission has been experimentally demonstrated by two groups in the world[2,3].

Before 2010, due to the limitation of the experimental equipment and the technical issues, China obviously lagged behind the developed countries in the field of ultra-high capacity optical fiber transmission. In the past 5 years, WRI as the main force of China in this field gradually approached or reached the international leading level.

Table 1. Our Work in Ultra-high Capacity SMF Transmission

Total Capacity (Tb/s)	Modulation Format per Channel	Bands	Channel Spacing (GHz)	Distance (km)	Fiber Type	Application Scheme	Year
30.7	PDM-16QAM-OFDM	C, L	25	80	SSMF	EDFA	2011
16.7[6]	DFT-S PDM-8PSK OFDM	C, L	25	2240	SSMF	Raman	2012
63[7]	PDM-16QAM-OFDM	C, L	25	160	SSMF	Raman	2013
100.3[8]	DFT-S PDM-128QAM OFDM	C, L	25	80	SSMF	Raman	2014

Table 1 is a summary of ultra-high capacity SMF transmission experiments that were demonstrated by us in the last 5 years.

Specifically, in 2014, we also realized optical fiber transmission at a capacity of 100 Tb/s. In the experimental demonstration, the coherent optical orthogonal frequency

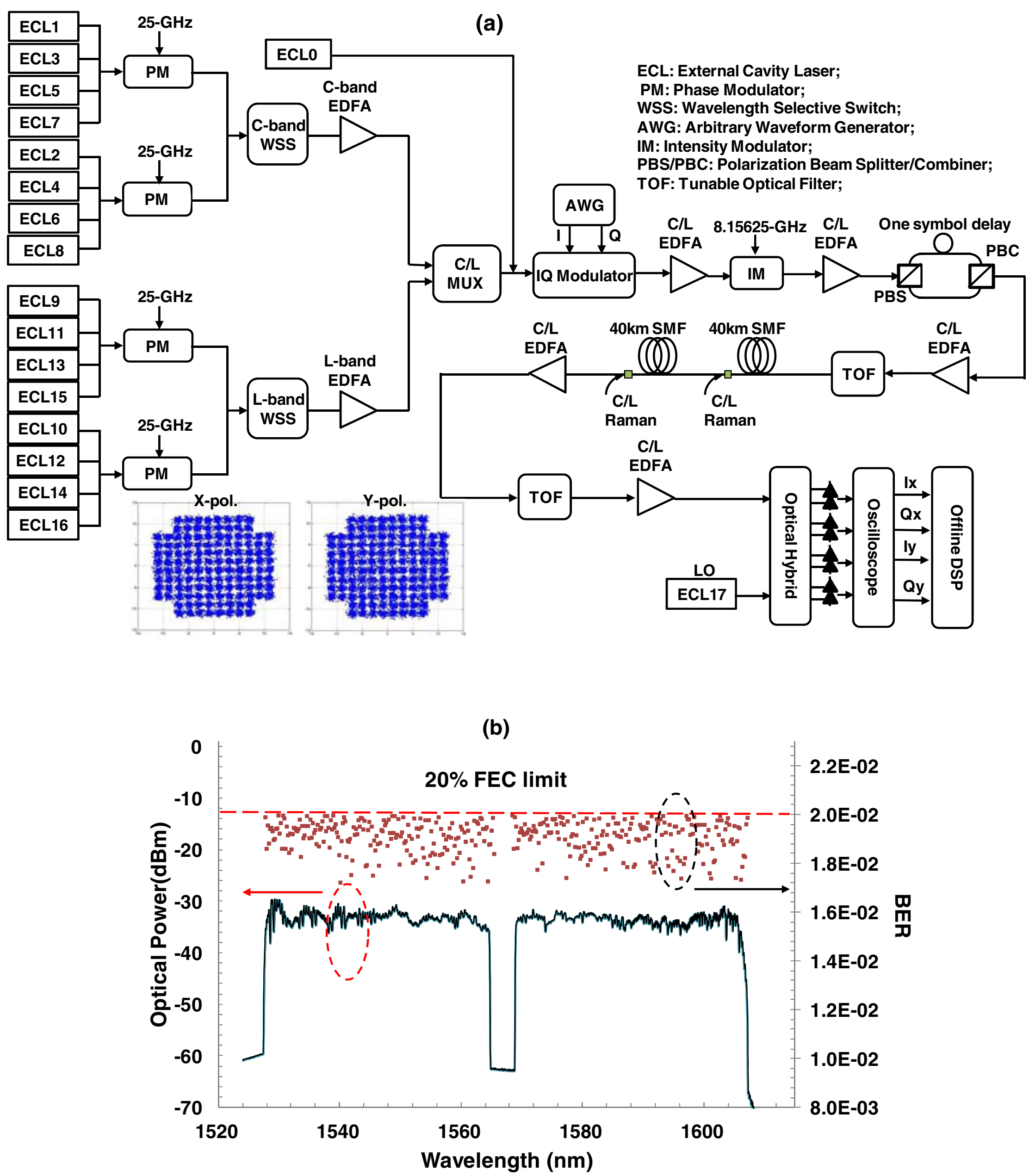

Fig. 1. (a) Experimental setup for a 375 × 267.27 Gb/s DFT-S OFDM 128-QAM transmission; (b) BER performances for the 375 WDM channels after an 80 km transmission.

division multiplexing (CO-OFDM) with discrete Fourier transform spreading (DFT-S) and 128-QAM format was applied. It is noted that DFT-S can reduce the peak-to-average power ratio (PAPR) and mitigate the fiber nonlinearity[9,10]. After C- and L-band transmission over an 80 km standard single-mode fiber (SSMF) at International Telecommunication Union Telecommunication (ITU-T) standardized 25 GHz channel spacing, the SE can be as high as 10.7 bit/s/Hz.

Figure 1(a) shows the experimental setup for the 100 Tb/s DFT-S OFDM 128-QAM transmission system. As shown in Fig. 1(b), the bit error rates (BERs) of all the subchannels are under the 20% forward error correction (FEC) threshold of 2×10^{-2}[8]. The result of the experiment indicates that the academic institutes of China can reach the same level as the foreign counterparts in this field.

In SMF transmission systems, 100 Tb/s is considered as the capacity upper bound, which is constrained by the optical signal-to-noise ratio (OSNR) and fiber nonlinear noise. Recently, researchers around world have turned their attention to space division multiplexing optical technology to explore other dimensions in optical transmission, including few mode fiber (FMF) transmission, multi core fiber (MCF) transmission, and optical angular momentum (OAM) transmission.

In the past two years, we have made some breakthroughs in the field of space division multiplexing optical transmission technology. In 2014, we collaborated with Huazhong University of Science and Technology (HUST) and completed a free-space data transmission with an aggregate transmission capacity of 1.036 Pb/s and a high SE of 112.6 bit/s/Hz[11]. One year later, we experimentally demonstrated the first all-optical wavelength conversion (AOWC) in a mode division multiplexed (MDM) super channel in the world, with an optical signal conversion capacity exceeding 100 Gbit/s[12].

In the field of high-speed real-time transmission, we also has done a lot of works, some of these results have been used in the real commercial systems. In 2015, we experimentally demonstrated a 200 Tb/s ($375 \times 3\times$ 178.125-Gb/s) transmission system over a 1 km FMF using mode multiplexing[13]. The FMF was designed to support three spatial modes (LP01, LP11a, and LP11b). DFTS-OFDM-32QAM was used as the modulation format. A 6×6 multi-input multi-output (MIMO) OFDM DSP scheme was used in the channel estimation and equalization steps. After a 1 km FMF transmission, the BERs of all the subchannels were under the 20% FEC threshold of 2×10^{-2}. With mode multiplexing, the SE can be as high as 21.375 bit/s/Hz. The constellations of the recovered signal of the three modes with two polarizations are shown in the insets of Fig. 2.

100 G polarization-multiplexed quadrature phase shift keying (PM-QPSK) coherent optical single-carrier transmission technology has been widely used in commercial optical networks. How to maximize the use of limited spectrum resources and enhance the spectrum utilization of 100 G commercial systems is a hot topic for researchers. In 2013, we demonstrated a real-time 3.2 Tb/s (32×100-Gb/s) PM-QPSK transmission over 2080 km SSMF using only one laser[14].

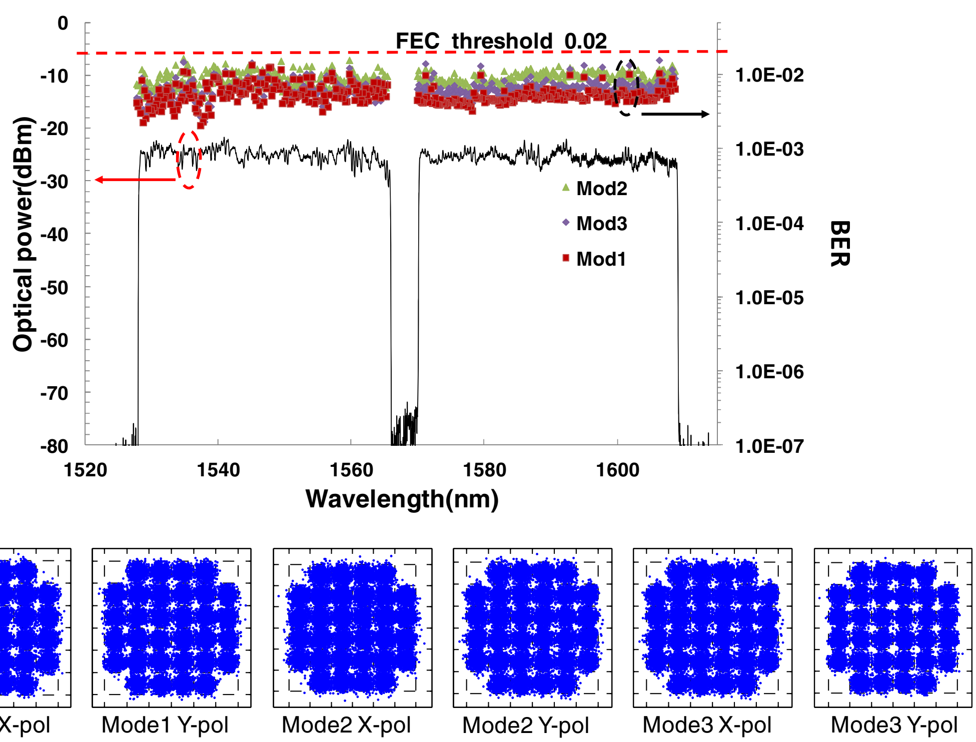

Fig. 2. BER performances of all 375 channels after a 1 km FMF transmission. Inset: received optical spectrum and received constellations of the recovered OFDM signal.

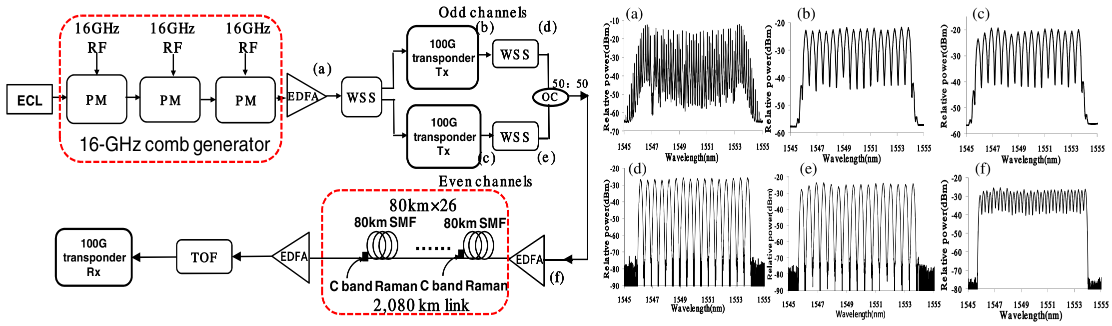

Fig. 3. Experimental setup and optical spectra.

Figure 3 shows the experimental setup as well as the optical spectra of the 32 × 100 Gb/s PM-QPSK after a 2080 km transmission. The real-time 32 × 100 Gb/s PM-QPSK modulated signal in our experiment was received using coherent detection based on a 100 G transponder at 31.78 Gbaud/s. Only one laser was used to generate all the 32 WDM channel sources on a 32 GHz grid, resulting in an SE of 3.11 bit/s/Hz. Each 100 G channel was sent into an optical filter (3 dB bandwidth of 30 GHz) to reduce the cross talk between the channels. The BERs of all the 32 WDM channels after the 2080 km transmission are shown in Fig. 4(a). It was shown that all the BERs were below the 20% FEC threshold. The optical spectrum of the 32 × 100 Gb/s signal after the 2080 km transmission is shown in the inset. The Q factor performances of the PM-QPSK signals versus distances are shown in Fig. 4(b). It can be seen that the Q factor has a 1.2 dB remaining margin and the reach can be extended to more than 3500 km when considering the soft decision low-density parity check FEC (SD-LDPC + FEC) limit with a 20% overhead. The experimental results show that the spectrum utilization of the commercial 100 G coherent DWDM transmission system can reach as high as 3.11 bit/s/Hz.

Recently, we proposed a novel polarization switched (PS) QPSK technique called manipulated rotating (MR) PS-QPSK. The corresponding correlated constant modulus algorithm (CMA) is also proposed for recovering the signal[15]. The correlated CMA uses the correlation between the PS-QPSK symbols in the two polarizations, which enable locking of the phase of signals at the output of the CMA equalizer. The equalized signals in the two polarizations are merged according to the recovered switching bit, which suppresses the noise and simplifies the processes of frequency offset and carrier phase recovery. The real-time platform is built for experimental demonstration based on the field programmable gate array (FPGA). A real-time experimental platform is built up to investigate the performance of MR-PS-QPSK, as shown in Fig. 5.

The BER versus OSNR in the back-to-back case is shown in Fig. 6(a). It can be seen that there is a 3.2 dB OSNR improvement for MR-PS-QPSK when compared with dual polarization (DP)-QPSK at a BER threshold of 2×10^{-3}, which corresponds to around a 2 dB improvement for the same bit rate (3/4 bit rate ratio subtracted). As shown in Fig. 6(b), 3.8 dB OSNR improvement can be achieved when comparing the proposed MR-PS-QPSK modulation format with correlated CMA with the conventional QPSK modulation at the same symbol rate. It is noted that improvement corresponds to be about a 2 dB OSNR improvement at the same bit rate. Only a small number of additional computational effort is required by MR-PS-QPSK with a correlated CMA after analyzing the resource consumption in the FPGA digital signal processing blocks and logic utilizations. This technique has been used for a long span of product lines of the Accelink Technologies Company Limited.

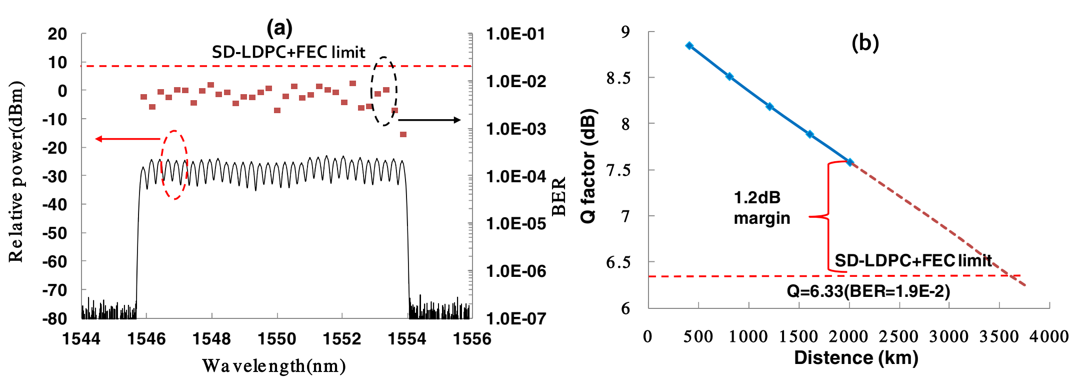

Fig. 4. (a) BER performance for the 32 WDM channels after a 2080 km transmission; (b) Q factor versus distance for the 32 × 100 Gb/s PM-QPSK signals.

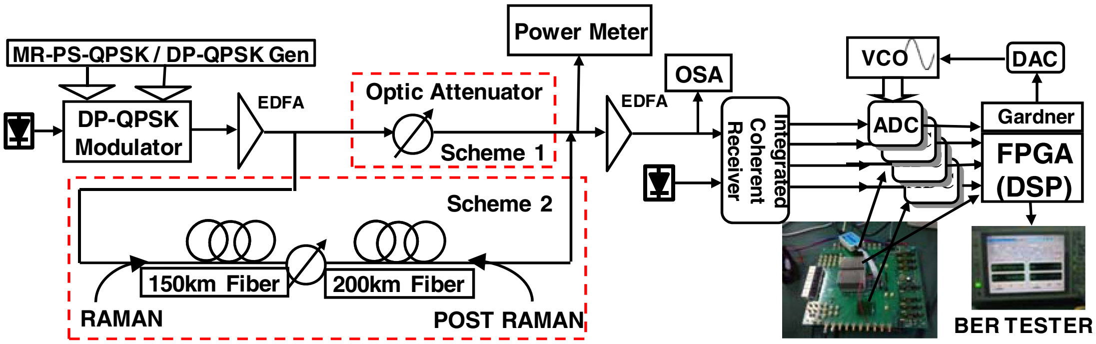

Fig. 5. Experimental setup for the real-time evaluation of the MR-PS-QPSK transmission system.

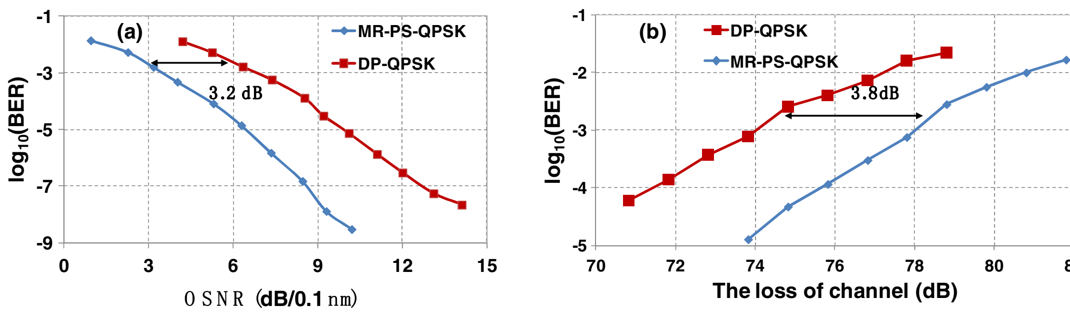

Fig. 6. (a) Back-to-back performance of DP-QPSK and MR-PS-QPSK at the same baud rate; (b) the unrepeated transmission performance of DP-QPSK and MR-PS-QPSK at the same baud rate.

In the past 5 years, Wuhan Research Institute of Posts and Telecommunications obtained a series of achievements in the field of "3U" optical transmission. Some techniques have been used in actual commercial systems. In the future, we will conduct a more in-depth research in the field of low cost IM-DD transmission, low cost coherent PON, and silicon-based optoelectronic integration, making more contributions to the optical communication industry of China.

This work was supported by the Major Scientific and Technological Innovation Projects of Hubei Province (No. 2014AAA001) and the National 973 Program of China (No. 2010CB328300).

References

1. X. Zhou, J. Yu, M. F. Huang, Y. Shao, T. Wang, L. Nelson, P. Magill, M. Birk, P. Borel, D. Peckham, and R. Lingle, in *National Fiber Optic Engineers Conference*, OSA Technical Digest (CD) (Optical Society of America, 2010), paper PDPB9.
2. D. Qian, M. F. Huang, E. Ip, Y.-K. Huang, Y. Shao, J. Hu, and T. Wang, in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2011* OSA Technical Digest (CD) (Optical Society of America, 2011), paper PDPB5.
3. A. Sano, T. Kobayashi, S. Yamanaka, A. Matsuura, H. Kawakami, Y. Miyamoto, K. Ishihara, and H. Masuda, in *National Fiber Optic Engineers Conference*, OSA Technical Digest (Optical Society of America, 2012), paper PDP5C.3.
4. S. Okamoto, K. Toyoda, T. Omiya, K. Kasai, M. Yoshida, and M. Nakazawa, in *36th European Conference and Exhibition on Optical Communication (ECOC)* (IEEE, 2010), paper PD2.3.
5. M. F. Huang, D. Qian, and E. Ip, in *Optical Fiber Communication Conference* (IEEE, 2011), paper PDPP1.
6. Q. Yang, in *Asia Communications and Photonics Conference*, OSA Technical Digest (online) (Optical Society of America, 2012), paper PAF4C.3.
7. C. Li, M. Luo, X. Xiao, Q. Yang, J. Li, Z. He, Z. Yang, and S. Yu, Chin. Opt. Lett. **12**, 040601 (2014).
8. M. Luo, C. Li, Q. Yang, Z. He, J. Xu, Z. Zhang, and S. Yu, in *Asia Communications and Photonics Conference 2014*, OSA Technical Digest (online) (Optical Society of America, 2014), paper AF4B.1.
9. Q. Yang, Z. He, Y. Zhu, S. Yu, X. Yi, and S. William, Opt. Express **20**, 2379 (2012).
10. C. Li, Q. Yang, T. Jiang, Z. He, M. Luo, C. Li, X. Xiao, D. Xue, X. Yi, and S. Yu, IEEE Photon. Technol. Lett. **24**, 1704 (2012).
11. J. Wang, S. Li, M. Luo, L. Zhu, C. Li, D. Xie, Q. Yang, S. Yu, J. Sun, X. Zhang, W. Shieh, and A. E. Willner, in *European Conference on Optical Communication* (ECOC, 2014), paper Mo.4.5.1.
12. J. Gong, J. Xu, M. Luo, X. Li, Y. Qiu, and Q. Yang, Opt. Express **14**, 24 (2016).
13. M. Luo, Q. Mo, X. Li, R. Hu, Y. Qiu, C. Li, Z. Liu, W. Liu, H. Yu, W. Du, J. Xu, Z. He, Q. Yang, and S. Yu, Front. Optoelectron. **8**, 394 (2015).
14. M. Luo, Z. Zhang, C. Li, J. Xu, Y. Cheng, D. Liu, X. Zhang, J. Li, Z. He, R. Hu, Q. Yang, and S. Yu, in *Asia Communications and Photonics Conference 2014*, OSA Technical Digest (online) (Optical Society of America, 2014), paper ATh4E.2.
15. H. Li, T. Zeng, J. Li, F. Jiang, Z. Liu, R. Hu, M. Luo, Y. Wang, X. Li, Q. Yang, S. Yu, L. Huang, and L. Cao, Opt. Express **24**, 16609 (2016).