High Speed Polarization–Division Multiplexing Transmissions Based on the Nonlinear Fourier Transform

Abstract: Polarization-division multiplexing (PDM) with modulation in the nonlinear frequency domain consisting of the discrete and/or continuous spectrum has been recently regarded as a useful method to be utilized in optical fiber communication system. It can compensate the optical fiber nonlinearity based on the nonlinear Fourier transform (NFT). In this paper, we combine PDM with the method of nonlinear frequency division multiplexing (NFDM) and demonstrate the achievable transmission rate by increasing the number of multiplexing nonlinear channels. For the selected subcarriers (i.e. 32, 64, and 128), the transmission rates are 64 Gbit/s, 76.8 Gbit/s, and 109.7 Gbit/s respectively by applying 64-quadrature amplitude modulation (64-QAM) on the nonlinear continuous spectrum. For the transmission distance shorter than 1 200 km, the transmission rate of 128-NFDM PDM system can even reach up to 153.6 Gbit/s.

Keywords: fiber optics communications; multiplexing; nonlinear optical signal processing

WANG Jia, ZHAO Yilong, HUANG Xin, and HE Guangqiang
(State Key Laboratory of Advanced Optical Communication Systems and Networks, Electronic Engineering Department, Shanghai Jiao Tong University, Shanghai 200240, China)

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1 Introduction

With the development of modern information technology, optical fiber communication plays an increasingly important role in information transmission. However, the presence of nonlinearity in optical fiber greatly hinders the improvement of transmission capacity in optical fiber communication systems [1]. When a single-channel transmission rate reaches 50 Gbit/s, nonlinearity has become a major factor affecting system performance [2].

In 1993, HASEGAWA and NYU [3] first used the nonlinear Fourier transform (NFT) to transform the signal from the time domain to the nonlinear frequency domain consisting of nonlinear discrete spectrum and/or nonlinear continuous spectrum for coding and multiplexing, which can overcome the communication constraints caused by optical fiber nonlinearity. The method is now called eigenvalue communication because of the invariance of eigenvalues. With the development of coherent detection and digital signal processing (DSP) technology recently, any complex signals can be generated and processed in communication systems. Thus, the optical fiber nonlinearity compensation coherent optical communication system based on the NFT algorithm has attracted more and more attention [4], [5].

The nonlinearity compensation algorithm based on NFT has the advantages of stable transmission and independent algorithm complexity of transmission distance. It does not affect the mixed use of various linear modulation methods [6], [7]. Taking into consideration overcoming the nonlinear effect, the transmission speed of the systems can be further improved. In 2014, YOUSEFI and KSCHISCHANG carried out theoretical modeling and numerical derivation of the NFT algorithm, and put forward the feasibility of nonlinear frequency division multiplexing (NFDM) [8]–[10]. In 2017, GOOSSENS and YOUSEFI did the similar work in polarization-division multiplexing (PDM) system and then applied it to PDM-NFDM simulation system, achieving the data rate of 44.8 Gbit/s by 112 nonlinear subcarriers and 64-quadrature amplitude modulation (64-QAM) format [11].

In this paper, the transmitted data are modulated only on the nonlinear continuous spectrum through 64-QAM, i.e. there are 6 bits per symbol. We also combine the PDM with NFDM (PDM-NFDM) and demonstrate the achievable transmission rate by increasing the number of multiplexing nonlinear channels [2] through simulation, followed by the analysis of the transmission performance of different schemes. The simulation results show the data rate is obviously increased and is more than 100 Gbit/s by utilizing 128 subcarriers, with a Q-factor about 8.19 dB at 960 km away.

2 Theory

2.1 Channel Model

The propagation of light in two polarizations in a standard single mode fiber (SSMF) is described by the coupled nonlinear Schrödinger equation (CNLSE) [11], [12]. Without considering the noise and polarization mode dispersion (PMD), the model can be expressed as following [13]–[15]:

$$\frac{\partial \vec{Q}(\tau,l)}{\partial l} = -\frac{\alpha}{2}\vec{Q}(\tau,l) - j\frac{\beta_2}{2}\frac{\partial^2 \vec{Q}(\tau,l)}{\partial \tau^2} + j\frac{8}{9}\gamma\left\|\vec{Q}(\tau,l)\right\|^2 \vec{Q}(\tau,l), \tag{1}$$

where $\vec{Q}(\tau,l)$ is the 2×1 Jones vector containing the complex envelops $Q_1(\tau,l)$ and $Q_2(\tau,l)$ of the signal components in two polarizations, τ represents time, l represents the distance along the optical fiber, α denotes the loss coefficient of the optical fiber, and β_2 and γ are constants denote fiber dispersion and Kerr nonlinearity respectively.

The system (1) is obviously not integrable because of the fiber loss term. Since the NFT is based on the integrability of NLSE [8]–[10], measures should be taken to avoid the effect of fiber attenuation. Here we use the Erbium Doped Fiber Amplifier (EDFA) to compensate the fiber loss in transmission system and adopt the idea of the lossless path-average (LPA) in [16] to derive the following model without loss term [17], [18]:

$$\frac{\partial \overline{\vec{Q}}(\tau,l)}{\partial l} = -j\frac{\beta_2}{2}\frac{\partial^2 \overline{\vec{Q}}(\tau,l)}{\partial \tau^2} + j\frac{8}{9}\gamma_1\left\|\overline{\vec{Q}}(\tau,l)\right\|^2 \overline{\vec{Q}}(\tau,l), \tag{2}$$

where the $\overline{\vec{Q}}$ and γ_1 is defined as:

$$\overline{\vec{Q}} = \vec{Q}\sqrt{G(l)}, \tag{3}$$

$$\gamma_1 = \gamma\left(\frac{1}{L_{span}}\int_0^{L_{span}} G(x)\,\mathrm{d}x\right), \tag{4}$$

where $G(x) = e^{2\int_0^x g(l)\,\mathrm{d}l}$ and $g(l) = -\frac{\alpha}{2}$.

For simplicity, it is useful to normalize (2). Let:

$$P = \frac{|\beta_2|}{\frac{8}{9}\gamma_1 T_0^2}, T_0 = \frac{T_{FWHM}}{2\ln(1+\sqrt{2})}, Z_0 = \frac{T_0^2}{|\beta_2|}, \tag{5}$$

where T_{FWHM} which represents the full width at half maximum of the pulse is a free parameter relating to the bitrate [19], [20]. Introducing the normalized variables:

$$\vec{q} = \frac{\overline{\vec{Q}}}{\sqrt{P}}, t = \frac{\tau}{T_0}, Z = \frac{l}{Z_0}, \tag{6}$$

the normalized CNLSE is derived as follows [8]–[10]:

$$j\frac{\partial \vec{q}(t,z)}{\partial z} = -\frac{1}{2}\frac{\partial^2 \vec{q}(t,z)}{\partial t^2} - \left\|\vec{q}(t,z)\right\|^2 \vec{q}(t,z). \tag{7}$$

Through the nonlinear Fourier transform, the difficulty of analysis can be simplified and the nonlinear effect can be compensated.

2.2 PDM-NFDM Scheme

According to the theory of two-dimensional electrical signals in [21], $\vec{q}(t,z)$ in (7) can be represented by a series of scattering coefficients or data (also called nonlinear spectrum). In general, the nonlinear spectrum consists of nonlinear discrete spectrum and nonlinear continuous spectrum. The process of obtaining the corresponding nonlinear spectrum from a time domain signal is called NFT, and the inverse process is known as inverse nonlinear Fourier transform (INFT). For a two-dimensional signal, its nonlinear continuous spectrum is defined as [21]–[23]:

$$q_i(\lambda) = \frac{b_i(\lambda)}{a(\lambda)}, \lambda \in \mathbb{R}, i = 1,2, \tag{8}$$

where $a(\lambda)$,$b_1(\lambda)$, and $b_2(\lambda)$ are called the nonlinear Fourier coefficients [24]. If necessary, the reader can refer to [11] for calculation of these coefficients in detail. The evolution of the nonlinear continuous spectrum along the optical fiber can be expressed as [2], [17], [25]–[27]:

$$q_i(\lambda,z) = q_i(\lambda,0)\cdot e^{2j\lambda^2 z}, i = 1,2. \tag{9}$$

It is observed that the effect of fiber dispersion and Kerr nonlinearity on the signal's nonlinear spectrum can be regarded as a simple phase rotation. The principle of eigenvalue communication is actually to use this property to compensate the fiber nonlinearity and dispersion in the nonlinear frequency domain, so is the PDM-NFDM transmission system. At the transmitter of the transmission scheme, the bit information to be transmitted is encoded on the nonlinear spectrum which can be discrete spectrum and/or continuous spectrum [28]–[33]. Subsequently, a specific time domain signal can be calculated through INFT and then be sent into the optical fiber. At the receiver, the received time domain signal is then processed by NFT to obtain the corresponding nonlinear spectrum, $q(\lambda,z)$, when the transmission distance is z. According to (9), the initial nonlinear continuous spectrum $q(\lambda,0)$ can be recovered through a phase compensation and thus we can obtain the bit information by decoding the recovered nonlinear spectrum. It can be found that the complexity of the nonlinear compensation algorithm based on NFT in the coherent optical communication system is independent of the transmission distance and does not affect the mixed use of various linear modulation schemes, so it can be utilized in NFDM, PDM and other transmission systems.

3 Simulation

Fig. 1 shows the scheme of simulation system and data processing process based on the theories above. Details about the specific data processing can be found in the following sections.

3.1 Transmitter

This part mainly introduces the process of data processing on the transmitter. For the generated transmitted bits, we first start with a string-to-parallel transformation for data mapping of 64-QAM format. In this way, each 6 bits of data will correspond to a special amplitude and phase in total 64 cases. Next, we modulate the transmitted information on the nonlinear continuous spectrum. For each polarization component, the spectrum is shown in the following formula [17], [25], [29].

$$U_i(\lambda,m)=A\sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1}C_{i,m,k}\frac{\sin(\lambda T_p+k\pi)}{\lambda T_p+k\pi}e^{-2jm\lambda T_1},i=1,2. \quad (10)$$

In the upper formula, λ is the nonlinear frequency, m is the data block index, $U_i(\lambda,m)$ denotes the synthetic continuous spectrum, A is the power control parameter, N represents the number of multiplexed nonlinear channels, and $C_{i,m,k}$ is a complex number drawn from the 64-QAM constellation diagram. In addition, $T_p = 2ns/T_0$ represents the useful data duration, where T_0 is the parameter given in (5) and T_1 denotes the total data duration taking into consideration the delay in the system transmission. For the selected subcarriers (i.e. 32, 64, and 128), the corresponding T_1 are $6ns/T_0$, $10ns/T_0$, and $14ns/T_0$ respectively. Thus, when the baud rate is set to 0.5 Gbaud/s, the transmission rates of the PDM-NFDM systems are 64 Gbit/s, 76.8 Gbit/s and 109.7 Gbit/s, respectively. According to the theory in [11] and [34], $U_i(\lambda,m)$ obtained above is actually within the area called U-domain, so we should subsequently convert the data from U-domain to nonlinear Fourier domain. The relationship between them is [34]:

$$q_i(\lambda)=\sqrt{e^{\left|U_i(\lambda)\right|^2}-1}\cdot e^{j\angle(U_i(\lambda))}, i=1,2. \quad (11)$$

After that, we can calculate the two-dimensional time domain signal through INFT, inversely normalize the signal, carry out the electro-optic conversion, and then send the corresponding optical signal together with the protection interval to the optical fiber.

3.2 Optical Fiber

The standard single mode fiber is used here for simulation. The dispersion and nonlinear coefficients of the fiber are calculated by the following formulas [19]–[20]:

$$\beta_2=-\frac{\lambda^2}{2\pi c}D_\lambda, \quad (12)$$

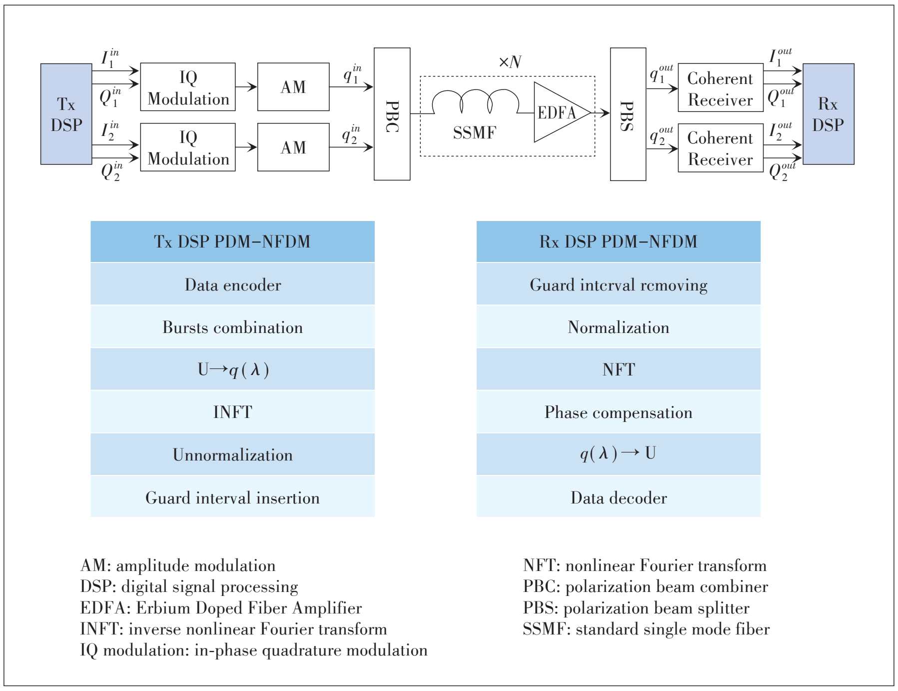
$$\gamma=\frac{2\pi n_2 f_{ref}}{cA_{eff}}, \quad (13)$$

where λ is the wavelength of the reference light, f_{ref} is the reference frequency, D_λ denotes the dispersion coefficient in terms of wavelength, c is the velocity of light in vacuum, n_2 represents the nonlinear refractive index, and A_{eff} refers to the effective core area of the fiber for nonlinearity calculations. In our simulation, the parameters related to β_2 and γ are set as: f_{ref} = 193.1 THz, $D_\lambda = 16e^{-6}$ s/m^2, $n^2 = 2.6e^{-20}$ m^2/W, and $A_{eff} = 80.0e^{-12}$ m^2 and then useful parameters can be calculated through (12) and (13).

As mentioned in Section 2.1, the system (1) is obviously not integrable in the presence of fiber loss and thus NFT does not apply. For the sake of lossless transmission model, we utilize EDFAs to equalize the fiber attenuation each 80 km and the fiber loss is set as 0.2 dB/km. The length of total optical fiber could be increased by loop links.

3.3 Receiver

At the receiver, we first demodulate the received optical signal by a coherent demodulator and subsequently carry on the



AM: amplitude modulation
DSP: digital signal processing
EDFA: Erbium Doped Fiber Amplifier
INFT: inverse nonlinear Fourier transform
IQ modulation: in-phase quadrature modulation
NFT: nonlinear Fourier transform
PBC: polarization beam combiner
PBS: polarization beam splitter
SSMF: standard single mode fiber

▲Figure 1. PDM-NFDM transmission system with data processing process in the transmitter and receiver.

optic-electro conversion. By this way, we can get the time domain electrical signal of two polarization components. Before we carry on the NFT to the two-dimensional time domain signal, we first normalize it according to (5). For the method that the evolution of nonlinear spectrum is just a simple phase rotation as expressed in (9), we then compensate the effect of fiber dispersion and Kerr nonlinearity by this way to obtain $q(\lambda,0)$. Later, we refer to (11) to recovery the data from nonlinear Fourier domain to U-domain, i.e. the formula in (11) will be rewritten as:

$$U_i(\lambda) = \sqrt{\log(1 + \left|q_i(\lambda)\right|^2} \cdot e^{j\angle(qi(\lambda))},\ i = 1,2. \tag{14}$$

Due to the presence of phase noise and frequency offset, the carrier recovery algorithm [35] is necessary. Then the transmission performance of the system can be analyzed by drawing the 64-QAM constellation diagram, decoding the symbols and calculating the symbol error rate (SER) or Q-factor.

4 Results

In this paper, we first demonstrate the achievable transmission rate by increasing the number of multiplexing nonlinear channels through simulation. For the subcarriers utilized (i.e., 32, 64, and 128), the transmission rates are 64 Gbit/s, 76.8 Gbit/s and 109.7 Gbit/s respectively by 64-QAM on the nonlinear continuous spectrum. We then show it is necessary to eliminate the frequency offset and phase noise in the NFDM transmission systems, especially when the number of multiplexing channels is large. Finally, we mainly analyze the high-speed transmission performance of system with 128 subcarriers, in which case the transmission rate of the PDM-NFDM system reaches 109.7 Gbit/s.

4.1 Reachable Transmission Rate

Table 1 shows some parameters we used in different PDM-NFDM transmission systems. The achieved spectral efficiency of each system and the corresponding SER with the launched power around -3 dBm (-3.22 dBm for the case of 32-subcarriers, -2.75 dBm for 64-subcarriers and -3.07 dBm for 128-subcarriers) are also given in the table. It is worth noticing that the launched power here is not the optimal power, which means that each transmission system may be able to achieve a more reliable transmission performance in other cases. In this section, just phase noise and additive white Gaussian noise (AWGN) are taken into consideration and thus the optical signal to noise ratio (OSNR) used here are all over 18 dB.

It can be inferred from Table 1 that the transmission rate of optical fiber communication system increases significantly with the increase of multiplexed nonlinear channels, but a higher spectral efficiency is achieved in the PDM-NFDM system with 32 subcarriers than other cases, which is largely due to the effect of optical fiber dispersion. It is well known that different frequency components of the optical signal transmitted in the optical fiber will travel at different speeds, which inevitably cause signal distortion after reaching a certain distance. The signal distortion is shown as pulse broadening in the time domain. The phenomenon is certain to get serious with the increase of the number of multiplexing channels or signal bandwidth and then a longer zero guard interval during the long distance transmission is required, thus decreasing the effective transmission rate correspondingly. Therefore, the guard interval used to reducing the inter-symbol interference is an important influencing factor to the balance of transmission rate and transmission distance.

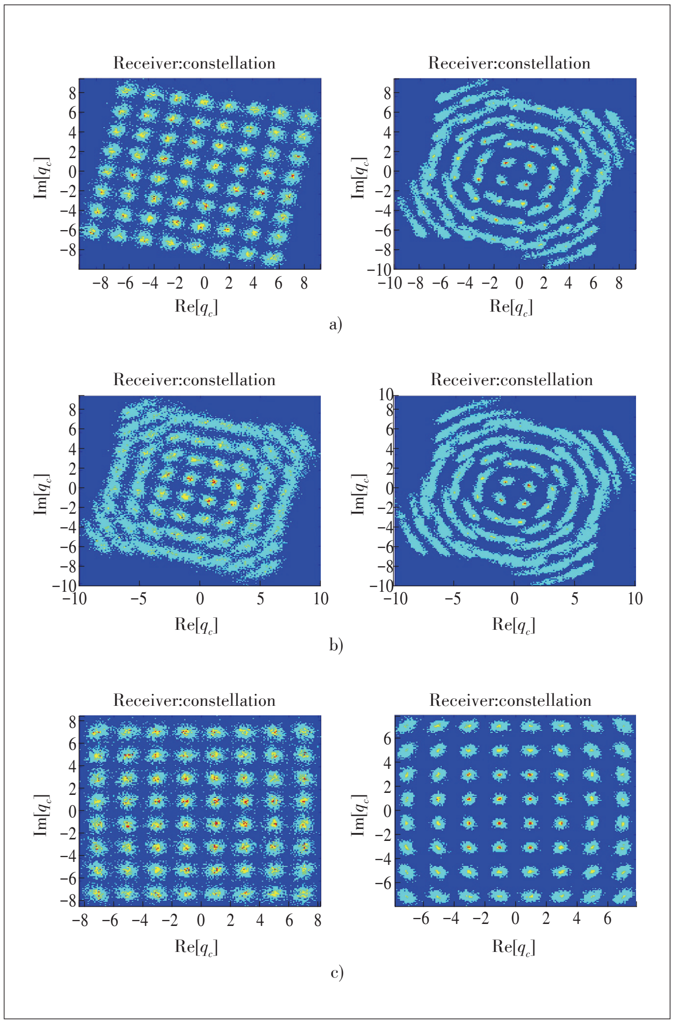
4.2 The Effect of Frequency Offset

Carrier synchronization is a very important problem in traditional orthogonal frequency division multiplexing (OFDM) systems, as is the case with NFDM systems. The carrier frequency offset caused by devices or nonlinear channels or other factors can damage the orthogonality between the subcarriers, thus introducing the subcarriers interference, as well as the rotation of the signal constellation diagram. Unsurprisingly, these effects will cause the decision error of a demodulation signal to a large extent and thus the carrier frequency offset should be compensated in the coherent NFDM systems. Here, the effect of frequency offset as well as the influence of laser linewidth is given through the simulation results in both cases where the number of subcarriers is 32 and 128, just as shown in **Fig. 2**. It should be noted that the launched power is approximately -3.07 dBm and the transmission distance is 960 km for all the simulation systems in this section. At the same time, in order to clearly observe the effect of frequency offset and phase noise on transmission performance, the additive noise of the channel is not considered in this section.

We simply set the laser linewidth in the simulation system

▼Table 1. The parameters used in different PDM-NFDM transmission systems

Channels	Baud rate /Gbaud	Guard interval /ns	Modulation format	Bandwidth /GHz	Transmission rate /(Gbit/s)	Spectral efficiency /(bit/s/Hz)	Distance /km	Q-factor
32	0.5	4	64-QAM	16	64	4	1 200	6.234
64	0.5	8	64-QAM	32	76.8	2.4	1 200	7.405
128	0.5	12	64-QAM	64	109.7	1.71	1 200	6.751
128	0.5	8	64-QAM	64	153.6	2.4	960	8.195



▲Figure 2. The constellation diagram at the distance of 960 km for the case of 32 subcarriers (left column) and 128 subcarriers (right column); a) linewidth=0, w/o carrier recovery; b) linewidth=1 kHz, w/o carrier recovery; c) linewidth=1 kHz, with carrier recovery.

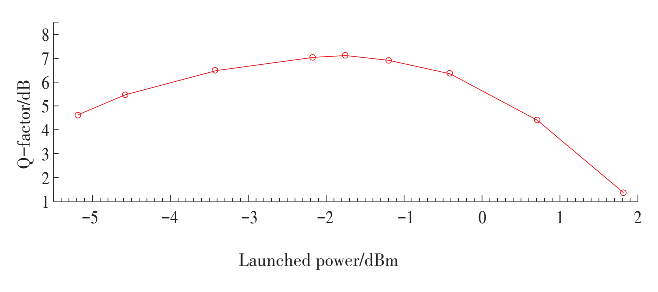
to 0 when the effect of frequency offset is studied only. At the receiver, we obtain the constellation diagram as Fig. 2a after utilizing the theory of NFT for compensation of fiber dispersion and Kerr nonlinearity. It can be inferred that the rotation of signal constellation diagrams here is due to the frequency offset that is estimated to be about 0.25 GHz for the case of 32 subcarriers and 0.36 GHz for 128 subcarriers, which severely affect the data decision. To be exact, the symbol error rate is calculated as 0.5254 in 32-NFDM PDM system and 0.3721 in 128-NFDM PDM system, neither of which can be served as an effective transmission of optical fiber communication system. Furthermore, the influence of laser linewidth is increased, i.e. the corresponding parameters in the simulation system are set to 1 kHz, and the receiver results are finally obtained as shown in Fig. 2b. As we can see from the diagrams, the additional phase noise is introduced to the transmission systems because of the laser linewidth, which increases the SER to 0.5681 in the case of 32 subcarriers and 0.5945 for 128 subcarriers, further degrading the transmission performance of the system. For the sake of effective transmission, we then adopt the carrier recovery algorithm [35] at the receiver after the compensation for fiber nonlinearity based on NFT and successfully improve the transmission performance (Fig. 2c). Under this situation, the SERs are calculated as 1.01e-2 and 1.53e-5, respectively.

We can conclude from the figures that the PDM-NFDM scheme based on NFT well compensates the negative effects of fiber nonlinearity on the optical fiber communication by simultaneously solving the problem of unsynchronization at both transmitters and receivers of the transmission systems. At the same time, it is obvious that the 128-NFDM PDM transmission system outperforms the 32-NFDM PDM case in this section, which is largely due to the launched power. In fact, different optimum launched powers will be applied to different transmission systems. However, we carry on the above simulation cases at the same launched power approximately -3.07 dBm for simplicity, which means that this value is not be in the best performance range for 32-NFDM PDM system while near the best performance range for 128-NFDM PDM system. As an example, the optimal power for 128-NFDM PDM system is given in the next section.

4.3 The Optimum Launched Power

In this part, we conduct the simulation of the relationship between Q-factor and the launched power by the PDM-NFDM transmission system with 128 multiplexed channels. **Fig. 3** shows the corresponding results with all the transmission distances at 1 200 km and OSNR over 18 dB.

As shown in Fig. 3, the Q-factor of this specific fiber nonlinear compensation communication system based on NFT reaches the maximum close to 7 dB when the launched optical power is around -1.75 dBm. That is to say, there is a choice of optimum launched power for this 128-NFDM PDM transmission system to achieve its best compensation performance, which can be utilized as a notice in engineering applications. In addition, we also give the comparison of the two received constellation diagrams with the launched power of -1.7563 dBm and



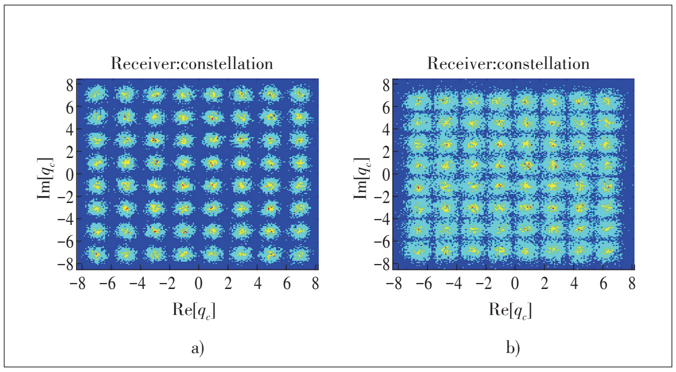
▲ Figure 3. Q-factor versus launched power with the case of 128 subcarriers.

1.8092 dBm respectively for a more obvious display (**Fig. 4**).

5 Conclusions

We present the process of modulating the necessary transmitted data on the nonlinear continuous spectrum through 64-QAM format, transmitting them through the optical fiber communication system and then compensating the effect of Kerr nonlinearity at the receiver. We also combine the PDM with NFDM technology to improve the transmission capacity and demonstrate the achievable transmission rate by increasing the number of multiplexing nonlinear channels through simulation. Moreover, we analyze the transmission performance of the different schemes. As a result, for the selected subcarriers (i.e., 32, 64, and 128), the transmission rates are 64 Gbit/s, 76.8 Gbit/s and 109.7 Gbit/s respectively. For the transmission distance shorter than 1 200 km, the transmission rate of 128-NFDM PDM system can even reach up to 153.6 Gbit/s. In addition to the effects of fiber dispersion and nonlinearity which can be compensated by the theory of NFT, carrier frequency offset and phase noise can degrade the system performance severely, especially when the number of multiplied nonlinear channels is large. It is demonstrated that a better transmission performance could be obtained for the PDM-NFDM transmission system by taking measures to compensate the frequency offset and phase noise simultaneously.

Aside from the launched power, many other factors will also have effects on the performance of this nonlinearity compensation system unavoidably, various noise included. In this paper, we just carry on a research related to the AWGN and phase noise, thus we still have a lot to do in the future to improve the transmission performance of high-speed optical fiber communication with various noise taken into account.



a)

b)

▲**Figure 4. Constellation diagram at the receiver a) with the launched power at −1.7563 dBm; b) with the launched power at 1.8092 dBm.**

References

[1] ESSIAMBRE R J, KRAMER G, WINZER P J, et al. Capacity Limits of Optical Fiber Networks [J]. Journal of Lightwave Technology, 2010, 28(4): 662–701. DOI: 10.1109/JLT.2009.2039464

[2] SON T Le, VAHID A, HENNING B. High Speed Precompensated Nonlinear Frequency-Division Multiplexed Transmissions [J]. Journal of Lightwave Technology, 2018, 36(6):1296–1303. DOI: 10.1109/JLT.2017.2787185

[3] HASEGAWA A, NYU T. Eigenvalue Communication [J]. Journal of Lightwave Technology, 1993, 11(3): 395–399. DOI: 10.1109/50.219570

[4] PRILEPSKY J E, DEREVYANKO S A. Nonlinear Inverse Synthesis and Eigenvalue Division Multiplexing in Optical Fiber Channels [J]. Physical Review Letters, 2014, 113(1): 013901. DOI: 10.1103/PhysRevLett.113.013901

[5] SON T L, PRILEPSKY J E, ROSA P, et al. Nonlinear Inverse Synthesis for Optical Links with Distributed Raman Amplification [J]. Journal of Lightwave Technology, 2016, 34(8): 1778–1786. DOI: 10.1109/JLT.2015.2511084

[6] TURITSYNA E G, TURITSYN S K. Digital Signal Processing Based on Inverse Scattering Transform [J]. Optics Letters, 2013, 38(20): 4186–4188. DOI: 10.1364/OL.38.004186.

[7] SON T Le, PRILEPSKY J E, TURITSYN S K. Nonlinear Inverse Synthesis for High Spectral Efficiency Transmission in Optical Fibers [J]. Optics Express, 2014, 22(22): 26720–26741. DOI: 10.1364/OE.22.026720

[8] YOUSEFI M I, KSCHISCHANG F R. Information Transmission Using the Nonlinear Fourier Transform, Part I: Mathematical Tools [J]. IEEE Transactions on Information Theory, 2014, 60(7): 4312–4328. DOI: 10.1109/TIT.2014.2321143

[9] YOUSEFI M I, KSCHISCHANG F R. Information Transmission Using the Nonlinear Fourier Transform, Part II: Numerical Methods [J]. IEEE Transactions on Information Theory, 2014, 60(7): 4329–4345. DOI: 10.1109/TIT.2014.2321151

[10] YOUSEFI M I, KSCHISCHANG F R. Information Transmission Using the Nonlinear Fourier Transform, Part III: Spectrum Modulation [J]. IEEE Transactions on Information Theory, 2014, 60(7): 4346–4369. DOI: 10.1109 / TIT.2014.2321155

[11] GOOSSENS J W, YOUSEFI M I, JAOUEN Y, et al. Polarization-Division Multiplexing Based on the Nonlinear Fourier Transform [J]. Optics Express, 2017, 25(22): 26437–26452. DOI: 10.1364/OE.25.026437

[12] MENYUK C R. Pulse Propagation in An Elliptically Birefringent Kerr Medium [J]. IEEE Journal of Quantum Electronics, 1989, 25(12): 2674–2682. DOI: 10.1109/3.40656

[13] WAI P K A, MENYUK C R. Polarization Mode Dispersion, Decorrelation, and Diffusion in Optical Fibers with Randomly Varying Birefringence [J]. Journal of Lightwave Technology, 1996, 14(2): 148–157. DOI: 10.1109/50.482256

[14] MARCUSE D, MENYUK C R, WAI P K A. Application of the Manakov-PMD Equation to Studies of Signal Propagation in Optical Fibers with Randomly Varying Birefringence [J]. Journal of Lightwave Technology, 1997, 15(9): 1735–1746. DOI: 10.1109/50.622902

[15] MENYUK C R, MARKS B S. Interaction of Polarization Mode Dispersion and Nonlinearity in Optical Fiber Transmission Systems [J]. Journal of Lightwave Technology, 2006, 24(7): 2806–2826. DOI: 10.1109/JLT.2006.875953

[16] SON T Le, PRILEPSKY J E, TURITSYN S K. Nonlinear Inverse Synthesis Technique for Optical Links with Lumped Amplification [J]. Optics Express, 2015, 23(7): 26720–26741. DOI: 10.1364/OE.23.008317

[17] SON T Le, HENNING B. 640.5 Gbaud Nonlinear Frequency Division Multiplexed Transmissions with High Order Modulation Formats [J]. Journal of Lightwave Technology, 2017, 35(17): 3692–3698. DOI: 10.1109/JLT.2017.2718105

[18] HASEGAWA A, KODAMA Y. Solitons in Optical Communications [M]. Oxford, U.K.: Oxford Univ. Press. 1995

[19] VPIsystems. Photonic Modules Reference Manual [Z]. Holmudd, USA, 2002: 337–350

[20] MYNBAEV D K, SCHEINER L L. Fiber-Optic Communications Technology [M]. Cambridge, USA: Academic press, 2008

[21] MANAKOV S V. On the Theory of Two-Dimensional Stationary Self-focusing of Electromagnetic Waves [J]. Soviet Journal of Experimental and Theoretical Physics, 1974, 38(2): 248–253.

[22] DEGASPERIS A, LOMBARDO S. Integrability in Action: Solitons, Instability and Rogue Waves [M]. New York City, USA: Springer International Publishing, 2016

[23] GAIARIN S, PEREGO A M, SILVA E P D, et al. Dual-Polarization Nonlinear Fourier Transform-Based Optical Communication System [J]. Optica, 2018, 5 (3): 263–270. DOI: 10.1364/OPTICA.5.000263

[24] GUI T, CHAN T H, LU C, et al. Alternative Decoding Methods for Optical Communications Based on Nonlinear Fourier Transform [J]. Journal of Lightwave Technology, 2017, 35(9): 1542–1550. DOI: 10.1109/JLT.2017.2654493

[25] SON T L, VAHID A, HENNING B. Nonlinear Signal Multiplexing for Communication Beyond the Kerr Nonlinearity Limit [J]. Nature Photonics, 2017, 11: 570–577. DOI: 10.1038/NPHOTON.2017.118

[26] TURITSYN S K, PRILEPSKY J E, SON T Le, et al. Nonlinear Fourier Transform for Optical Data Processing and Transmission: Advances and Perspectives

➡**To P. 62**

References

[1] WONG E, GRIGOREVA E, WOSINSKA L, et al. Enhancing the Survivability and Power Savings of 5G Transport Networks Based on DWDM Rings [J]. IEEE/OSA Journal of Optical Communications & Networking, 2017, 9(9): D74–D85. DOI: 10.1364/JOCN.9.000D74

[2] TANAKA T, INUI T, KADOHATA A, et al. Adaptive and Efficient Multilayer Elastic Optical Network Planning [C]//42nd European Conference on Optical Communication. Düsseldorf, Germany, 2016.

[3] THYAGATURU A S, MERCIAN A, MCGARRY M P, et al. Software Defined Optical Networks (SDONs): A Comprehensive Survey [J]. IEEE Communications Surveys & Tutorials, 2016, 18(4): 2738–2786. DOI: 10.1109 / COMST.2016.2586999

[4] THOUÉNON G, BETOULE C, KHODASHENAS P S, et al. Electrical v/s optical aggregation in multi-layer optical transport networks [C]//IEEE International Conference on Photonics in Switching. Florence, Italy, 2015: 28–30. DOI: 10.1109/PS.2015.7328942

[5] YANG H, WANG R, WRIGHT P, et al. Impact of WSS Passband Narrowing Effect on the Capacity of the Flexible-Spectrum Networks [C]//IEEE Optical Fiber Communications Conference and Exhibition. Los Angeles, USA, 2017: W1I.5. DOI: 10.1364/OFC.2017.W1I.5

[6] LI X, TANG Y, GUO J F, et al. A Novel BV-WSS Based Flow Aggregation (BV-WSS-FA) Scheme for Finer-Grained Services in Elastic Optical Networks [C]// 16th International Conference on Optical Communications and Networks (ICOCN), Wuzhen, China, 2017: 1–3. DOI:10.1109/ICOCN.2017.8121320

[7] DUAN Z W, LI H, LIU Y Z, et al. Effective Distance Adaptation Traffic Dispatching in Software Defined IP over Optical Network [C]//Proc. SPIE 10464, AOPC 2017: Fiber Optic Sensing and Optical Communications. Bellingham, USA: SPIE, 2017: 1046420. DOI: 10.1117/12.2285596

[8] LYU C J, LI H, JI Y F, et al. Holding-Time-Aware Asymmetric Spectrum Allocation in Virtual Optical Networks [C]// Proc. SPIE 10464, AOPC 2017: Fiber Optic Sensing and Optical Communications. Bellingham, USA: SPIE, 2017: 104641V. DOI: 10.1117/12.2285545

[9] GAVIGNET P, LE ROUZIC E, PINCEMIN E, et al. Time and Spectral Optical Aggregation for Seamless Flexible Networks [C]//IEEE International Conference on Photonics in Switching. Florence, Italy, 2015: 43–45. DOI: 10.1109/PS.2015.7328947

Biographies

NI Dong received the bachelor's degree in communication engineering from Jilin University, China in 2017. She is currently a graduate student in Information and Communication Engineering at Beijing University of Posts and Telecommunications, China. In the period of graduate study, her main research field is the theory and technology of IP over elastic optical networks.

Li Hui (lihui@bupt.edu.cn) is an associate professor in the Broadband Network Innovation Research Center Lab, School of Information and Telecommunication, Beijing University of Posts and Telecommunications, China. Her main research field is optical network planning and optimization.

JI Yuefeng is a Ph.D. supervisor and professor of Beijing University of Posts and Telecommunications, China. His research interests include optical communication and broadband networks.

LI Hongbiao has been working in the Wireline Product Operation Department of ZTE Corporation since 1999.He is currently a member of ZTE's strategic expert group and the chief planner of the transport network, mainly engaging in communication transport network technology research and planning work.

ZHU Yinan graduated from Nanjing University of Posts and Telecommunications, China in 2015. At present, he is engaged in the planning of transport network solutions in ZTE Corporation and is mainly responsible for SDN and IP+optical coordination. He has also been a CCIE since 2014.

⬅From P. 55

[J]. Optica, 2017, 4(3): 307–322. DOI: 10.1364/OPTICA.4.000307

[27] ZAKHAROV V E, SHABAT A B. Exact Theory of 2-Dimensional Self-Focusing and One-Dimensional Self-Modulation of Waves in Nonlinear Media [J]. Soviet Journal of Experimental and Theoretical Physics, 1972, 34: 62–69.

[28] SON T L, HENNING B, VAHID A. Demonstration of 640.5 Gbaud Nonlinear Frequency Division Multiplexed Transmission with 32QAM Formats [C]//Optical Fiber Communications Conference and Exhibition (OFC). Los Angeles, USA, 2017: W3J.1.

[29] VAHID A, HENNING B. Experimental Demonstration of Nonlinear Frequency Division Multiplexed Transmission [C]//European Conference on Optical Communication (ECOC). Valencia, Spain, 2015. DOI: 10.1109 / ECOC.2015.7341903

[30] VAHID A, SON T Le, HENNING B. Demonstration of Fully Nonlinear Spectrum Modulated System in the Highly Nonlinear Optical Transmission Regime [C]//European Conference on Optical Communication (ECOC). Duesseldorf, Germany, 2016: 18–22.

[31] HE G-Q, WANG L-N, LI C-Y, et al. Spectral Function Modulation Based on Nonlinear Frequency Division Multiplexing [J]. Scientific Reports, 2017, 7: 6058. DOI:10.1038/s41598-017-06427-1

[32] WANG L-N, LIU S-Y, LI C-Y, et al. A Combination of Eigenvalue and Spectral Function Modulation in Nonlinear Frequency Division Multiplexing [C]//OSA Nonlinear Optics Toptical Meeting (NLO). Waikoloa, Hawaii, USA, 2017: NW4A.21.

[33] LIU S-Y, WANG L-N, LI C-Y, et al. Spectral Function Modulation Based on Nonlinear Fourier Transform [C]//OSA Nonlinear Optics Toptical Meeting (NLO). Waikoloa, Hawaii, USA, 2017: NW4A.22

[34] YOUSEFI M I, YANGZHANG X. Linear and Nonlinear Frequency-Division Multiplexing [C]//2016 42nd European Conference on Optical Communication (ECOC). Duesseldorf, Germany, 2016: 342–344

[35] PFAU T, HOFFMANN S, NOÉ R. Hardware-Efficient Coherent Digital Receiver Concept with Feedforward Carrier Recovery for M-QAM Constellations [J]. Journal of Lightwave Technology, 2009, 27(8): 989–999. DOI: 10.1109 / JLT.2008.2010511

Biographies

WANG Jia (jwang_wj@sjtu.edu.cn) received her B.S. degree in communication engineering from Nanjing Tech University, China in 2017. She is currently a postgraduate in the School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, China. Her main research interest is nonlinear optics.

ZHAO Yilong is pursuing his bachelor degree in electronic science and technology at Shanghai Jiao Tong University, China. His research interests include fiber nonlinearity mitigation algorithm and artificial intelligence.

HUANG Xin is pursuing his bachelor degree in information engineering at Shanghai Jiao Tong University, China. His research interests include optical communication, nonlinear photonics, and embedded system.

HE Guangqiang received his Ph.D. degree in communication and information system from Shanghai Jiao Tong University, China in 2006. He joined the Department of Electronic Engineering, Shanghai Jiao Tong University as a lecturer in 2006. From 2009 to 2010, he was a visiting scientist in Department of Physics and Astronomy, University of Rochester, New York, USA. Since December 2011, he has been an associate professor in the Department of Electronic Engineering, Shanghai Jiao Tong University. He has published over 50 SCI papers and held 5 patents. His research interests include quantum information processing, quantum entanglement, quantum cryptography, and nonlinear optics.