International Journal of Science and Research (IJSR)
ISSN: 2319-7064
SJIF (2022): 7.942

NFDM - Analysis through Simulation

Maheshwari[1], S Akhila[2]

[1, 2]Department of ECE, BMS College of Engineering, Bangalore, India

[1]*maheshwari.ldc20[at]bmsce.ac.in*
[2]*akhilas.ece[at]bmsce.ac.in*

Abstract: ***The nonlinearity of optical fiber systems is believed to be the main limiting factor that declines the performance at high signal powers. This paper primarily investigates the use of fiber nonlinearity in a constructive way, rather than treating it as a problem. Through simulation we tried to come up with a unified method for communication over optical fiber networks using NFDM software suite in Windows environment. Furthermore, we investigated optical link performance parameters such as spectral efficiency, EVM, and for NFDM systems using a pre-compensation technique. The simulations were carried out with the open-source software environment NFDMlab, which uses FNFT, a software library to compute NFTs and INFTs. The NFDM (de-) modulator modules utilize the C software library FNFT to compute (inverse) NFTs, which is interfaced using the Python wrapper. We successfully built a working environment on the Windows platform, used Anaconda distribution package. Simulations are carried out to see higher data rate of NFDM systems by increasing the number of modulated nonlinear subcarriers along with the application of a pre-compensation technique. As a result, a record-high data rate up to 200 Gb/s and spectral efficiency (SE) over 3.72 bits/s/Hz in burst-mode, single-polarization NFDM transmissions were achieved over 976 km of standard single mode fiber (SSMF) with 222 64-QAM-modulated nonlinear subcarriers simultaneously.***

Keywords: Fiber-optic communication, Nonlinear frequency division multiplexing, Nonlinear Fourier transform, Dispersion decreasing fiber, Nonlinear Fourier Transform.

1. Introduction

Previously telecommunication system used smoke signals and drums. The advancement in telecommunication has been unstoppable since telegraph was invented in the first half of the 19th century. Then, after the invention of the laser in the 1960s, the arrival of light wave communication, which enable available bandwidth and increases the performance of communication systems. In 1970, the first optical fiber with sufficient low loss was developed. Fiber optic communication systems, use optical fibers to transmit information, till 1980.Next optical amplifiers are invented which enables longer distances without regenerating the signal. Further wavelength-division multiplexing (WDM) and higher order modulation formats allowed to further increase the bit rate-distance product.

The global data traffic is increasing exponentially, and it is becoming a challenging aspect in current-generation of optical fiber communication systems to meet the data rate demand. In the past few years, a revolutionary approach has been actively investigated to use fiber nonlinearity in a constructive way, rather than treating it as a perturbation. This approach uses the NFT [3]. A sort of nonlinear analog of the conventional Fourier transform (FT)—to decompose a signal into a set of discrete and continuous spectral components, together called nonlinear spectrum, that develops in a simple linear way along with the nonlinear fiber channel. The Nonlinear Fourier transform is a method for solving integrable non-linear partial differential equations like NLSE, control wave propagation in certain nonlinear media. Conventional Fourier transform was originally developed to solve the heat equation, is a standard example for a linear evolution equation. Nonlinear Fourier transforms (NFTs) are generalizations of the conventional Fourier transform that can be used to solve certain nonlinear evolution equations popular examples for nonlinear evolution equations are nonlinear Schrödinger equation (NLSE). NFT decomposes a signal into continuous spectrum and discrete spectrum. The continuous part consists of continuous spectral functions representing the radiative components of the signal. The discrete part consists of a set of isolated points called Eigen values representing the soliton components of the signal.

Simulations are carried out to see higher data rate of NFDM systems by increasing the number of modulated nonlinear subcarriers and investigated optical link performance parameters such as spectral efficiency, EVM with the application of a pre-compensation technique [1] for the channel-induced phase-shift in the nonlinear Fourier domain. The simulations were carried out with the open-source software environment NFDMlab, which uses FNFT, a software library to compute NFTs and INFTs [4] . The NFDM (de-) modulator modules utilize the C software library FNFT [5] to compute (inverse) NFTs, which is interfaced using the Python wrapper.

Table 1: Literature Survey

Title	Author	Year of publication	Description
High Speed Pre-Compensated Nonlinear Frequency-Division Multiplexed Transmissions	Son Thai Le, Vahid Aref	2018	In this paper, author experimentally demonstrated a practical approach for increasing the data rate of NFDM transmission systems by increasing the number of modulated nonlinear subcarriers together with the application of a pre-

			compensation technique for the channel-induced phase-shift in the nonlinear Fourier domain.
Exact NFDM Transmission in Presence of Fiber-Loss	Vinod Bajaj and Shrinivas Chimmalgi	2020	In this paper NFDM techniques is applied to the NLSE which models signal in a lossless fiber. True lossy NLSE is approximated by a lossless NLSE using the path-average approach. The error of the path-average approximation depends strongly on signal power, bandwidth, and the span length. But it degrades the performance of NFDM systems designing high data rate due to nonlinearity. So nonlinearity mitigation can be achieved in lossy fibers by designing an NFDM system with DDF Dispersion-decreasing fibers.
Linear and Nonlinear FDM	Mansoor Yousefi and XianheYangzhang	2020	In this paper, two signal multiplexing schemes for optical fiber communication are considered: Wavelength-division multiplexing (WDM) and nonlinear frequency-division multiplexing (NFDM), WDM is considered for linear multiplexing and NFDM is considered for NON-linear multiplexing The NFDM AIR(Achievable information rates) is greater than the WDM AIR subject to a bandwidth and average power Achievable information rates are theoretical values that are linked to information that is transmitted through a given channel.
FNFT: A Software Library for Computing Nonlinear Fourier Transforms	Wahls et al	2018	FNFT is one of the reliable and efficient software library for computing NFTs.
Information Transmission using the NFT - I	M. Yousefi and F.R. Kschischang	2014	This paper explains the mathematical tools that underlie the method to solve nonlinear Fourier transform (NFT); NFT is a powerful tool in soliton theory and exactly solvable models, is a method for solving integrable partial differential equations governing wave propagation in certain nonlinear media. Information is encoded in the nonlinear frequencies and their spectral amplitudes. Unlike most other fiber-optic transmission schemes, this technique deals with both dispersion and nonlinearity directly and unconditionally without the need for dispersion or nonlinearity compensation methods.
Information Transmission using the NFT - II	M. Yousefi and F.R. Kschischang	2014	In this paper, numerical methods are suggested to compute the discrete and the continuous spectrum of a signal with respect to the Zakharov–Shabat system, a Lax operator underlying numerous integrable communication channels including the nonlinear Schrödinger channel, modeling pulse propagation in optical fibers.
Information Transmission using the NFT - III	M. Yousefi and F.R. Kschischang	2014	PART-III of this paper, emphasis is placed on modulation of the discrete component of the nonlinear Fourier transform of the signal and some simple examples of achievable spectral efficiencies are provided.
Fast Numerical Nonlinear Fourier Transforms.	Wahls, S., and H. V. Poor.	2015	The nonlinear Fourier transform, which is also known as the forward scattering transform, decomposes a periodic signal into nonlinearly interacting waves. The nonlinear Fourier transform is eminently suited to address them – at least from a theoretical point of view. Although numerical algorithms are available for computing the transform, a "fast" nonlinear Fourier transform that is similarly effective as the fast Fourier transform is for computing the common Fourier transform has not been available so far. The goal of this paper is to address this problem. Two fast numerical methods for computing the nonlinear Fourier transform with respect to the NSE are presented.

NFDM System and Methodology

Nonlinear frequency division multiplexing (NFDM) is a signal multiplexing techniques, encode information in nonlinear spectrum which is obtained from the nonlinear Fourier transform (NFT) of a signal. Loss in NFDM is addressed using path average method. In this method true lossy optic fiber can be approximated by lossless optic fibers. Error of path-avg approximation is depending on signal power, bandwidth and duration. These errors degrade the performance of NFDM when designed at high data rate. The propagation of an optical pulse Q (ℓ, t) in an ideal lossy single-mode fiber can be given as

$$\frac{\partial Q}{\partial \ell} + i\frac{\beta_2}{2}\frac{\partial^2 Q}{\partial t^2} - i\gamma|Q|^2 Q = -\frac{\alpha}{2}Q. \quad (1)$$

Where ℓ represents the propagation distance and t is time. The parameters β2 and γ are the dispersion and nonlinear parameters respectively and α is loss parameter. In this case we consider dispersion β1 < 0. Above equation is not integrable. Hence it is not suitable for NFDM. This issue can be solved by the path-average model. In the path-average model, the change in the signal power due to loss is converted into change in the nonlinear parameter. Then, by approximating the varying nonlinear parameter with its average value over a time period, a lossless fiber model is obtained [2].

The propagation of an optical pulse Q (ℓ, t) in an ideal lossless single-mode fiber can be modeled by the NLSE

$$\frac{\partial Q}{\partial \ell} + i\frac{\beta_2}{2}\frac{\partial^2 Q}{\partial t^2} - i\gamma|Q|^2 Q = 0, \qquad (2)$$

The equation (2) is integrable and can be solved exactly by NFTs by a change of variable method and then transformed into the normalized form given below

$$\frac{\partial u}{\partial z} - i\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} - i|u|^2 u = 0, \quad u = u(z,\tau). \qquad (3)$$

As depicted in figure-1, at the transmitter, the transmitted signal was designed by multiplexing N overlapping sinc-shape subcarriers in the nonlinear continuous spectrum. In NFDM transmissions, data can be encoded onto the parameters of the nonlinear signal spectrum. Here in this experiment it is the modulation on continuous spectrum and the interplay between dispersion and nonlinearity is usually compensated at the receiver by cancelling the accumulated linear phase-shift in the nonlsinear Fourier domain. Simulation focus only on the modulation of the continuous part $q_c(\xi)$ because of the efficient available inverse NFT algorithm (INFT) which allows for a large number of nonlinear subcarriers to be modulated simultaneously. Simulation focus only on the modulation of the continuous part $q_c(\xi)$ because of the efficient available inverse NFT algorithm (INFT) which allows large number of nonlinear subcarriers to be modulated simultaneously. Since continuous part of the nonlinear signal spectrum is dispersive, signal broadening occurs during propagation. As a result, NFDM systems are designed in the burst mode, i.e. with zero guard intervals between neighboring bursts for preventing the inter-burst interference during propagation. In this case, the length of guard interval (GI) between neighboring bursts should be longer than the channel memory.

$$\text{GI} \geq \pi B \beta_2 L$$

For continuous-part signal channel memory is same as conventional OFDM signal:

$$T_c = 2\pi B\, \beta_2 L$$

Where B is the signal's bandwidth and β_2 is the second order dispersion coefficient. In fact, the required guard interval duration can be effectively reduced by a factor of 2 in the pre-compensated NFDM transmissions, as shown in figure-1.b. Where half of the transmission-induced phase shift of the nonlinear spectrum is pre-compensated at the transmitter and the other half is post-compensated at the receiver. In this scheme, the initial signal is broadened by half of the channel memory at the transmitter. During propagation, the pre-compensated signal will be compressed firstly, and then reached its most compact form at the middle of the link. Then in the second half of the link, the signal is broadened and receiver signal duration will be the same as the duration of the pre-compensated signal at the transmitter shown in (Figure-1.c). Therefore, the maximum signal broadening is only half of the channel memory ($T_c/2$).

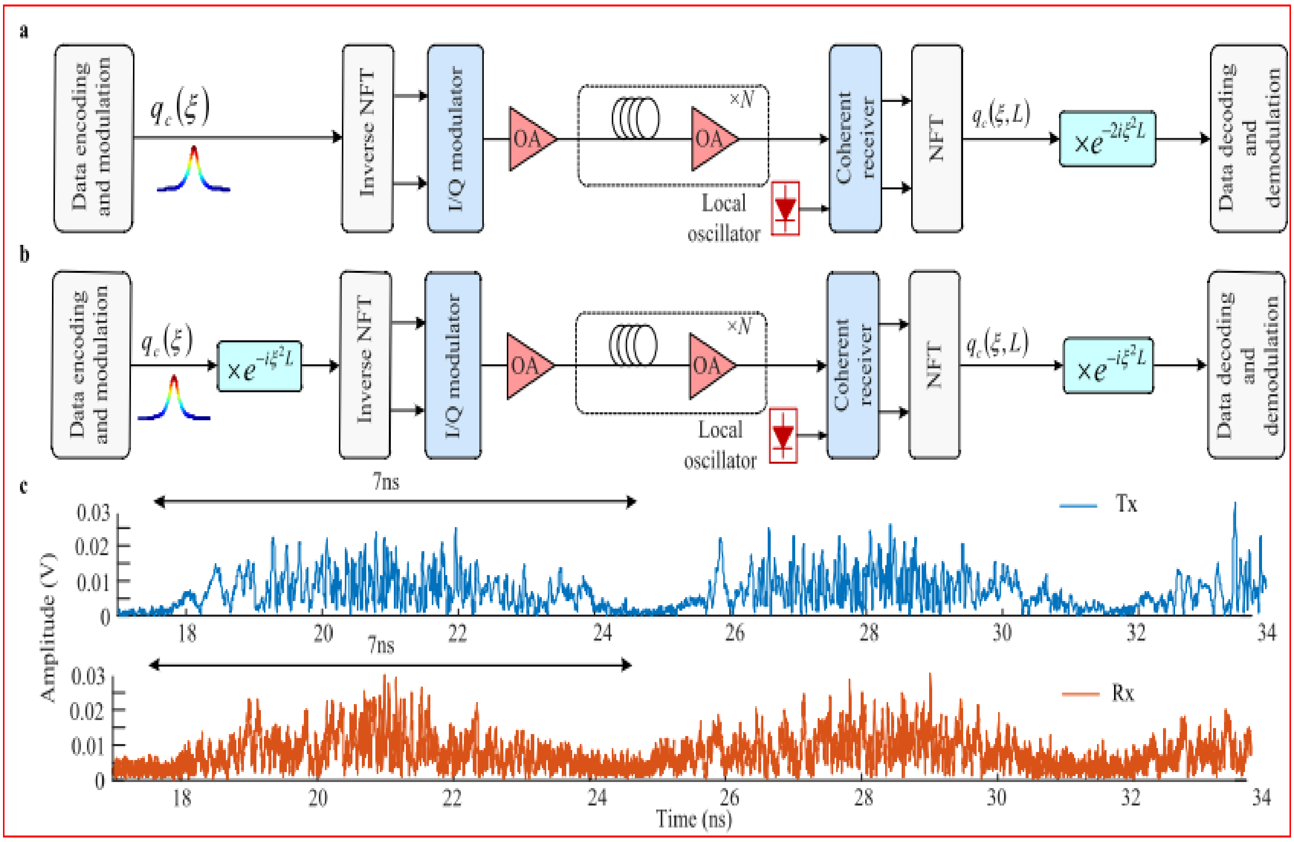

Figure 1

a) Basic block diagram of NFDM transmissions modulating the continuous part
b) Basic block diagram of the pre-compensated NFDM transmission modulating the continuous part
c) Receiver the signal duration will be the same as the duration of the pre-compensated signal at the transmitter

In this case, the achievable data rate and the corresponding SE of NFDM transmissions can be greatly increased. Based on T_c the upper bound of the normalized spectral efficiency

$$\mathrm{SE} = \frac{T_0}{T_0 + 2\pi B \beta_2 \mathrm{L}}, \quad \text{-------} \quad (6)$$

$$SE_{pre} = \frac{T_0}{T_0 + \pi B \beta_2 \mathrm{L}} \quad \text{--------} \quad (7)$$

T_0 = burst duration, N = Modulated subcarrier, If $T_0 = \frac{N}{B}$ Then

$$\mathrm{SE} = \frac{T_0}{T_0 + 2\pi B^2 \beta_2 \mathrm{L/N}}, \quad \text{---} \quad (8)$$

$$SE_{pre} = \frac{T_0}{T_0 + \pi B^2 \beta_2 \mathrm{L/N}} \quad \text{---} \quad (9)$$

To increase SE for NFDM transmission systems bandwidth and distance are fixed the number of subcarriers should be increased.

Simulation Setup and Results

Simulations were carried out with the open-source software environment NFDMlab, uses FNFT library together with NFDM (de-) modulator modules utilize the C software library FNFT to compute (inverse) NFTs, which is interfaced using the Python wrapper and built primarily to be functional in Linux environment.

From the results in Table-1, we successfully built a working environment for NFDMlab suite in Windows platform, using Anaconda distribution package. Further we could show the improvement of NFDM System performance parameters like Spectral efficiency, Error vector magnitude and Data rate

For a given constellation type by increasing the number of subcarrier from 64 to 222 it is observed in simulation environment that there is an obvious improvement in spectral efficiency. This observation holds good for constellation type 16, 32 and 64 and the trend is with increase in constellation type there is further improvement in spectral efficiency and so is in.

Table 2: NFDM Simulation Results

NFDM Simulation Input Parameters				NFDM Simulation Output Metrics			
Number of sub carriers	constellation type	Tx Rx signal bandwidth in GHz	Simulation bandwidth in GHz	Nonlinear length in km	Gross bit rate in Gb/s	Modulation efficiency in bits/sec/hz	Error vector magnitude
64	16	32	170.499	331.82	42	1.32	(-5.870148981605565, 3.1084288772496627, 6.110100926607786) dB
132		40	341.166	333.49	88	2.21	(4.510714059523772, 14.524429563125993, 8.640987597877146) dB
154		44	341.166	446.9	102	2.31	(1.3630590378192917, 10.960875449730317, 9.36897954837013) dB
176		50	341.166	243.47	117	2.36	(1.158935794130325, 11.299698898728977, 9.888264649460883) dB
198		55	341.166	345.28	132	2.41	(7.707983372043601, 25.05882299264788, 10.31719169369 4772) dB
222		60	341.166	282.17	148	2.48	(2.0262422891955736, 14.048613197028716, 11.125546178852424) dB
64	32	32	170.499	216.54	53.33	1.66	(-5.3413563380887865, 3.10428888778873, 5.7415605231835105) dB
132		40	341.166	331.08	110	2.72	(3.932691212978731, 12.279387145105325, 7.80804183143119) dB
154		44	341.166	296.58	128	2.91	(5.504726854237811, 15.876692336680645, 8.424103349400415) dB
176		50	341.166	237.83	146	2.93	(2.5351935840951763, 11.84083161994339, 8.843466319929314) dB
198		55	341.166	292.19	165	3	(2.141666387571696, 12.148904328650213, 9.494099801165076) dB
222		60	341.166	257.3	185	3.1	(0.6776552069515864, 10.672590352325013, 9.871589328070174) dB
64	64	32	170.5	438.81	64	2	(-4.701536002440733, 3.0975611802161653, 5.322267431484901) dB
132		40	341.16	248.72	132	3.3	(0.7016616788307886, 8.74194217919233, 8.063523309525761) dB
154		44	341.166	569.77	154	3.47	(-1.0686235194842912, 7.333068374727672, 8.293100156399994) dB
176		50	341.166	361.6	176	3.5	(1.3497873296626364, 10.123139831070498, 8.666143364630342) dB
198		55	341.166	325	194	3.62	(1.1254187993561493, 10.581526570310613, 9.29559913428425) dB

222		60	341.16	283.5	222	3.72	(0.35620185813785726, 10.026383193077155, 9.623525596056737) dB

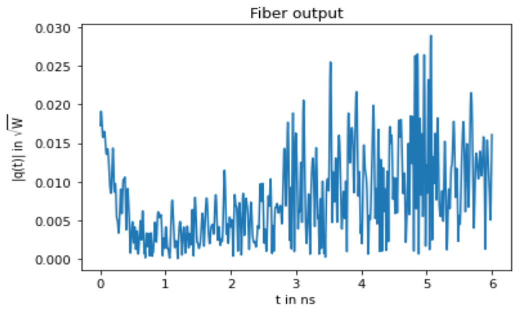

Figure 2: Fiber output for N=222 and 64QAM

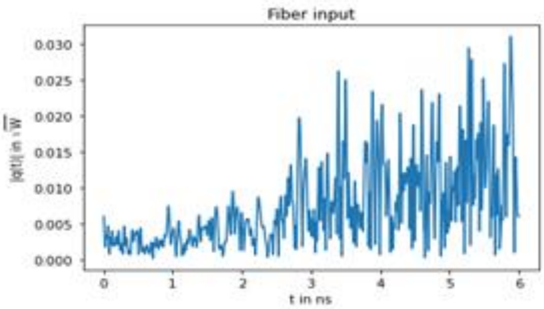

Figure 3: Fiber input for N=222 and 64QAM

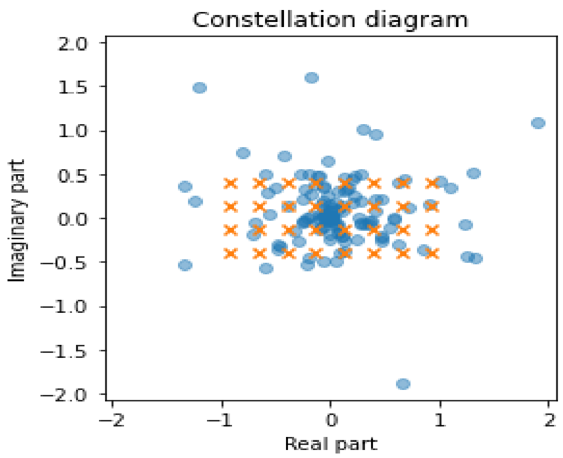

Figure 4: Constellation diagram of 64 QAM, N=222

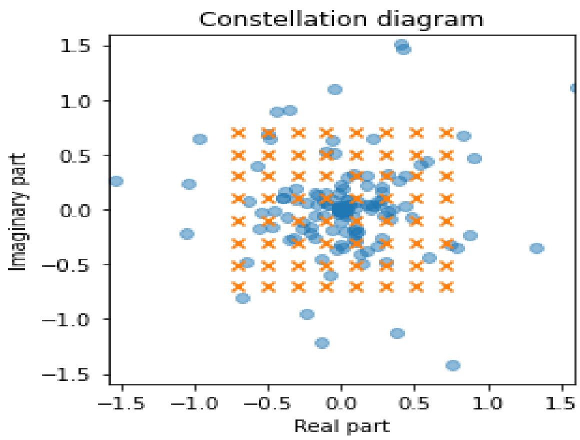

Figure 5: Constellation diagram of 32QAM, N=222

Figure 2 shows fiber input and Figure 3 shows fiber output for 222 No of subcarrier and 64QAM.By applying pre – compensated technique we observe in Figure 2 and 3 that fiber input is approximately same as fiber output .Figure 4 shows constellation diagram for 222 no of subcarrier and 64 - QAM and Figure 5 shows constellation diagram for 222 no of subcarrier and 64 - QAM.

2. Conclusion

The simulations were carried using open-source software environment NFDMlab, which uses FNFT, a software library to compute NFTs and INFTs. **This NFDMlab software suite is primarily built for LINUX environment and our goal of the project is to port the NFDMlab suite to Windows environment using Anaconda software package and simulate NFDM System with pre-compensated technique to show the performance improvement in higher QAM constellation cases.**

Pre-compensation of channel against induced phase shift at Tx and Rx instead of post-compensation and increasing the number of modulated subcarrier are two important rules for designing high data rate NFDM transmission systems. By applying these rules and increasing the number of modulated nonlinear subcarriers up to 222 we have achieved in simulation environment record-high net data rate of 200 Gb/s and SE of 3.72 bits/s/Hz in NFDM transmissions over 976 km of SSMF.

References

[1] Son Thai Le,Vahid Aref, Henning Buelow *"High Speed Pre-Compensated Nonlinear Frequency-Division Multiplexed Transmissions"* IEEE JOURNAL OF LIGHTWAVE TECHNOLOGY, Volume: 36, 6, 15 March 2018

[2] Vinod Bajaj , Shrinivas Chimmalgi, "Exact NFDM Transmission in the Presence of Fiber-Loss" IEEE JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 38, NO. 11, JUNE 1, 2020

[3] M. Yousefi and F.R. Kschischang, "Information Transmission using the Nonlinear Fourier Transform," IEEE Trans. Inf. Theor. 60, 4312–4369 (2014).

[4] S. Wahls, S. Chimmalgi, and P.J. Prins, "FNFT: A Software Library for Computing Nonlinear Fourier Transforms," J. Open Source Software 3, paper 597, 2018.

[5] Wahls, S., and H. V. Poor. 2015. "Fast Numerical Nonlinear Fourier Transforms." IEEE Transactions on Information Theory 61 (12):6957–74. https://doi.org/10.1109/TIT.2015.2485944.

[6] Mansoor Yousefi and XianheYangzhang "Linear and Nonlinear Frequency-Division Multiplexing" IEEE Trans. Int. Theory, 66. 478 - 495, Sept 2019.

[7] Hasegawa and T. Nyu, "Eigenvalue communication," J. Lightwave Technol. 11, 395–399, 1993.

[8] D. Ronnenberg, M. Brehler, and P.M. Krummrich, "Numerical Simulation of Bit-Pattern Dependent Stimulated Raman Scattering," CLEO/Europe-EQEC 2017, paper CI-P.14.

[9] J.E. Prilepsky, S.A. Derevyanko, K.J. Blow, I. Gabitov, S.K. Turitsyn, "Nonlinear inverse synthesis and eigenvalue division multiplexing in optical fiber channels," Phys. Rev. Lett. 113, 013901, 2014.
[10] Wahls, S., and H. V. Poor. 2013. "Introducing the Fast Nonlinear Fourier Transform." In 2013 IEEE International Conference on Acoustics, Speech and Signal Processing. IEEE. https://doi.org/10.1109/ICASSP.2013.6638772.
[11] V.F. Zakharov and A.B. Shabat, "Exact Theory of Two-dimensional Self-focusing and One-dimensional Self-modulation of Waves in Nonlinear Media," J. Exp. Theory. Phys. 34, 62–69, 1972.