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Improvement and Mitigation of Kerr Effects on Multichannel Communication Systems Using Efficient Optical Method

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Abstract

This paper studies the generation of an optical mitigation method for compensation of distortions in long distance fiber optic transmission caused by chromatic dispersion and the nonlinear Kerr effect in multi-channel systems. A hybrid new method known as Optical Phase Conjugation (OPC) based highly nonlinear fiber with Raman amplifier is used as part of the process of improving the performance of communication systems with an 800 km standard single mode fiber link Single Polarization Quadrature Amplitude Modulation (SP-QAM) signaling. This work presents two scenarios in which backward Raman amplification is employed in conjunction with OPC to improve the performance of an optical link of 1.728 Tb/s over sixteen channels with a channel spacing of 50 GHz. In this study, through the use of multiple OPC, the performance of dense wavelength division multiplexing (DWDM) transmission systems with 16 ×108 Gbps 8-QAM channels can be significantly improved over that of systems with either a mid-span optical phase conjugation or no optical phase conjugation. The strategy of using multiple OPCs is effective over a variety of transmission links. The nonlinear threshold in the proposed transmission system was enhanced by 4 dB when employing multiple OPCs, compared to the case with no OPC, and by 2 dB when using a mid-span OPC. The simulation results show that compared to the scenario without employing the compensation approach, the Q-factor, Bit Error Rate (BER) performance, and total length of the transmission link are all improved by utilizing this optical method of nonlinearity compensation.

Keywords: HNLF, OPC, Kerr effects, Multichannel, Raman amplifier.

Introduction

Single mode fiber with direct detection intensity modulation (DD-IM) is typically used for intercontinental base stations (BSs), making long-haul optical fiber cables the favored method of transmission due to their speed and security. To accommodate the rise in required data capacity, it is crucial to expand the capabilities and reach of fiber optic transmission networks [1]. In order to increase spectral efficiency and allow for flexible bandwidth allocation, polarization division multiplexing and other forms of advanced modulation format have been extensively researched for use in both short and long range optical interconnects [2]. Optical signal to noise ratio (OSNR) improvement for supporting higher order modulation across shorter distance lines and longer transmission ranges in long haul links are both desirable outcomes of increased launched power. Nevertheless, performance degrades with increasing input power due to Kerr nonlinearities in the optic fiber [3]. When the intensity of a light wave is high enough, the response of optical fiber to light waves becomes nonlinear. The refractive index effect and stimulated scattering effects are the two most common types of nonlinear effects in fiber optics which are classified as shown in Fig. 1 [4].

The many studies that have been done on the performance of optical fiber transmission systems can be improved with the use of nonlinearity compensating strategies [5]. It has been proposed in [6-9] to compensate for distortion caused by fiber nonlinearity in the digital domain by employing digital backpropagation and machine learning algorithms. However, digital

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compensation techniques have always been hard to use because of the frequency difference between the local oscillator laser and the transmitter changes over time [10]. Equivalent phase conjugated twin wave-based fiber nonlinearity compensation and polarization coding scheme are alternatives to digital domain nonlinearity compensation [11]. However, they both require more processing at the transmitter and cut the spectral efficiency in half. Turbo equalization is widely used for reducing impairments in coherent optical receivers [12]. This approach was proposed for inter-channel nonlinearity compensation in polarization multiplexed systems. The optical carrier stability is used to cancel out the nonlinear distortions caused by Kerr effects using the frequency referenced transmission method [13]. This approach uses nonlinear pre-distortion to compensate for multi-channel nonlinearity at the transmitter. The use of an Optical Backpropagation (OBP) device at the fiber output has been proposed to compensate for chromatic dispersion and fiber nonlinearity [14]. The OBP system has excellent transmission performance, but it necessitates very good polarization alignment between the signal and the pumps. Another interesting technique to mitigate fiber nonlinearity is by using Optical Phase Conjugation (OPC) [15]. OPC is a promising technique to supplement digital equalization by optically compensating for distortion caused by fiber Kerr nonlinearities and the accumulated Chromatic Dispersion (CD) [16-19]. The feasibility of OPC over long and ultra-long distance networks has been demonstrated in [20] due to the flexibility of OPC for signal format and bit rate [21, 22]. Four wave mixing (FWM) based third order nonlinearity in a nonlinear medium such as zero dispersion single mode fiber (SMF) [23], semiconductor optical amplifiers (SOA) [24], or highly nonlinear fiber (HNLF) [22] allows creating OPC.

In this research demonstrates a multichannel modulation which has a various requirement in terms of lunched power and nonlinear compensation implementation. This work demonstrates compensation of fiber Kerr nonlinear distortion of a 108 Gbps 8QAM single polarization signals, using hybrid phase conjugation with backward Raman amplifier. To demonstrate fiber nonlinear distortion compensation, this study compares the performance of the link for various power levels launched into the fiber over 800 km using Mid Span Spectral Inversion (MSSI) and multiple OPC methods with and without using backward Raman amplification propagation to compensate for the fiber's nonlinear distortion. The ability to generate phase conjugated

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duplicates of such DWDM signals with a high total bandwidth is a significant benefit of Four Wave Mixing (FWM) based phase conjugation utilizing High Nonlinear Fiber (HNLF) medium.

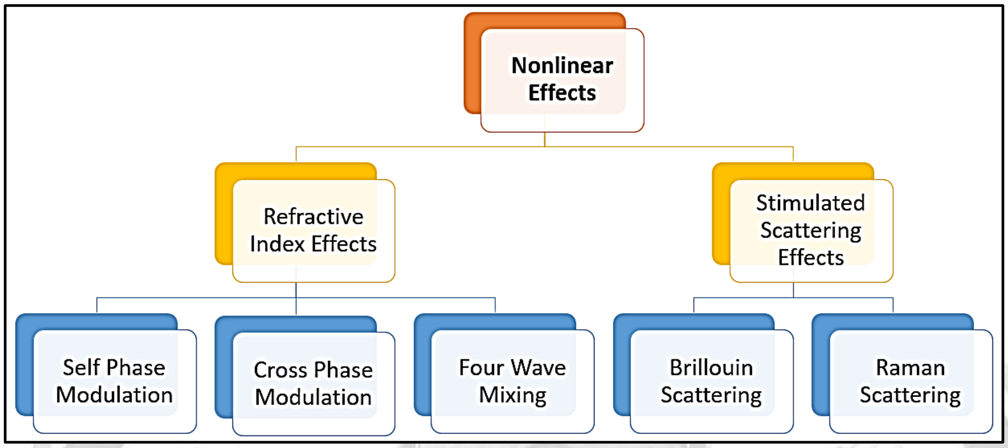

Fig. 1. Diagram of nonlinear fiber optic effects [4]

Optical Phase Conjugation Concept based HNLF

Fisher et al. [25] proposed using optical phase conjugation to reduce nonlinear distortion caused by the Kerr effect. In that study, theoretical and numerical analyses demonstrated that the combined effect of GVD and SPM on a pulse propagating in a dispersive nonlinear media, such as an optical fiber, may be counteracted by first subjecting the pulse to optical phase conjugation and then retraversing the medium. The waveform's propagation equation before and after OPC is examined to understand its working mechanism. The equation of propagation for a signal with a single polarization refers to nonlinear Schrödinger equations as follows [26]:

$$\frac{\partial E_X}{\partial z} = -\frac{i\beta_2}{2}\frac{\partial^2 E_X}{\partial t^2} + \frac{g(z)-\alpha(z)}{2}E_X + i\gamma|E_X|^2E_X \qquad (1)$$

where E represents the complex amplitude signal, α is the coefficient of attenuation, β_2 is the group velocity dispersion, and γ is the Kerr effect. The propagation equation for the conjugated waveform can be obtained by performing a complex conjugation.

$$\frac{\partial E^*{}_X}{\partial z} = \frac{i\beta_2}{2}\frac{\partial^2 E^*{}_X}{\partial t^2} + \frac{g(z)-\alpha(z)}{2}E^*{}_X - i\gamma|E^*{}_X|^2E^*{}_X \qquad (2)$$

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where * refers to complex conjugation. Changing the signs of the GVD and SPM terms reveals that the impacts of both these two factors are reversible. The term denoted by (α) is of real value and does not undergo any significant changes.

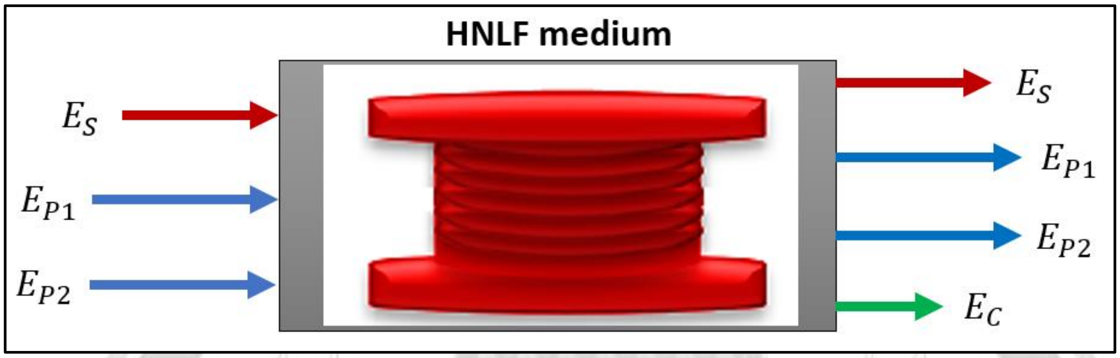

Fig. 2. Generation of phase conjugate wave (E_c) in HNLF medium [27]

Optical phase conjugation can be implemented by FWM based on third order nonlinearity in a nonlinear medium as used in this work namely highly nonlinear fiber (HNLF). The schematic configuration of the OPC generation process in the HNLF medium is shown in Fig. 2. Here, E_{P1} and E_{P2} are CW pump waves at frequencies W_{P1} and W_{P2}, and E_S is the signal wave at frequency W_S. A parametric mixing between the pump and signal wave will generate a new idler at frequency $W_C = 2W_P - W_S$, where the idler field is identical to the signal wave except that its phase is conjugated.

One technique to implement OPCs is to place the OPC unit at the mid link so that for N spans, the OPC unit is placed after N/2 spans; this is also known as mid span spectral inversion (MSSI) since the spectrum is inverted at the OPC unit [28, 29]. Another method is to place a multiple number of OPC units, known as inline OPCs or multiple OPC [30, 31]. The two most fundamental forms of phase conjugation in optical fiber configuration are depicted in Fig. 3. An optical phase conjugator is applied halfway along the length of the fiber in the first approach. The amount of attenuation in the optical power in the second half of the fiber's length is what determines the nonlinearity parameter. The one disadvantage of using this strategy is that the OPC position might move from the middle of the span length to some other spot. At the bottom portion of Fig.3, see another phase conjugation scheme, called multiple OPC, used to change the phase of a signal after a fixed distance of fiber transmission and then again after another fixed distance of fiber transmission. When transmitting with an even number of OPCs, the wavelength of the signal is preserved, making it easier to implement at the receiving end. Digital signal processing is simplified by using multiple OPCs to account for bulk dispersion during transmission.

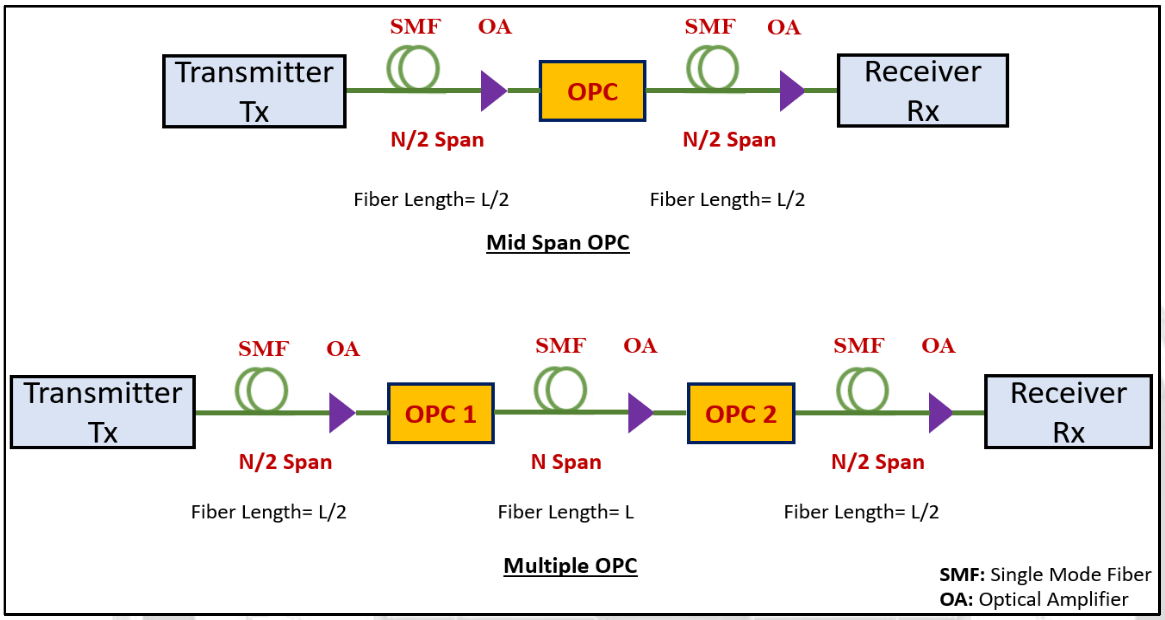

Fig. 3. OPC implementation: mid span schemes (upper) and multiple span schemes (lower)

Design Principle of System Configuration

Figures 5 and 6 are schematic of the proposed system using the "optisystem 19" optical simulation platform to transmit 1.728 Tbps of 8-QAM data over 800 km of fiber using a mid and multiple OPC. In the transmitter section, 16 signals are put into parallel at 50 GHz and modulated using a pair of parallel dual drive Mach Zehnder modulators (MZM) with opposing polarity. The first signal has a laser frequency of 192.95 THz, while the last signal is at 193.70 THz, with a linewidth of 0.1 MHz in between. Dual optical 8-QAM signals, one in phase and one in quadrature, are produced by the MZM. Later, the DWDM signal is modified and transferred through an optical fiber to OPC module. Table 1 displays the detailed parameters of the simulation.

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Table 1: Parameters of simulation

Parameter	Value
Bit rate	108 Gb/s
Sequence length	8192
Guard bit	10
CW laser power	-15 dBm to 15 dBm
Azimuth	45 deg
Bit per symbol	3 bits
Length of HNLF	600 m

Fig. 5 shows the setup of the proposed mid OPC system, which was used to simulate the research in the paper. This simulation uses 16 channels of 8QAM signal with a bit rate of 108 Gb/s. We describe the transmitter's details based on the bit sequence that is modulated into an 8QAM optical signal at 50 GHz at the DWDM input. Figure 5's drawing in the upper left corner shows a detailed diagram of the 8QAM transmitter.

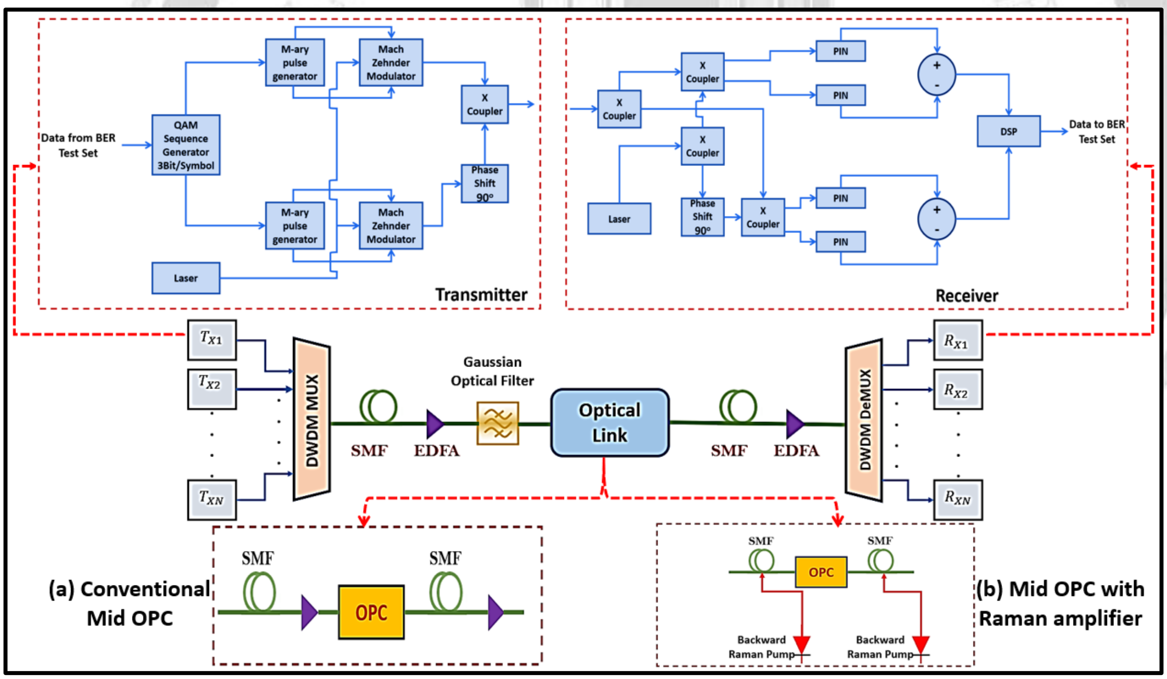

Fig. 5. model of an 8QAM mid OPC system with and without a backward Raman amplifier with transmitter part (upper left) and receiver part (upper right)

After then, the fiber link uses an erbium doped amplifier (EDFA) and 8 spans of 100 km standard single mode fiber with optical amplifiers of 16 dB gain per channel. To cut down on amplified spontaneous emission noise on the transmitter side, a Gaussian optical filter with a bandwidth of (4×bit rate) is used. The optical fiber has a loss of 0.2 dB/km, a dispersion slope of

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0.075 ps/km/nm2, and a dispersion of 16.75 ps/km/nm. EDFA with a noise figure of 4 dB is utilized to make up for all fiber per span losses. After N/2 spans, the transmission line has an (OPC) module in the middle. The OPC accepts two signals, one of which is a dual pump laser signal at 199.51 THz (1502.06 nm), and the other at 187.30 THz (1600.06 nm). To make the polarization of the pump insensitive, a polarization beam combiner PBC mixes their polarizations into a single beam. The signal, generated via wavelength division multiplexing (WDM), is transmitted via optical phase conjugation at a center frequency of 193.40 THz (1550.11 nm) based on FWM, which takes advantage of HNLF with a length of 600 m, a zero-dispersion wavelength of 1550 nm, and a nonlinear coefficient of 10.1 /W/km.

In the second scenario, the span loss caused by using OPC is compensated for by a hybrid with a backward Raman amplifier. When it comes to effective OPC based fiber nonlinearity mitigation, distributed Raman amplification outperforms discrete amplifiers in satisfying the power symmetry criteria.

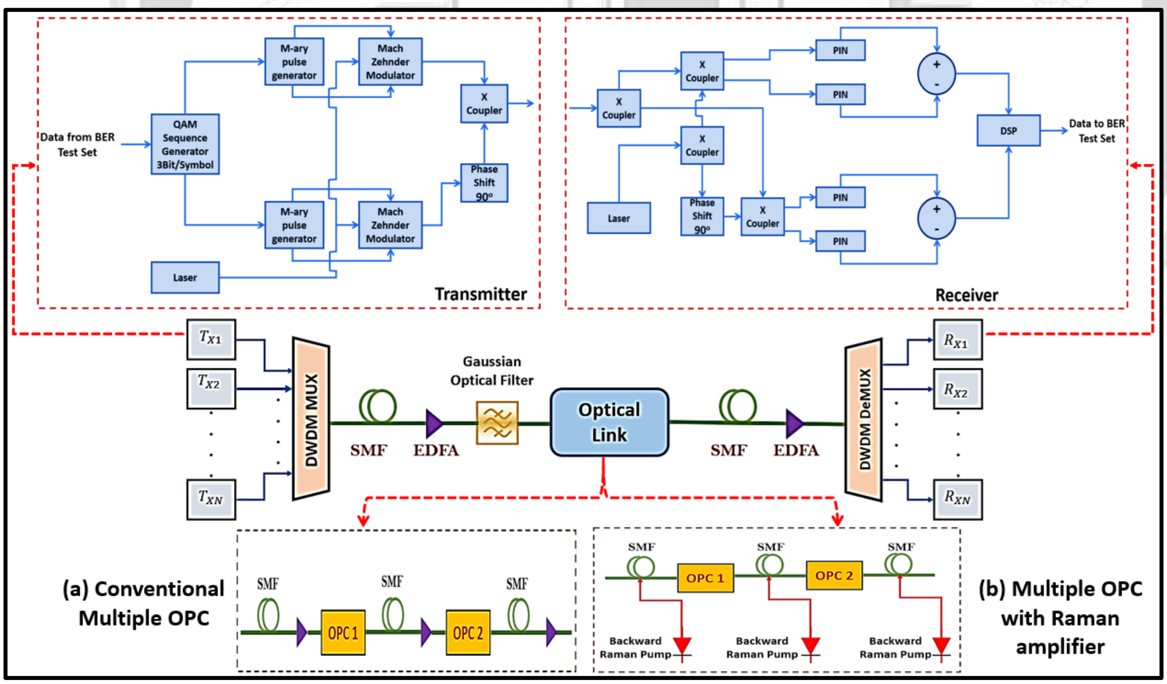

Fig. 6. 8QAM system model of multiple OPC with and without Raman amplifier

The second way OPC can be set up is in line, which is also called multiple OPC. As shown in Fig. 6, this module is looked into as a mid OPC with two cases. By inserting an optical fiber twice as long as the one used in the transmitter and receiver, we can distinguish between multiple and mid OPC. The output optical signal of a DWDM system moves through the first fiber optical with a 20 dB optical amplifier. After going through the optical filter, this signal has the same parameter as when it goes through the first OPC. The idler wave generated by the first OPC (carries the same information as the signal) is carried via the second fiber optic, whose length (L = 400 km). After traveling via HNLF media, the idler wave enters a second OPC with identical characteristics as the first OPC, unless the signal representing the idler wave is reinterpreted as the new signal that combines with the two pumps of the second OPC to generate the new idler wave. After that, the signal goes through an optical filter and a fiber optical whose length (L = 200 km) is equal to the length of a transmission part. The signal is then sent through a demultiplexer to be received.

At the receiver's final stage, after demultiplexing, optical signals are sent through 90^{o} hybrid coherent detection, made up of balanced photodiodes, to down convert the optical signal into electrical signals for use in digital signal processing (DSP). DSP is used to conduct signal processing operations like phase timing, chromatic dispersion adjustment, and frequency recovery. Fig. 6's upper right shows an 8QAM receiver schematic.

Results and Discussion

The effectiveness of OPC based compensation of nonlinear is evaluated using two system configurations: hybrid OPC with and without Raman pumps in mid and multiple implementations; with 8 quadrature amplitude modulation (QAM) optical signal, symbol rate 108 Gbps. Certain channels in the middle of the bandwidth in DWDM will be affected by the effects of nonlinear, so this study concentrated on studying the variance in the quality of the received signal when compensation of nonlinear was performed using the OPC technique. To illustrate the effect of OPC on the performance of 8-QAM, firstly show the performance of the system that operates back-to-back. Fig. 7 show the constellation diagram for 8-QAM for middle channels (channel 8 and 9).

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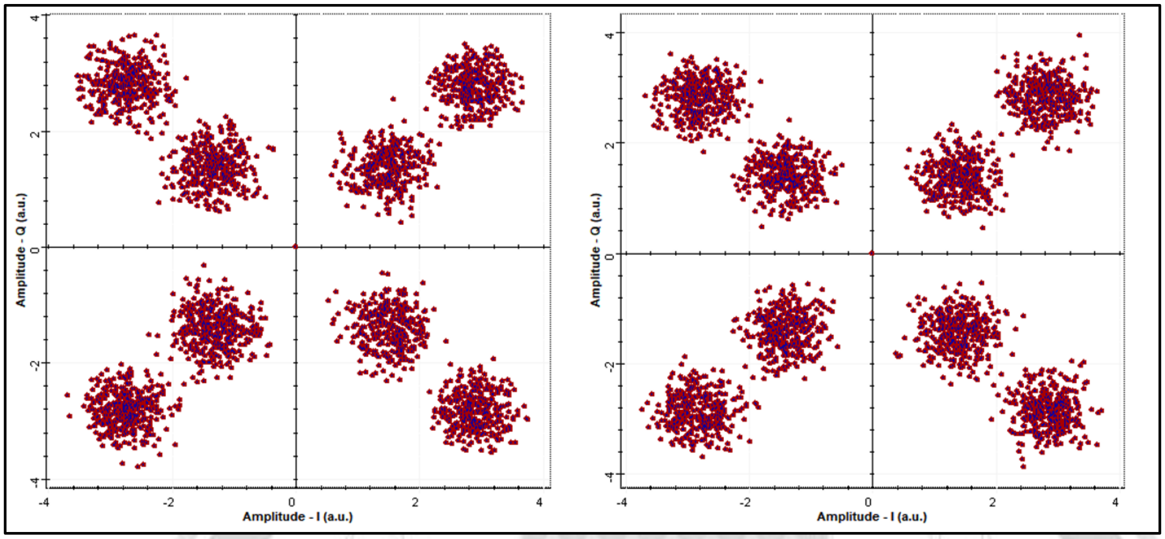

Fig. 7. Constellation diagram of the received 8-QAM signal 16 channels after transmission back-to-back (left) channel 8 (right) channel 9

As shown in Fig. 7, the constellation diagram is clear and BER for the middle channel is equal to 4.8×10^{-4} and 2.4×10^{-4} with Q factor 10.37 and 10.86 for channels 8 and 9, respectively. Also, the Error vector magnitude (EVM) is 0.096 and 0.092. Now insert optical fiber with a length of 800 km. The constellation diagram is illustrated in Fig. 8.

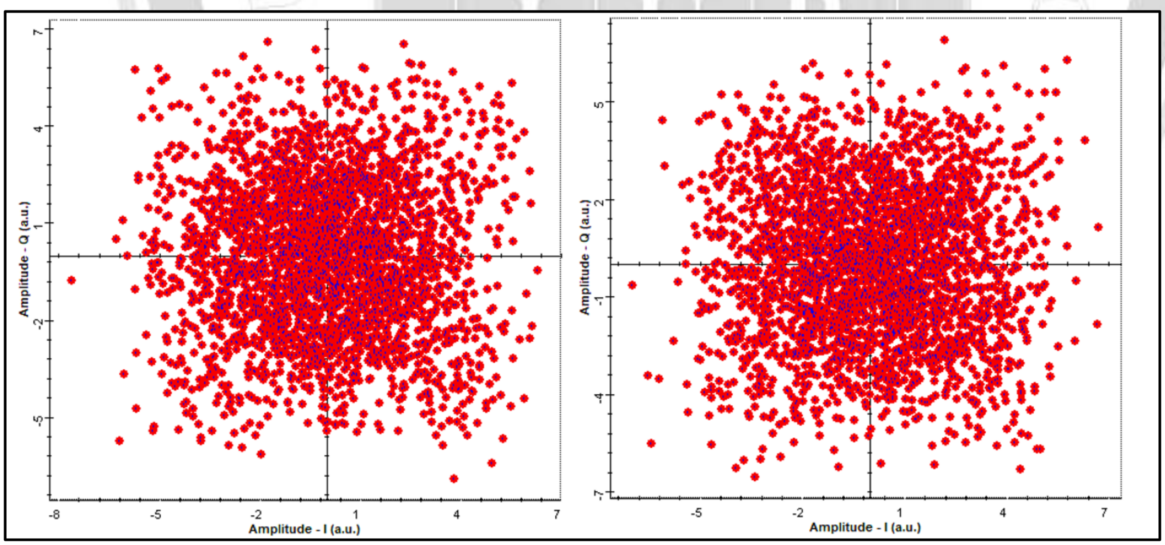

Fig. 8. Constellation diagram of the received 8-QAM signal 16 channels after transmission over 800 km SMF for (left) channel 8 (right) channel 9

As shown in the above figure, the constellation diagram is bad due to the effect of nonlinearity with a high bit rate equal to (0.494) and (0.495) with (1.74) and (1.72) Q factor and (0.574) and

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(0.581) error vector magnitude for channel 8 and 9, respectively. The degradation of the received signal back to Kerr effects. At this point, using an OPC device enhances the performance of the system against nonlinear effects.

a. Mid-Way Optical Phase Conjugation with and without Raman Amplifier

In this method, insert OPC in the middle of a transmission link with a two-part optical fiber link each length is 400 km before and after OPC. In the OPC, the idler wave is formed after passing through the nonlinear medium. Fig. 9 shows the spectrum of the signal before and after a pass through HNLF.

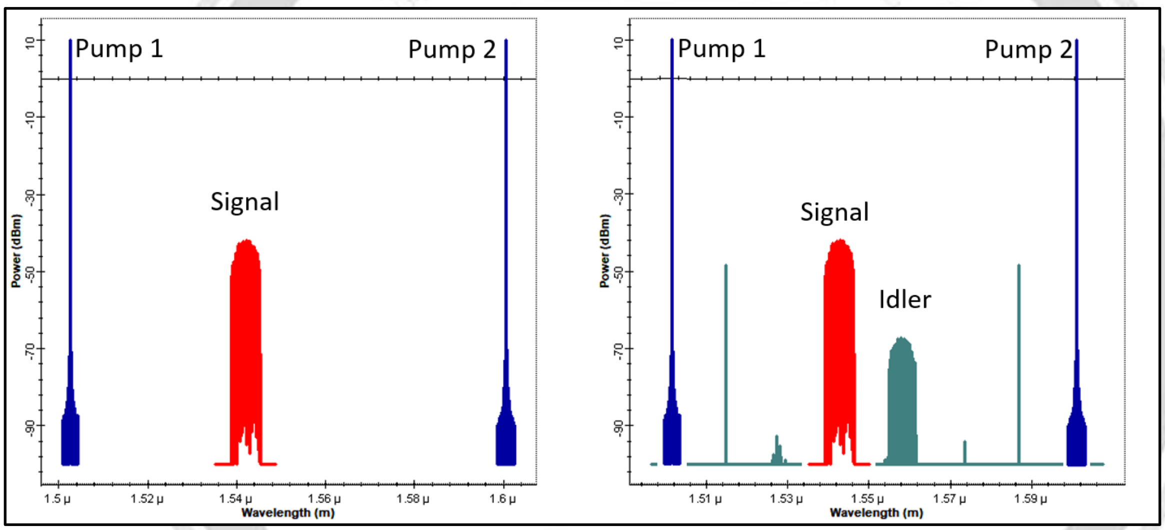

Fig. 9. The spectrum of the 8-QAM signal with OPC (left) before pass through HNLF (right) after pass HNLF

After the signal of DWDM was sent 400 km away, its performance was tested at different power levels with and without a Raman amplifier. First, as shown in Fig. 5, we looked into how well the proposed system worked with mid span OPC. The optimal transmit power per channel for the mid OPC (conventional) is around 2 dBm, with a bit error rate (BER) of 1.52×10^{-1} for channel 8 with the Q-factor and error vector magnitude (EVM) are 3.13 and 0.319, respectively.

When Raman amplification is added to a conventional OPC module as illustrated in Fig.5 (b), the output OSNR will improve while the nonlinear penalty is decreased. The components of a Raman amplified link are a single mode fiber and a Raman backward bumping source. The broadband gain provided by Raman amplification of the interacting light waves with a lower

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input signal strength is employed to enhance the FWM process in the HNLF. A 1452 nm nonpolarized continuous wave laser is used as the Raman pump to achieve maximum amplification. It is necessary to adjust the Raman pump to 31 dBm to compensate for the power loss caused by the output idler. Hence, the Q factors of the OPC with Raman amplifier and the conventional OPC are compared at a constant idler power level. As can be shown in Fig. 10, when OPC is combined with a Raman amplifier, the best possible value of input power is increased by 1 dB to be about 3 dBm, while the Q factor is increased by 4.45 dB for the middle channel with enlarged by 22.4% when the conventional method is used.

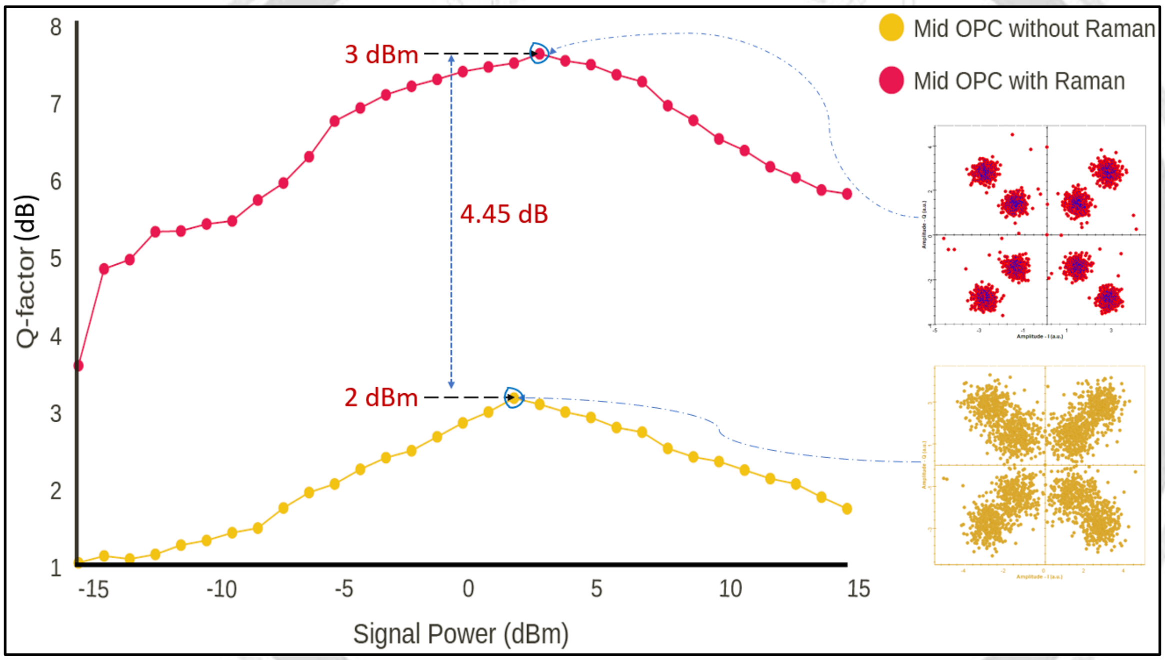

Fig. 10. Signal power vs. Q-factor and eye diagram for the middle channel (ch.8) of mid OPC module with and without Raman amplifier

On the right side of Fig. 10, the constellation diagram for the middle-received signal before and after using the Raman amplifier is illustrated. It can show that the constellation diagram is clear after using hybrid OPC with Raman amplifier as compared without using it with increasing of BER from 7.6×10^{-2} to 8.3×10^{-3}.

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b. Multiple Optical Phase Conjugation with and without Raman Amplifier

The simulation implementation in the previous method is repeated here but using multiple OPC. We also illustrate the use of multiple OPC with two different cases, as shown in Fig. 6, to reduce the impact of interchannel nonlinear impairments. Analyses are done on the nonlinearity effects in fibers that are exposed to different levels of input signal power. First, we evaluate the transmission performance of the multiple OPC module without a Raman amplifier (conventional OPC). According to the data, the max Q factor for the center channel is 5.48 dB at 4 dBm signal power and BER $3{\times}10^{-2}$. As can be seen in Fig. 11, Comparing multiple OPC to conventional mid OPC, the results reveal that the first causes less distortion with an improved Q-factor by 2.35 dB with enlarge by 42% to conventional mid OPC.

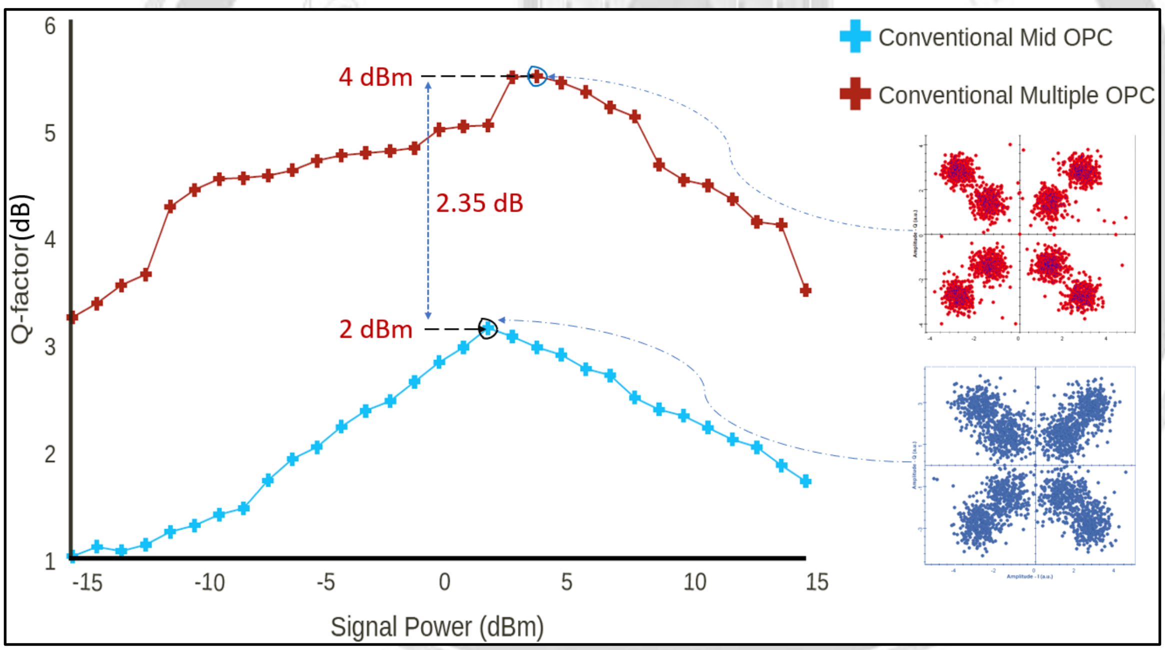

Fig. 11. Signal power vs. Q-factor and eye diagram for the middle channel of conventional mid and multiple OPC module

Later, the distortion of nonlinear in the system is reduced by the OPC's use of Raman amplification, as seen by the box in Fig. 6 (b). Two pumps' signals are input to the OPC at 23 dBm while the backward Raman pump is set to 30 dBm. As a result, the idler's output power is unaffected by the conventional multiple OPC. The performance of transmission of multiple OPC module with and without a Raman amplifier is illustrated in Fig. 12. It has been demonstrated that, as compared to conventional OPC, multiple OPCs outfitted with a Raman pump provides superior performance in terms of both peak Q factor and optimal launched signal power. The improvement of the Q factor is increased from 5.48 dB at 4 dBm in conventional multiple OPC to 9.55 dB at 5 dBm with a backward Raman amplifier that enhanced about 4.07 dB for the middle channel with enlarged by 24.5%. When compared to the experimental results given in [22], these results show that they are in good agreement.

Finally, a comparison of the mid OPC and the multiple OPC transmission performance using a Raman amplifier is analyzed in Fig. 13. The best value of input power is increased by 2 dBm when using an OPC with a Raman amplifier, and the Q factor is increased by 1.97 dB, for a total gain of 50.7% in the middle channel (channel 8).

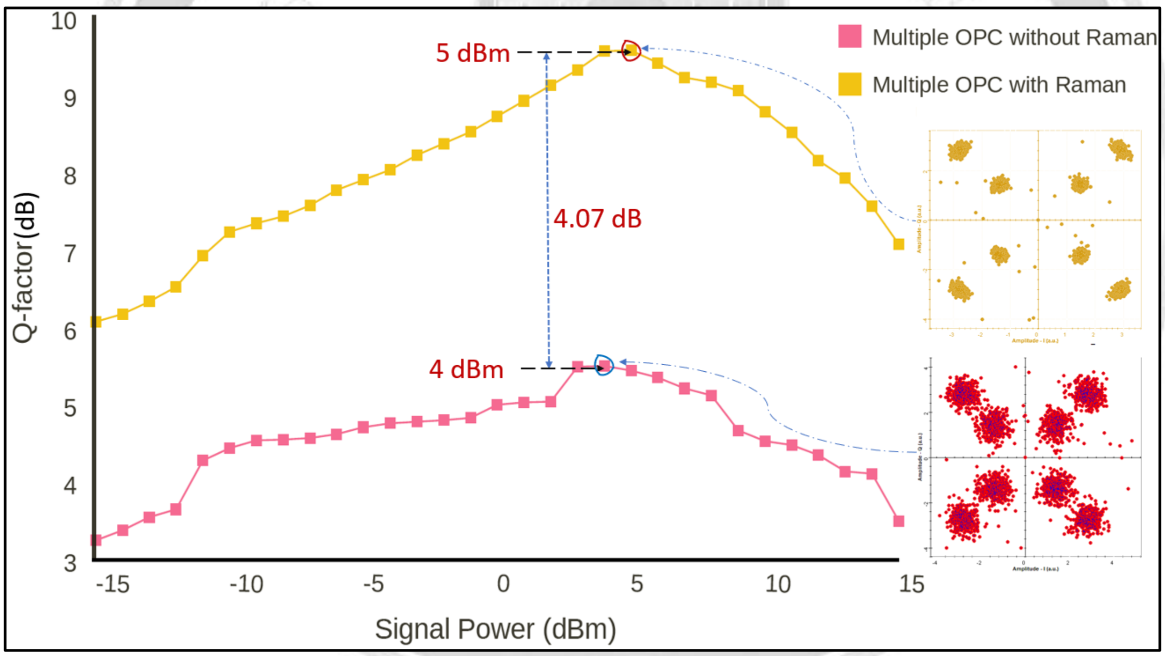

Fig. 12. Signal power vs. Q-factor and eye diagram for the middle channel (ch.8) of multiple OPC module with and without Raman amplifier

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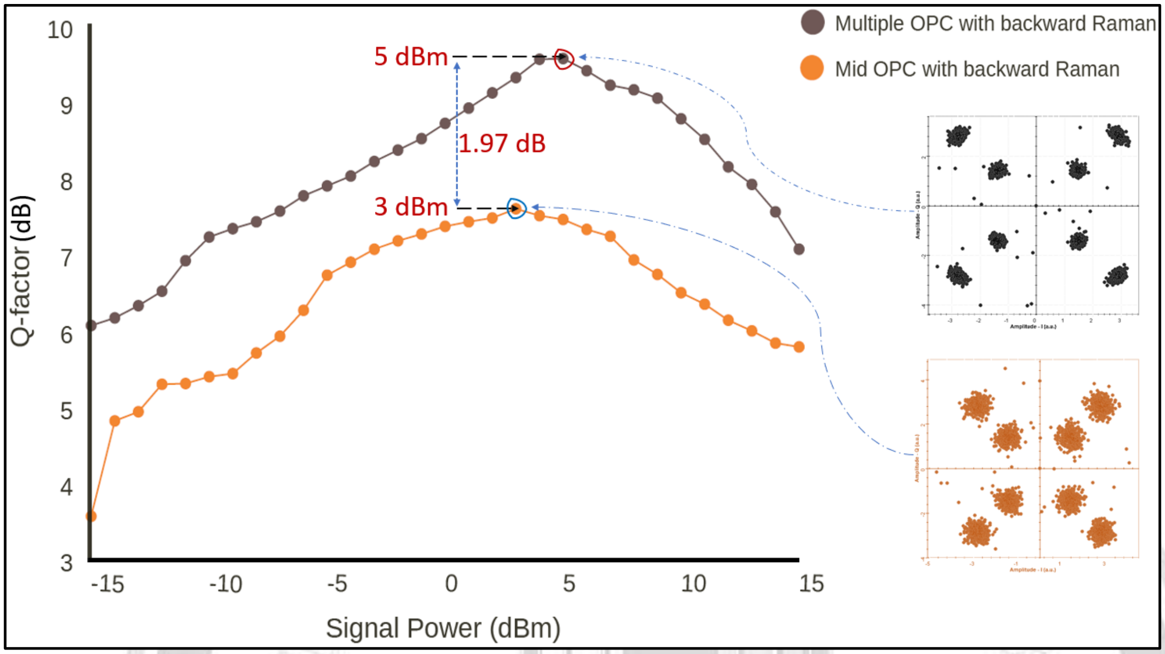

Fig. 13. Signal power vs. Q-factor and eye diagram for the middle channel of mid and multiple OPC module with Raman amplifier

Table 2 provides a comparison of the current study with previously published works of different nonlinear compensation methods. The table shows that the data transfer rate is better and higher than the rest of the research, reaching 1.728 Tb/s for 16 channels with a transfer rate of 108 per channel using DWDM technique compared with the previous research that use WDM technique. In addition, the use of (multiple OPC with Raman) has been employed, which greatly improved the efficiency of the system against nonlinear effects compared to (mid OPC) used in most researches. Over all, the proposed nonlinear compensation method-based hybrid OPC with Raman amplifier is efficient and improvement the performance of communication system against Kerr effects as comparing with conventional methods. The evaluation methodology given in this research offers valuable information for fiber impairment mitigation and can also be used to expand the transmission range and increase the data rate for future work using advanced modulation format techniques.

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Table 2. Comparison of proposed work with previously published work

Parameters	Ref. [32]	Ref. [33]	Ref. [34]	Ref. [22]	Ref. [35]	Ref. [36]	Ref. [29]	Ref. [19]	Proposed work
Type of compensation	XPM	FWM	FWM	FWM	Kerr nonlinear	Kerr nonlinear	FWM	FWM	Kerr effects
Method of compensation	DBP	Hybrid OPC with DCF & FBG	Mid OPC	Mid OPC	Mid OPC	Mid OPC with Raman	Mid OPC	Mid OPC	Mid & Multiple OPC with Raman amplifier
Multiplexing type	WDM	WDM	WDM	WDM	AWG	—	WDM	—	DWDM
Input power	Variable	-10 to 10	-20 to 20	10	-4 to 12	-6 to 12	Variable	-25 to 10	-15 to 15
Modulation format	QAM & QPSK	ASK	16 QAM	16QAM CO-OFDM	QPSK & 16QAM CO-OFDM	16QAM	—	QPSK	SP-8QAM
No. of channel	5	8	7	2	2	Single	Multi	Single	16
Data rate per channel (Gb/s)	—	2.5	—	320	40 & 80	200	80	20	108
Transmission distance (km)	800	185	350	800	200	Variable	160	—	800
Channel spacing (GHz)	32	100	100	80	20	—	100	—	50

Conclusions

Fiber nonlinearities mitigation for 1.728 Tbps 8-QAM over 8×100 km fiber optic link with a mid and multiple OPC uses FWM based HNLF medium were demonstrated in this work. Two distinct varieties of OPC, one with and one without a Raman amplifier, have been studied. The simulation results show that for a middle channel at 194.325 THz, the optimum signal power into OPC is 3 dBm and 5 dBm for mid and multiple OPC with Raman amplifier, respectively, while in the conventional case are 2 dBm and 4 dBm, respectively. Hybrid Raman amplifier with OPC improved the performance evaluation over conventional OPC in terms of BER, Q-factor improvement, and received signal constellation. According to the findings of an analysis of received 8 QAM signal constellation diagrams, OPC plays a more significant role in dispersion compensating of fiber and nonlinearity effect than it would in the event where it was not used. As compared to the case of mid OPC, the results of the simulation demonstrate that multiple link

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OPC with Raman amplifier gives BER of 1.33×10^{-3} and Q-factor of 9.55 dB. This represents an improvement in Q-factor of 1.97 dB and an improvement in BER of over two orders.

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تحسين وتخفيف تأثيرات كير على أنظمة الاتصالات متعددة القنوات باستخدام طريقة بصرية فعالة

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الخلاصة

في هذا البحث، تم دراسة توليد طريقة التخفيف البصري لتعويض التشوهات في نقل الألياف البصرية لمسافات طويلة الناتجة عن التشتت اللوني وعدم خطية كير في الأنظمة متعددة القنوات. يتم استخدام طريقة هجينة جديدة تُعرف باسم اقتران الطور البصري (OPC) باستخدام الألياف غير الخطية مع مضخم رامان كجزء من عملية تحسين أداء أنظمة الاتصالات باستخدام إشارة أحادية النمط القياسي لوصلة الألياف أحادية الوضع بطول ٨٠٠ كيلومتر. في هذا العمل، نقدم طريقتين يتم فيهما استخدام تضخيم رامان الخلفي بالتزامن مع اقتران الطور البصري لتحسين أداء ارتباط بصري يبلغ ١.٧٢٨ تيرابايت / ثانية عبر ستة عشر قناة مع تباعد قناة قدره ٥٠ جيجا هرتز. من خلال استخدام اقتران الطور البصري المتعدد، فأن أداء أنظمة نقل مضاعف تقسيم الطول الموجي الكثيف (DWDM) مع قنوات ١٦ × ١٠٨ جيجا بت في الثانية QAM-٨ يمكن تحسينه بشكل كبير مقارنة بالأنظمة التي تحتوي إما على اقتران طور بصري واحد متوسط المدى أو بدون اقتران طور بصري. استراتيجية استخدام OPCs متعدد فعال عبر مجموعة متنوعة من وصلات الإرسال. تم تحسين العتبة غير الخطية (إشارة الطاقة المثالية) في نظام الإرسال المقترح بمقدار ٤ ديسيبل عند استخدام OPCs متعدد، مقارنة بالحالة التي لا تحتوي على OPC، وبنسبة ٢ ديسيبل عند استخدام OPC متوسط المدى. تظهر نتائج المحاكاة أنه بالمقارنة مع السيناريو دون استخدام نهج التعويض، تم تحسين عامل جودة الإشارة (Q)، وأداء معدل الخطأ في البت(BER) ، والطول الإجمالي لوصلة النقل من خلال استخدام هذه الطريقة البصرية للتعويض غير الخطي.

الكلمات الدالة: ألياف غير خطية، اقتران الطور البصري، التأثيرات الغير خطية (كير)، متعدد القنوات، مضخم رامان.