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Enhanced Mitigation of Nonlinearity Signal Distortion by Hybrid Optical Compensation Technique

***Abstract**. This work investigates and proposes a method for mitigating the negative effects of nonlinearities in the fiber with dense wave division multiplexing transmission systems by combining the optical phase conjugation (OPC) approach with a Raman amplifier. The OPC technique uses a polarization diversity loop configuration to suppress the original input signal. As a result, phase conjugated idlers can be generated across a wide frequency range without introducing any spectral inefficiencies due to wavelength shifts. Idle waves are created by mixing four waves in nonlinear fibers with pump waves that are out of band and orthogonally polarized. Finally, the OPC subsystem is put to use in transmission experiments spanning 800 km over dispersion managed fiber spans with lumped amplification by Improved Raman amplifiers to reduce the effects of fiber nonlinearity caused by mid-link spectrum inversion or multiple links. Simulated results of a 50 GHz channel spacing and a 1.792 Tbps made up of eight 224 Gbps polarization division multiplexed (PDM) sixteen ary quadrature amplitude modulation (DP-16QAM) subchannels reveals a Q-factor improvement of up to ~3 dB in mid OPC compared to ~3.37 dB in multiple OPC in the absence of a backward Raman amplifier. In addition, using the OPC would result in an approximate of 10^{-6} improvement in BER compared to the conventional method. Furthermore, the average enhancement in error vector magnitude (EVM) for the DWDM situation would be larger than 15% with the inclusion of hybrid OPC with backward Raman amplifier.*

Streszczenie.** Ta praca bada i proponuje metodę łagodzenia negatywnych skutków nieliniowości we włóknie za pomocą systemów transmisyjnych z multipleksowaniem z gęstym podziałem fali poprzez połączenie podejścia optycznej koniugacji fazy (OPC) ze wzmacniaczem Ramana. Technika OPC wykorzystuje konfigurację pętli różnorodności polaryzacji do tłumienia oryginalnego sygnału wejściowego. W rezultacie sprzężone fazowo koła pasowe mogą być generowane w szerokim zakresie częstotliwości bez wprowadzania jakichkolwiek nieefektywności widmowych z powodu przesunięć długości fali. Fale jałowe są tworzone przez zmieszanie czterech fal we włóknach nieliniowych z falami pompy, które są poza pasmem i spolaryzowane ortogonalnie. Wreszcie, podsystem OPC jest wykorzystywany w eksperymentach z transmisją na dystansie 800 km na światłowodach zarządzanych dyspersyjnie ze wzmocnieniem skupionym przez ulepszone wzmacniacze ramanowskie w celu zmniejszenia skutków nieliniowości światłowodów spowodowanej odwróceniem widma łącza środkowego lub wieloma łączami. Symulowane wyniki odstępu międzykanałowego 50 GHz i przepustowości 1,792 Tb/s składającej się z ośmiu 224 Gb/s zmultipleksowanych z podziałem polaryzacji (PDM) szesnastu podkanałów kwadraturowej modulacji amplitudy (DP-16QAM) ujawniają poprawę współczynnika Q do ~3 dB w średnim OPC w porównaniu do ~ 3,37 dB w wielu OPC przy braku wstecznego wzmacniacza Ramana. Ponadto użycie OPC spowodowałoby poprawę BER w przybliżeniu o 10-6 w porównaniu z metodą konwencjonalną. Co więcej, średnie zwiększenie wielkości wektora błędu (EVM) dla sytuacji DWDM byłoby większe niż 15% przy uwzględnieniu hybrydowego OPC z wstecznym wzmacniaczem ramanowskim.* (Udoskonalone łagodzenie zniekształceń sygnału nieliniowości dzięki hybrydowej technice kompensacji optycznej***)

Keywords: Phase conjugation, backward Raman amplifier, Nonlinear effects, Bit error rate.
Słowa kluczowe: zniekształcenie sygn ału, kompensacja optyczna

Introduction

The nonlinear Kerr effects of fiber optics pose a significant challenge to long-distance optical fiber transmission systems. Nonlinearity compensation techniques can boost the performance, range, and capacity of optical fiber transmission systems. Digital [1-5] or optical [6-8] implementations of those methods are able to be done. It is possible to apply digital nonlinearity compensation in either the transmitter [9] or the receiver [1, 5], or in both [2, 3, 10]. Due to the potential dominance of nonlinear interference from surrounding WDM channels, nonlinearity correction in the digital domain is improbable to adequately compensate the effect of the noise [11]. With frequency-locked transceivers, complete knowledge of connection parameters, and sufficient processing capabilities, comprehensive signal-signal compensation of nonlinearity is indeed only realizable in the digital realm [12]. All optical signal processing methods, as well as digital methods like split-step backpropagation or Volterra back propagation, can be used to reduce the Kerr nonlinearity of a fiber. Over the past few decades, there has been a lot of research on these techniques [13], mostly because of the hope that optical signal processors could be low loss, broadband, modulation format agnostic, wavelength transparent, and polarization insensitive. One common use of all optical signal processing is to fix the Kerr nonlinearity of the fiber by using optical phase conjugation (OPC) as lumped mid link spectral inversion (MLSI) or multiple link [14]. This makes it possible to extend the transmission range. Whether used either once along the transmission link (mid link OPC) [15, 16] or several times (multi OPC) [17, 18], the optical technique of phase conjugation is an inline all optical processing of signal that allows nonlinearity compensation and transparent dispersion [19]. In large bandwidth systems [20], nonlinearity compensation is only partially possible in distributed Raman amplified transmission systems or discretely amplified with large spacing of Raman pumping [21]. When an OPC is implemented in a quasi-lossless distributed Raman amplified system, such as one that uses very small lengths of span [22] or Raman fiber laser based amplification [23], complete elimination of nonlinear, deterministic (signal-to-signal) effects. To compensate for nonlinearities, an ideal OPC based system would have to deal with either a drop in efficiency of compensation due to polarization mode dispersion (PMD) [24] or, eventually, nonlinear signal noise interactions [25]. The use of numerous OPCs is anticipated to boost performance in such setups, either by mitigating the effects of PMD or by compensating, at least in part, for the debilitating effects of nonlinear signal-noise interactions [26]. If an OPC assisted system is constrained by signal-signal-interactions of nonlinear, however, the performance boost attributable to improved matching phase due to the OPC's in-line compensation of dispersion may be attenuated if many OPCs are deployed [27, 28].

In this paper will be show how OPC can improve reach by 1.792 Tb/s using a wide bandwidth (8×50) Gbaud DWDM DP-16QAM) over a distance of 800 km in terms of nonlinear compensation and launched power. It will be comparing the performance of the link for different power levels launched using mid span spectral inversion (MSSI) and multiple OPC methods with and without using backward Raman amplification propagation to make up for the nonlinear distortion of the fiber. The ability of FWM-based phase conjugation using nonlinear media as (HNLF) to create phase-conjugated duplicates of these DWDM signals with a large total bandwidth is a significant advantage of this technique.

OPC model with coupled nonlinear Schrödinger equations

OPC is a nonlinear dispersion regulated approach that corrects for both the Group velocity dispersion (GVD) and the Kerr effects [29]. Figure 1 depicts the fundamental idea behind optical phase conjugation. Nonlinear dispersion impairments, in the first span of transmission link before the OPC module, can be cancelled by those generated after OPC module. The module of optical phase conjugation can be placed between the middle of SMF transmission links or in the second span of transmission link along the optical transmission. Thus, the OPC method boosts long-haul optical transmission systems' nonlinear performance [30]. Equation 1 refers to Nonlinear Schrödinger equation (NLSE) under slowly varying envelope approximation describes signal propagation in nonlinear, dispersive, and lossy medium [31, 32].

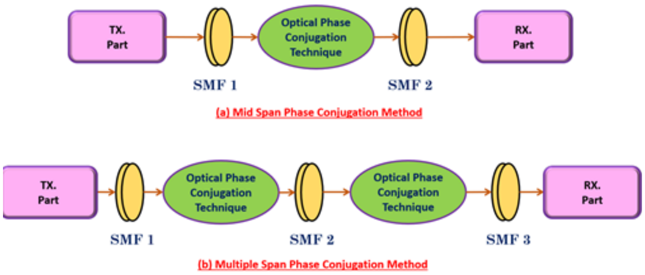

Fig.1. Basic concept of OPC implementation (a) mid span (b) multiple span

$$\frac{\partial E}{\partial z} = -\frac{\alpha}{2}E - \frac{i}{2}\beta_2\frac{\partial^2 E}{\partial t^2} + \frac{1}{6}\beta_3\frac{\partial^3 E}{\partial t^3} + i\gamma|E|^2E \quad (1)$$

where E represents the complex amplitude signal, α is the coefficient of attenuation, β_2 and β_3 are the group velocity dispersion and dispersion slope, respectively. Finally, γ is the Kerr effect. The complex conjugated can be illustrated based (NLSE) as.

$$\frac{\partial E^*}{\partial z} = -\frac{\alpha}{2}E^* + \frac{i}{2}\beta_2\frac{\partial^2 E^*}{\partial t^2} + \frac{1}{6}\beta_3\frac{\partial^3 E^*}{\partial t^3} - i\gamma|E^*|^2E^* \quad (2)$$

where * refers for complex conjugation. Both the chromatic dispersion term (β_2) and the Kerr effect term (γ) in this expression have their signs inverted. Chirp caused by group velocity dispersion (GVD) grows linearly with distance along the link. The group velocity dispersion generated chirp that happens after OPC eliminates the group velocity dispersion induced chirp that happens before OPC because the sign of this term is inverted by the effect of OPC module. Since the OPC module uses the same fiber in both directions of a transmission link, full GVD compensation is achieved.

Kerr effect, unlike the group velocity dispersion, is a nonlinear and depends on power of the signal optical. Hence, transmission link design affects Kerr effect compensation. 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 figure 2. Here, pump1 and pump2 are CW pump waves at frequencies F_{P1} and F_{P2}, and input signal is the signal wave at frequency F_S. A parametric mixing between the pump and signal wave will generate a new idler at frequency $F_C = 2F_P - F_S$, where the idler field is identical to the signal wave except that its phase is conjugated.

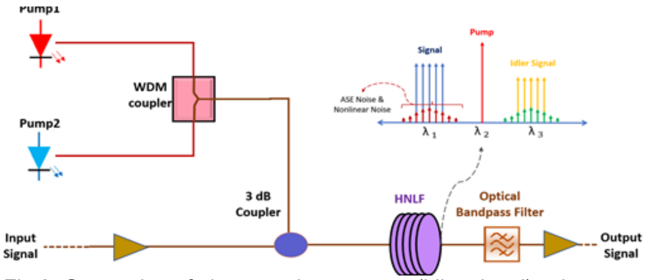

Fig.2. Generation of phase conjugate wave (idler signal) using HNLF medium

Description of proposed system

The proposed system is seen in figures 3 and 4 and is modelled in the "Optisystem 19" optical simulation environment. It uses a mid and multiple OPCs to transmit 1.792 Tbps of dual polarization 16-QAM data over 800 km of fiber. Opposite polarity of parallel dual drive Mach Zehnder modulators are used to modulate 8 signals at 50 GHz in the transmitter section. There is a linewidth of 0.1 MHz between the first signal's laser frequency of 193.1 THz and the last signal's frequency of 193.45 THz. The MZM generates a pair of 16-QAM optical signals, one in phase and one in quadrature. The DWDM signal is then processed and sent through an optical fiber to the OPC module. The simulation parameters are listed in Table 1.

Table 1. The parameters of simulation

Parameter	Value
Bit rate	224 Gb/s
Sequence length	16384
Guard bit	10
CW laser power	-15 dBm to 15 dBm
Azimuth	45 deg
Bit per symbol	4 bits
Length of HNLF	200 m

In figure 3, we see the configuration of the suggested mid OPC system that was described in the paper. In this work, 224 Gb/s of data are transmitted via 8 channels of DP-16QAM signals. Information about the transmitter is provided in terms of the bit sequence that is used to modulate the 50 GHz 16QAM optical signal at the DWDM input. Figure 5's bottom left diagram is an in-depth look at the 16QAM transmitter. 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 the noise of amplified spontaneous emission (ASE) on the transmitter side, a bandwidth of optical Gaussian filter equal to (4×bit rate) is used. The optical fiber has a loss (α) of 0.2 dB/km, a dispersion slope of 0.075 ps/km/nm2, and a dispersion of 16.75 ps/km/nm. EDFA with a noise figure of 3 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 193.275 THz (1551.11 nm) based on FWM, which takes advantage of HNLF with a length of 200 m, a nonlinear coefficient of 10.2 /W/km and a zero-dispersion wavelength (λ_o) of 1550 nm.

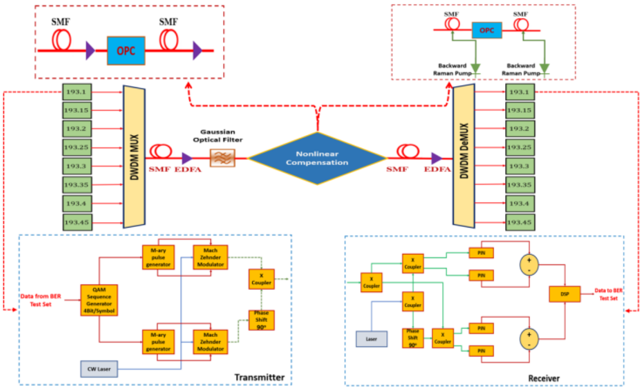

Fig.3. System model of the transmitter and receiver 16QAM mid OPC with and without Raman amplifier

In the second scenario, the span loss caused by using OPC is compensated for by a hybrid with a backward Raman amplifier. Distributed Raman amplification is better than discrete amplifiers at reducing the effects of OPC based fiber nonlinearity when it comes to meeting the power symmetry criteria.

The second configuration of using phase conjugation called multiple OPC. As shown in figure 4, this module is looked into as a mid OPC with two cases. By substituting an optical fiber with a length double that of the ones 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 20 dB optical amplifier. After going through the optical filter, this signal has the same parameter when it passes through the first OPC. The conjugated wave generated (also known idler wave) 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 conjugated wave enters a second OPC with the identical characteristics as 1st OPC, except the signal representing the conjugated wave is reinterpreted as new signal that combines with two pumping of the 2nd OPC to generate the new conjugated wave. Later, 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. Figure 4's lower right shows an 16QAM receiver schematic.

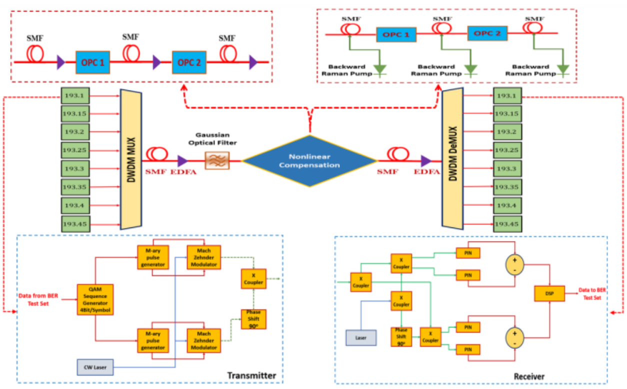

Fig.4. System model of the transmitter and receiver 16QAM multiple OPC with and without Raman amplifier

Simulation 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 DP-sixteen quadrature amplitude modulation (16QAM) optical signal, bit rate 224 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 16QAM, firstly show the performance of the system that operates back-to-back. Figure 5 show the constellation diagram for 16QAM for middle channels (channel 4 with x and y polarization).

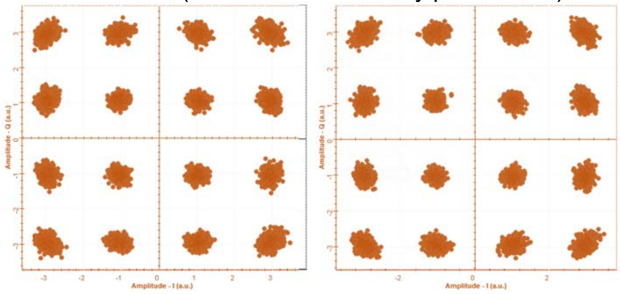

Fig.5. Constellation diagram of the received DP-16QAM signal 8 channels after transmission back-to-back (left) x-polarization (right) y-polarization

As shown in figure 5, the constellation diagram is clear and BER for the middle channel is equal 2.1×10^{-6} and 3.6×10^{-6} with Q-factor 13.25 and 13.13 for middle channels for x and y polarization, respectively. Also, the Error vector magnitude (EVM) is 0.075 and 0.076. Now insert optical fiber with a length 800 km. The constellation diagram is illustrated in figure 6.

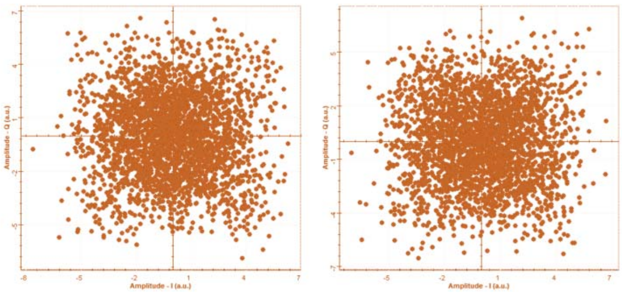

Fig.6. Constellation diagram of the received 16QAM signal 8 channels after transmission over 800 km SMF for (left) x-polarization (right) y-polarization

As shown in the above figure, the constellation diagram is bad due to the effect of nonlinearity with a high bit rate equal (0.24) and (0.25) with (1.84) and (1.82) Q-factor and (0.543) and (0.549) error vector magnitude for middle channel with x and y polarization, respectively. The degradation of received signal back to Kerr effects. At this point, using OPC device to enhance the performance of the system against nonlinear effects.

I. Mid-way OPC 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. Figure 7 shows the spectrum of the signal before and after a pass through HNLF.

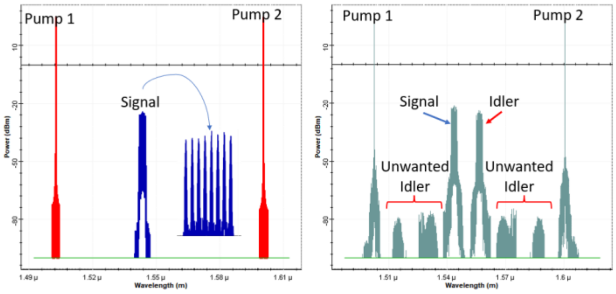

Fig.7. The spectrum of the 16QAM signal with OPC before pass through HNLF (left) and after pass HNLF (right)

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 figure 3, we will look into how well the proposed system worked with respect to OPC module mid span. The optimal transmit power per channel for the mid OPC (conventional) is around 2 dBm, with a bit error rate of 6.5×10^{-2} and 5.3×10^{-2} for the middle polarization channel for x and y with the Q-factor 4.07 and 4.14 and error vector magnitude (EVM) are 0.245 and 0.241, respectively.

When Raman amplification is added to a conventional OPC module as illustrated in figure 3 (upper right), the output OSNR will improve while the nonlinear penalty is decreased. In order to create a Raman amplified link, a backward Raman pumping source and a single mode fiber are required. The four-wave mixing process in the nonlinear medium (HNLF) is improved by using the broadband gain offered by Raman amplification of the interacting a reduced input signal strength with light waves. 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 1.5 w to compensate for the power loss caused by the output idler. Hence, the Q-factors of hybrid OPC module with backward Raman amplifier and the conventional OPC are compared at a constant idler power level. As can be shown in figure 8, 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 value of Q-factor is increasing by 3.07 dB for x polarization and 2.84 dB for y polarization of the middle channel with enlarged by 32.5% and 35.2% when the conventional method is used.

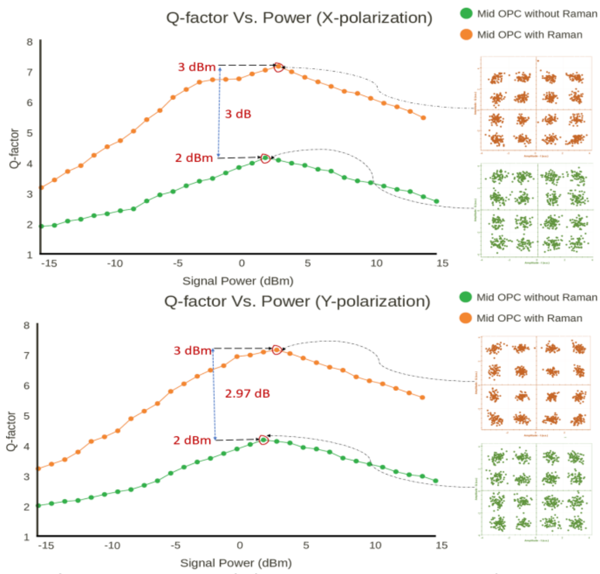

Fig.8. Signal power vs. Q-factor and eye diagram for the middle channel (ch.4) of mid OPC module with and without Raman amplifier (upper) x-polarization and (lower) y-polarization

On the right side of figure 8, 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 5.5×10^{-2} to 1.1×10^{-2} for x-polarization and 5.3×10^{-2} to 1.25×10^{-2} for y-polarization.

II. Multiple OPC 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 figure 4, to reduce the impact of interchannel nonlinear impairments.

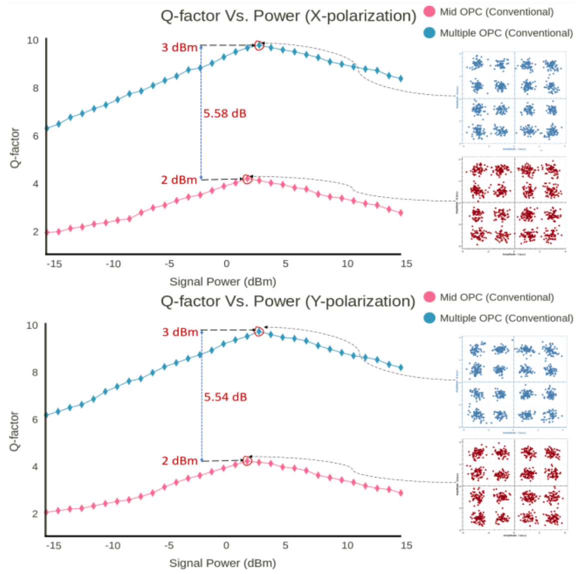

Fig.9. Signal power vs. Q-factor and eye diagram for the middle channel of conventional mid and multiple OPC module (upper) x-polarization and (lower) y-polarization

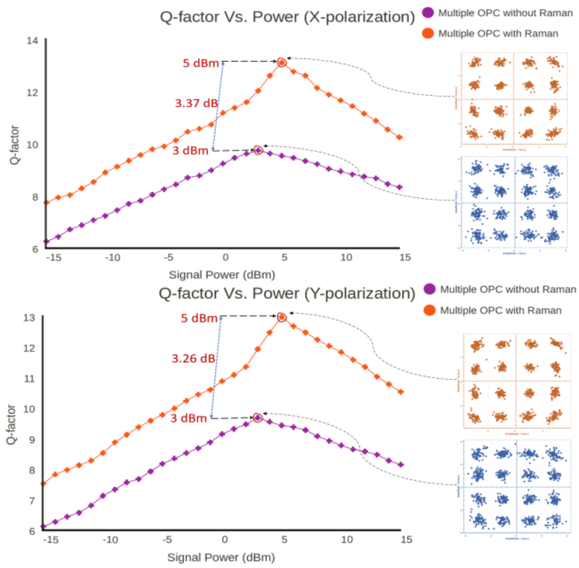

Fig.10. Signal power vs. Q-factor and eye diagram for the middle channel (ch.4) of multiple OPC module with and without Raman amplifier (upper) x-polarization and (lower) y-polarization

The consequences of nonlinearity in fibers are analyzed as a function of the input signal power. First, we test the multiple OPC module's transmission capabilities in the absence of a Raman amplifier (conventional OPC). According to the data, the max Q-factor for the center channel is 9.72 dB for x polarization and 9.69 for y polarization at 3 dBm power of signal and BER 1.09×10^{-3}

and 1.13×10^{-3} respectively. As can be seen in figure 9, comparing conventional multiple OPC with mid OPC, the results reveal that the first causes less distortion with an improved Q-factor by 5.65 dB and 5.55 dB with EVM equal to 0.179 and 0.18 for x and y polarization, respectively.

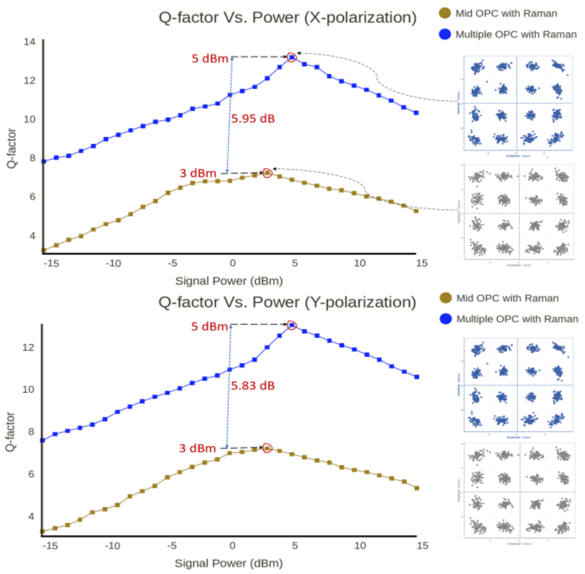

Fig.11. Signal power vs. Q-factor and eye diagram for the middle channel of mid and multiple OPC module with Raman amplifier (upper) x-polarization (lower) y-polarization

Later, the distortion of nonlinear in the system is reduced by the OPC use of Raman amplification, as seen by the box in figure 4 (upper right). Two pumps' signals are input to the OPC at 0.3 w while the backward Raman pump is set to 1.5 w. 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 figure 10. It has been demonstrated that, as compared to conventional OPC, multiple OPCs outfitted with a Raman pump provides superior performance of optimized launched power and the peak Q-factor. The Q-factor improvement is increasing from 9.72 dB and 9.69 dB at 3 dBm in conventional multiple OPC to 13.08 dB and 13.03 dB at 5 dBm with a backward Raman amplifier that enhanced about 3.36 dB for x polarization and 3.34 dB for y polarization of the middle channel with enlarged by 29.7%. When compared to the experimental results given in [33], 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 figure 11. The best value of power input is increased by 2 dBm when using an OPC with a Raman amplifier, and the Q-factor is increasing by 5.94 dB for x polarization and 6.05 dB for y polarization, led to a total gain of 15.7% in the middle channel (ch.4).

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 with the nonlinear compensation method with DWDM technology compared to previous studies is the best using hybrid OPC.

Table 2. Comparison of proposed work with previously published work

Parameters	Ref.[34]	Ref.[35]	Ref.[36]	Ref.[33]	Ref. [18]	Ref. [21]	Ref.[37]	Ref.[38]	Proposed work
Method of compensation	DBP	Hybrid OPC with DCF & FBG	Mid Span OPC	Mid Span OPC	Mid Span OPC	Mid Span OPC with Raman	Mid Span OPC	Mid Span OPC	Hybrid Mid & Multiple OPC with Raman amplifier
Multiplexing type	WDM	WDM	WDM	WDM	AWG	—	WDM	—	DWDM
Channel spacing (GHz)	32	100	100	80	20	—	100	—	50
Type of compensation	XPM	FWM	FWM	FWM	Kerr nonlinear	Kerr nonlinear	FWM	FWM	Kerr effects
Modulation format	QAM & QPSK	ASK	16 QAM	16QAM CO-OFDM	QPSK & 16QAM CO-OFDM	16QAM	—	QPSK	DP-16 QAM
No. of channel	5	8	7	2	2	Single	Multi	Single	8
Data rate per channel (Gb/s)	—	2.5	—	320	40 & 80	200	80	20	224
Input power	Variable	-10 to 10	-20 to 20	10	-4 to 12	-6 to 12	Variable	-25 to 10	-15 to 15
Transmission distance (km)	800	185	350	800	200	Variable	160	—	800

Conclusion

In this study was demonstrated how a mid and multiple OPC can use an FWM-based HNLF medium to reduce the impact of fiber nonlinearities on a 1.792 Tbps DP-16QAM link over 8×100 km of fiber optic link. Researchers have looked into OPC with and without a Raman amplifier. The simulation findings reveal that the optimal signal power into OPC for a middle channel at 193.275 THz is 3 dBm for a hybrid Raman amplifier with mid-OPC and 5 dBm for a hybrid Raman amplifier with multiple OPCs, compared to 2 dBm and 3 dBm in the conventional scenario, respectively. When compared to conventional OPC, the performance evaluation of the hybrid Raman amplifier with OPC showed significant improvements in BER, Q-factor improvement, and received signal constellation. According to the findings of an analysis of received 16 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. The simulation results demonstrate that the multiple links of hybrid OPC with a Raman amplifier can improve upon the performance of a mid-level OPC module, with BERs of 6.3×10^{-6} and 7×10^{-6} and Q-factors of 13.08 dB for x polarization and 13.03 dB for y polarization, respectively. This represents an improvement in the value of Q-factor to 5.94 dB and an improvement in BER of over two orders. The evaluation method given in this study is useful for fiber impairment mitigation and can also be used in the future with advanced modulation format techniques to increase the data rate and increase the transmission range.

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