BJET
(Bayero Journal of Engineering and Technology)
https://bjet.ng/index.php/jet

Research Article
2025, Vol. 20 (1), 1-7

OPTICAL PHASE CONJUGATION OUTPERFORMS DIGITAL BACKPROPAGATION IN 50-GBPS DWDM SYSTEMS: EVM AND FWM SUPPRESSION ANALYSIS

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Received: 19-05-2025
Revised: 24-05-2025
Accepted: 31-05-2025
Published: 10-06-2025

Abstract: *The unending demand for high-speed optical communication networks led to the advancement of Dense Wavelength Division Multiplexing (DWDM) systems characterized by enhanced capacity and higher data transmission rates. However, these systems encounter considerable challenges due to propagation impairments, such as chromatic dispersion and nonlinear phenomena including Four-Wave Mixing (FWM), which compromise signal integrity and limit overall system efficiency. This investigation examines the efficacy of two prominent compensation methodologies, Optical Phase Conjugation (OPC) and Digital Backpropagation (DBP), in alleviating fiber impairments in a 5-channel dual-polarization quadrature phase-shift keying (DP-QPSK) DWDM system on a 50-GHz channel grid. The simulation of the system was conducted utilizing MATLAB, with the input power systematically altered from -2 dBm to 10 dBm, and performance metrics such as Error Vector Magnitude (EVM) and FWM efficiency were scrutinized to assess the efficacy of the techniques. The findings show that OPC outperforms DBP in tackling signal distortions during transmission. OPC significantly reduces unwanted FWM products and achieves better EVM performance. At 6 dBm input power, OPC reduces EVM to 7.2%. DBP only gets it to 10.8%. That is a 33.3% boost in signal clarity for OPC. OPC also cuts FWM products by an extra 1.5 dB across the power range. It handles nonlinear effects better. DBP has complexity and heavy computing needs, which likely makes it less efficient. OPC is more efficient overall. It improves signal quality in multi-channel optical systems. These findings are significant for the design of next-generation networks, with improved signals, capable of handling more data and reaching farther distances.*

Key words: Optical Phase Conjugation, Digital Backpropagation, Error Vector Magnitude, Four-Wave Mixing Efficiency

1. Introduction

The demand for fast optical networks is rising, due to emerging, high-performance applications such as 4K streaming, real-time AI, and telemedicine. This pushes researchers to enhance Dense Wavelength Division Multiplexing (DWDM) systems to 100-Gbps or more. However, fiber impairments create huge problems. They weaken signal quality, slow data rates, and limit transmission distances. Chromatic dispersion (CD) is a key issue. It spreads signals over time because light travels at different speeds for different wavelengths. Polarization mode dispersion (PMD) adds more distortion. Nonlinear issues also cause trouble. These include self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS). All these effects distort the signal as it moves from transmitter to receiver. The consequence lower system performance (Bi et al., 2025; Karanov et al., 2018; Lawan et al., 2020; Tong, Huang, Cao, Zhang, & Zhang, 2024).

In DWDM systems, channels are packed close together. Power levels are high. This makes impairments serious issue (Saif, Soman, & Dobre, 2024). Chromatic dispersion spreads signals. It slows down data speeds (Lawan & Ajiya, 2013; Lawan, Ajiya, & Shu'aibu, 2012; Maghrabi, Kumar, & Bakr, 2018). Four-wave mixing (FWM) is another problem. It is a nonlinear effect tied to power. FWM mixes wavelengths and creates unwanted frequencies (Kumar & Kaur, 2021; Lawan & Mohammad, 2018). These effects will collectively degrade high-capacity DWDM performance. We need advanced solutions to fix this (Lawan & Ajiya, 2013; Lawan et al., 2012; Lawan & Mohammad, 2018; Maghrabi et al., 2018). Researchers are tackling these issues with some number of techniques. Among the most important are Optical Phase Conjugation (OPC) and Digital Backpropagation (DBP). OPC flips the signal phase midway through the fiber. This counters dispersion and nonlinear effects later on. It helps restore integrity of the signal. But OPC needs to be placed exactly at the midpoint of the link. That can make it tricky for complex networks (Paweł, Rizzelli, Ania Castañón, & Tan, 2023; Rosa, Martella, & Tan, 2022). DBP takes a different approach. It uses digital signal processing at the receiver. It reverses fiber impairments by solving the nonlinear Schrödinger equation. DBP is more flexible. It is easier to set up. But it needs a lot of computing power. This is especially true for long-haul systems or high data rates (Bi et al., 2025; Saif et al., 2024). Despite these challenges, both OPC and DBP have proven effective in improving signal quality, making them strong contenders for enhancing DWDM system performance and supporting the next generation of high-speed optical networks (Yi, 2022).

In this research endeavor, the efficacy of OPC and DBP is rigorously assessed within the context of a 5-channel Differential Phase Shift Keying (DP-QPSK) DWDM transmission architecture. The operational framework of the system, is characterized by a channel separation of 50 GHz, while the input power is systematically varied within the range of -2 dBm to 10 dBm. In order to allow for an effective side-by-side comparison and evaluation of the performance of these two prominent mitigation techniques, Error Vector Magnitude (EVM) and FWM efficiency, are carefully considered and recorded. The findings show that in Dense Wavelength Division Multi-plexing (DWDM) systems, Optical Phase Conjugation (OPC) outperforms Digital Backpropagation (DBP) in addressing signal impairments. These results shed light on the trade-offs and practical applications of each method, offering valuable insights for enhancing system performance.

2. Methodology

This study evaluates how well two techniques OPC and DBP can reduce signal distortions in a 5-channel DWDM system using DP-QPSK. The system faces challenges from dispersion and nonlinear effects, and we compare the performance of OPC and DBP in addressing these issues. Some theoretical model equations involved are presented first then the simulation setup is also presented.

2.1. Fiber Channel Model

This is based on Nonlinear Schrodinger Equation (NLSE), which governs optical signal propagation in fibers, modelling the effects of attenuation, dispersion and nonlinear effects. Beginning from Maxwell's equations considering slowly varying envelope approximation and a weakly nonlinear regime, the NLSE given by Equation (1) is derived as in (Agrawal, 2012; Lawan & Ajiya, 2013):

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + i\gamma \mid A \mid^2 A \qquad (1)$$

where $A(z,T)$: Optical field complex envelope. α: Attenuation coefficient. β_2: Group velocity dispersion coefficient. $\gamma = \frac{n_2\omega_0}{cA_{\text{eff}}}$: Nonlinearity coefficient (n_2: Nonlinear refractive index, A_{eff}: effective mode area). $T = t - \beta_1 z$: Retarded time frame.

2.2. Split-Step Fourier Method (SSFM)

This is the method for solving NLSE for a given step size h it is represented by Equation (2) (Agrawal, 2012):

$$A(z+h,T) \approx \exp\left(\frac{h}{2}\widehat{D}\right)\exp\left(h\widehat{N}\right)\exp\left(\frac{h}{2}\widehat{D}\right)A(z,T) \qquad (2)$$

where $\widehat{D} = -\frac{\alpha}{2} - i\frac{\beta_2}{2}\frac{\partial^2}{\partial T^2}$, is the linear operator, $\widehat{N} = i\gamma \mid A \mid^2$ is the nonlinear operator. SSFM alternates between solving linear and nonlinear operators or effects in the Fourier or time domains. DBP uses this method to digitally reverse the distortions by working backward through the NLSE.

2.3. Optical Phase Conjugation (OPC)

This is the simple model of the OPC given by Equation (3), it phase conjugate the signal at the middle of the link ($z = L/2$) to reverse distortions in the second half (Lawan et al., 2020; Paweł et al., 2023)

$$A_{\text{OPC}}(z) = A^*(L-z)\cdot e^{i\phi_{\text{NL}}} \qquad (3)$$

where A^*: Complex conjugate of the signal. ϕ_{NL}: Nonlinear phase shift compensation term. This symmetry cancels dispersion and mitigates nonlinear effects.

2.4. Error Vector Magnitude (EVM)

It quantifies signal quality by measuring deviations in the constellation diagram (Qin & Xiao, 2018), it is given by Equation (4):

$$\text{EVM (\%)} = \sqrt{\frac{\sum_{k=1}^{N} |S_{\text{measured},k} - S_{\text{ideal},k}|^2}{\sum_{k=1}^{N} |S_{\text{ideal},k}|^2}} \times 100 \qquad (4)$$

where $S_{\text{measured},k}$: Measured symbol k. $S_{\text{ideal},k}$: Ideal symbol k.

2.5. Four-Wave Mixing (FWM) Efficiency

FWM generates new frequencies ($\omega_3 = \omega_1 + \omega_2 - \omega_4$). The efficiency η_{FWM} it is given by Equation (5), depends on phase mismatch $\Delta\beta$ (Agrawal, 2012):

$$\eta_{\text{FWM}} = \frac{P_{\text{FWM}}}{P_{\text{channel}}} = (\gamma P_0 L_{\text{eff}})^2 \cdot \frac{\sin^2\left(\frac{\Delta\beta L_{\text{eff}}}{2}\right)}{\left(\frac{\Delta\beta L_{\text{eff}}}{2}\right)^2} \qquad (5)$$

where P_0 is the input power per channel. $L_{\text{eff}} = \frac{1-e^{-\alpha L}}{\alpha}$ is the effective fiber length and $\Delta\beta = \beta_2(\omega_1 - \omega_2)^2$ is the phase mismatch.

2.6. Simulation Setup

This section involves system setup and the specific details of how these methods were implemented. The proposed setup of the DWDM system, as depicted in Figure. 1, is comprised of several integral components, including a transmitter assembly, which constitutes a 5-channel DP-QPSK DWDM transmission system where the separation between each channel is maintained at 50 GHz. Each channel functions with an output power ranging from -2 to 10 dBm and utilizes Non-Return-to-Zero (NRZ) modulation techniques. The transmitter sends signals, which are combined with a Wavelength Division Multiplexing (WDM) multiplexer. The fiber link segments into three sections. The first is a 50 km section of single-mode fiber (SMF). Its cross-sectional area is 80 μm². It has a dispersion coefficient of 17 ps/nm-km. Its dispersion slope is 0.075 ps/nm²-km. This dictates how dispersion varies by wavelength. Each channel runs at 10 Gbps. Total capacity hits 50 Gbps. An erbium-doped fiber amplifier (EDFA) boosts the signal in the first section. The middle section holds an OPC module. It fixes dispersion and nonlinear distortions. Those distortions can impair the signal. The third section adds another 50 km of SMF. It matches the first section in specifications. Another EDFA keeps the signal in this section as well. At the receiver, a coherent optical receiver works with a demultiplexer (DEMUX). They sort the incoming signal, filtering it at cut-off frequency of 0.75 times the bit rate. This maintains the signal integrity. Figure 1 illustrates the schematic representation of the system configuration.

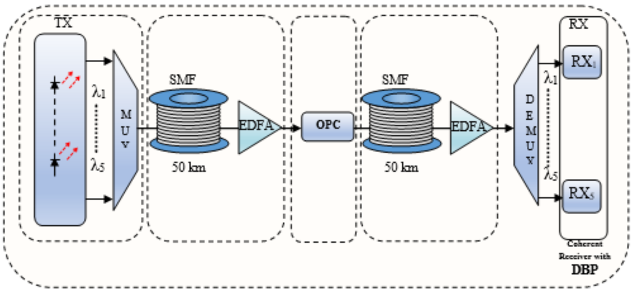

Figure 1: Schematic of the simulation setup

The compensation methodologies employed encompass OPC and DBP. To eliminate signal distortions, we put an OPC module in the middle of the fiber link. It flips the signal phase. This creates a mirror image. The mirror image cancels distortions from the half of its propagation distance. In the final segment, the flipped signal smooths out the distortions. It delivers a clean signal to the receiver. Imagine a assignal spread by dispersion, OPC makes it narrow again. We modeled this OPC module in MATLAB (Lawan et al., 2020). The coherent receiver uses a digital processing chain as presented in (Lawan & Mohammad, 2018). It starts with timing recovery. Then comes polarization demultiplexing, using a 2×2 adaptive equalizer. Frequency-domain filtering for chromatic dispersion, then carrier phase recovery, which corrects frequency and phase offsets via feedforward algorithms. These steps prepare the signal for DBP. DBP uses a split-step Fourier method. It solves the inverse NLSE. This mimics backward travel through the fiber. It mitigates chromatic dispersion and nonlinear effects, which include self-phase modulation, cross-phase modulation, and four-wave mixing. The result is a restore signal at the end of the WDM link (Lawan et al., 2020).

We looked at two main metrics. One is EVM. The other is FWM Efficiency. EVM shows signal quality. It catches small distortions. These are like small misalignments in the signal. They do not always show up as bit errors. EVM finds subtle issues unlike the bit error rate, which only counts wrong bits. These small distortions can affect the performance. FWM efficiency was also key to DWDM systems packed with channels spaced at 50 GHz. This makes them prone to wavelength interference (Giovannini et al., 2022; Qin & Xiao, 2018).

We used MATLAB and OptiSystem co-simulation in this work. OPC and DBP are compared for fiber impairments mitigation. We checked the signal spectrum at various points. We recorded FWM effects formed and get reduced, how the five channels broadened due to CD and get narrowed after compensation and how signal constellations were scattered and get corrected and recovered. By comparing EVM and FWM efficiency, we saw how well OPC and DBP performed in restoring optical signals quality.

These metrics were systematically compared across an array of input power levels ranging from -2 dBm to 10 dBm to evaluate the robustness of the techniques under different power levels. The results were corroborated by comparing the received signal quality across three distinct scenarios: before, with OPC, and with DBP compensation. The overall system performance was graphically represented and analyzed from the perspective of signal constellations, percentage of EVM values, and FWM efficiency.

3. Results and Discussion

An investigation into the performance characteristics of a 5-channel DP-QPSK DWDM transmission system was conducted, wherein the inter-channel spacing was established at 50 GHz, and the input power was varied in the range of -2 to 10 dBm, concurrently, the resultant received power and the corresponding EVM percentages were recorded. For the analytical assessment of dispersion and nonlinearity compensation, a graph was generated illustrating the percentage EVM in the system in relation to the optical power at the terminal span. Figure 2-5 elucidates the optical signal spectra at various phases of the 5-channel DP-QPSK DWDM transmission system: Figure 2 is the central channel at the transmitter side prior to any filtering, Figure 3 is the spectrally filtered and efficiently multiplexed channels preceding transmission, Figure 4 is the channels post-propagation, which reveal propagation impairments such as the dispersion and generation of new frequencies attributable to Four Wave Mixing (FWM), with at least four distinct frequencies and all five channels slightly broadened being evident as depicted herein, and Figure 5 is the representation of the central channel subsequent to demultiplexing at the receiver end.

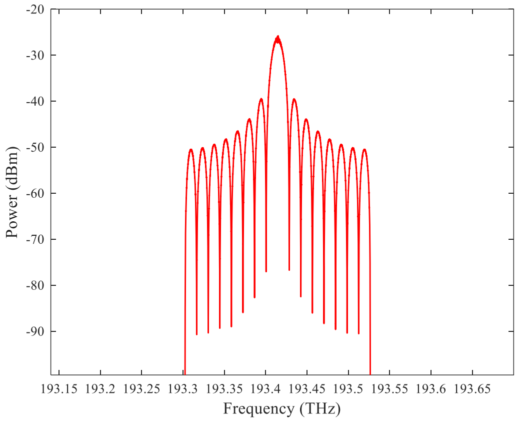

Figure 2: Optical signal spectrum for the center channel at the transmitter side

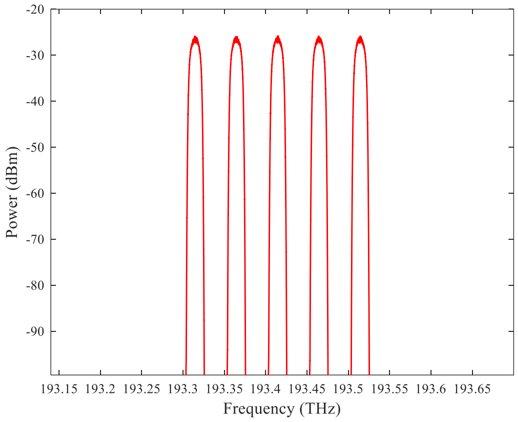

Figure 3: Optical signal spectrum for the mutliplexed channels before transmission

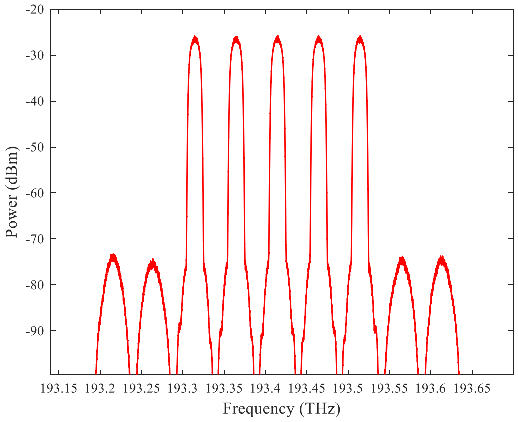

Figure 4: Optical signal spectrum for the 5 channels after propagation

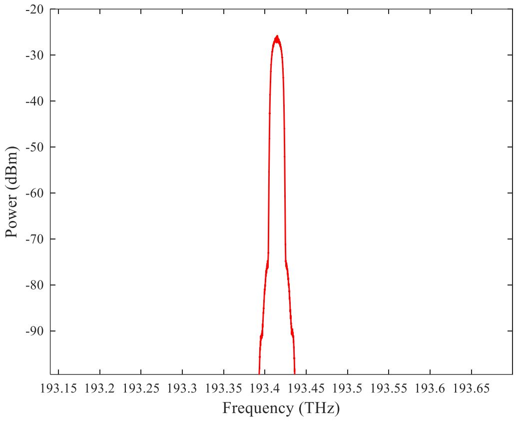

Figure 5: Center channel after demultiplexing at the receiver side

Figure 6 illustrates the constellation diagram corresponding to the system characterized by uncompensated fiber dispersion and nonlinear effects, revealing a notably substandard constellation diagram devoid of distinct symbols. The performance of the back-to-back system, depicted in Figure 7, was achieved by establishing a back-to-back direct connection between the transmitter and receiver, effectively eliminating the nonlinear transmission link, in this scenario, the absence of dispersion and nonlinearities resulted in a remarkably clear constellation diagram featuring distinctly identifiable symbols, this is considered ideal situation, devoid of any impairments. In instances where OPC and DBP techniques were implemented, the corresponding constellations are represented in Figure 8 and 9 respectively, with both methodologies yielding significantly distinct symbols within their respective constellation diagrams, in stark contrast to the scenario wherein the deleterious impacts of dispersion and fiber nonlinearities remain unmitigated.

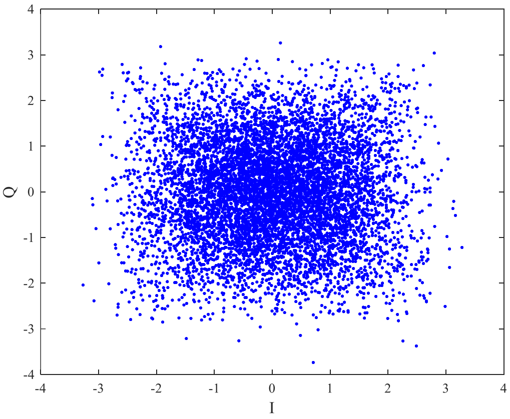

Figure 6: Constellation diagrams for the 5-channel DP-QPSK transmission system, before compensation due to dispersion and nonlinearities

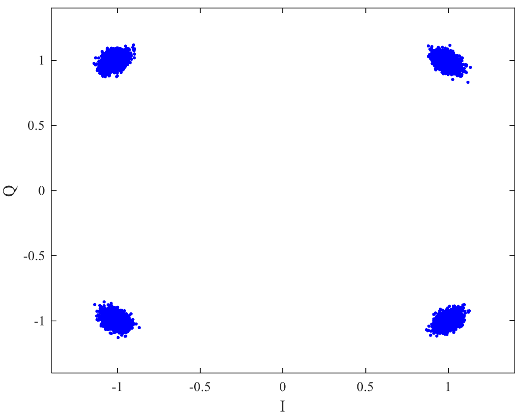

Figure 7: Back-to-back constellation, more like an ideal transmission

Both techniques demonstrate substantial improvements in performance. It is evident OPC yields clearer constellation, more closer to ideal situation than DBP, such difference may not be detected by looking at BER only.

To gain a comprehensive understanding of the extent of enhancement achieved by each of the two methodologies, the metrics of percentage EVM in Figure 10 and FWM efficiency in Figure 11 were employed to assess the effectiveness of both approaches.

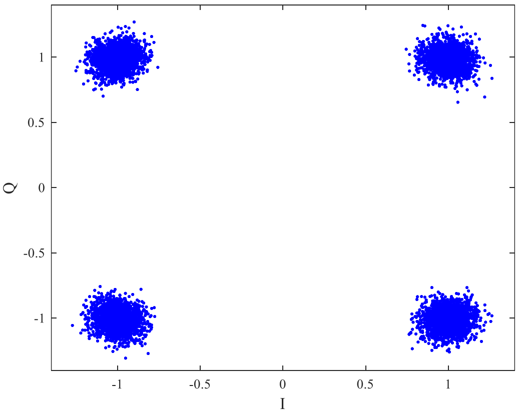

Figure 8: Constellation diagrams for the 5-channel DP-QPSK transmission system after OPC implementation

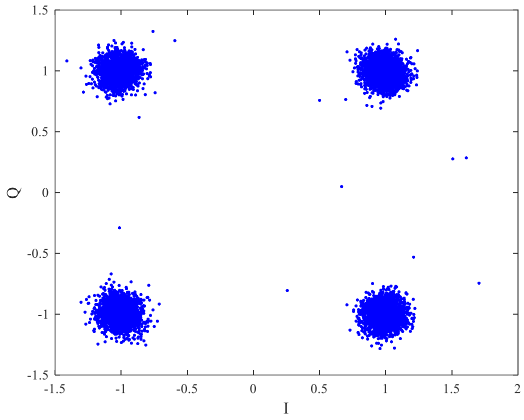

Figure 9: Constellation diagrams for the 5-channel DP-QPSK transmission system after DBP implementation at the receiver side

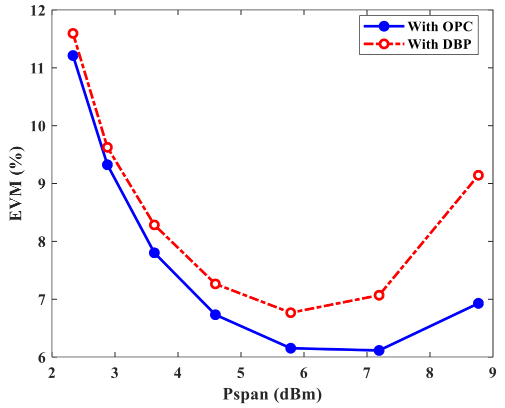

Fig. 10. Performance comparison of the two mitigation techniques side-by-side in 5-channel DP-QPSK transmission system, EVM performance comparison for OPC and DBP

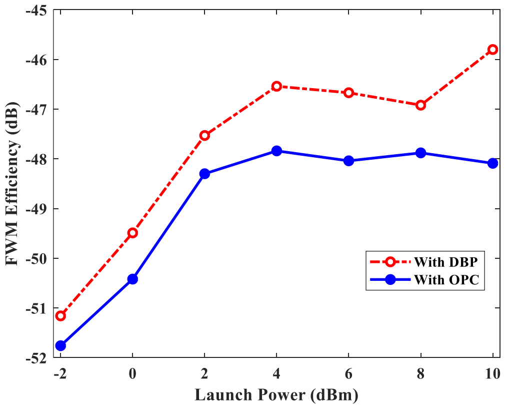

Figure 11: Performance comparison of the two mitigation techniques side-by-side in 5-channel DP-QPSK transmission system, FWM efficiency comparison for OPC and DBP

Upon examination of Figures 10 and 11, it becomes obvious that, although both methodologies offer a considerable degree of compensation regarding the level of mitigation attained, the OPC demonstrates superior improvements in percentage EVM and reduced FWM efficiency relative to DBP. Subsequently, this renders OPC a more advantageous technique for the purposes of dispersion and nonlinearity mitigation within such systems, which is in agreement with (Yi, 2022).

Table 1 provides summary table of key performance metrics, highlighting the extent to which OPC outperforms DBP in the mitigation of fiber propagation impairments, especially in multi-channel DP-QPSK systems. OPC gives 33.3% reduction in EVM and 1.5 dB reduction in FWM product power.

Table 1: Performance metrics at 6 dBm input power, underlining advantages of OPC over DBP

Metric	OPC	DBP	Improvement with OPC
EVM (%)	7.2	10.8	33.3% reduction
FWM Suppression (dB)	−15.2	−13.7	1.5 dB enhancement

4. Conclusions

An investigation was conducted to evaluate the efficacy of impairment mitigation methodologies, specifically OPC and DBP, within a five-channel DP-QPSK DWDM transmission system. The channel separation was set at 50 GHz, while the input power was varied within the range of -2 to 10 dBm, allowing for a comparative analysis of their performance in terms of EVM and FWM efficiency. The results indicated that the OPC technique exhibits superior performance in the mitigation of both dispersion and nonlinear effects when compared to DBP, as evidenced by its lower EVM and FWM efficiency, thus, it emerges as a highly viable alternative for addressing linear and nonlinear distortions in optical communications.

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