A numerical analysis is presented on the long-haul wavelength-division multiplexing (WDM) transmission system employing fiber-optic parametric amplifier (FOPA) cascades based on one-pump FOPA model with Raman effect taken into account. The end-to-end equalization scheme is applied to optimize the system features in terms of proper output powers and signal-to-noise ratios (SNRs) in all the channels. The numerical results show that—through adjusting the fiber spans along with the number of FOPAs as well as the channel powers at the terminals in a prescribed way—the transmission distance and system performance can be optimized. By comparing the results generated by different lengths of fiber span, we come to the optimal span length to achieve the best transmission performance. Furthermore, we make a comparison among the long-haul WDM transmission systems employing different inline amplifiers, namely, FOPA, erbium-doped fiber amplifier (EDFA), and Fiber Raman Amplifier (FRA). FOPA demonstrates its advantage over the other two in terms of system features.

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1. Introduction

In recent years, Fiber-optical parametric amplifiers (FOPAs) are attracting widespread interest among researchers in fiber-optic field because of efficient broadband amplification [1] and wavelength conversion [2]. They are also candidates for performing all-optical networking functions [3, 4]. FOPAs are being studied as online amplifiers to compensate for the fiber loss and to increase the transmission distance without O/E/O regeneration. Researchers have demonstrated the ultra long-haul WDM links with hundreds of channels in the range of thousands of kilometers without regeneration [5], and also presented a quantum theory of nondegenerate phase-insensitive FOPA, including the noninstantaneous response time of the fiber medium, which causes Raman loss and gain [6]. A low noise figure is the most important concern in such amplifiers because noise accumulation along the amplifier links has to be minimized. It was reported that the noise figure of a phase-insensitive parametric amplifier exceeds that of an ideal phase-insensitive amplifier by 3 dB [7].

Another major problem in implementing amplified WDM transmission systems is “gain equalization.” As the gain spectrum of FOPA is nonuniform and wavelength-dependent, each channel in a WDM system will experience different optical gain, which leads to unacceptable BER performance in certain channels of the long-haul transmission system. Therefore, considerable effort has been made in inventing components that equalize the output powers at each amplifier repeater in all channels. Various equalizer proposals have been presented, including “smoothing filters” such as Fabry-Perot or tunable Mach-Zehnder interferometers [8]. To ensure the performance of long-haul transmission system, a practical and cost-effective equalization technique should be applied in the system.

In this paper, we numerically analyze the one-pump FOPA model with Raman Effect. And then, a FOPA-based
FOPA can be expressed as and developed in [5]. The parametric gain of one-pump pump case the nondegenerate case, which are both described FOPA is also called the degenerate case, whereas the two-

The one-pump case of 2.1. Mathematical Model of FOPA.

2. Analysis

The mathematical model of one-pump FOPA with Raman Effect is developed in Section 2.1, while Section 2.2 designs and numerically calculates a long-haul WDM transmission system employing cascaded FOPAs, using end-to-end equalization, and based on different lengths of fiber span. Section 2.3 compares and presents an analysis on these results.

2.1. Mathematical Model of FOPA. The one-pump case of FOPA is also called the degenerate case, whereas the two-pump case the nondegenerate case, which are both described and developed in [5]. The parametric gain of one-pump FOPA can be expressed as

\[ G_s = 1 + \left( \frac{y P_0}{g} \sinh(gz) \right)^2. \]  

(1)

When FOPA is operated phase-insensitively, a coherent-state input signal is injected at the Stokes (anti-Stokes) frequency while the input at the anti-Stokes (Stokes) frequency remains in the vacuum state. The NF is then defined as NF\(_{\text{PIA}} \equiv \text{SNR}_{\text{in},j}/\text{SNR}_{\text{out},j} \) [9], where \( j = s(a) \), if the signal frequency is on the Stokes (anti-Stokes) side and SNR is the signal-to-noise ratio.

The quantum-limited NF of a FOPA exceeds the standard 3 dB limit at high gains due to the Raman Effect [7]. When the input-signal photon number is much greater than the amplifier gain, we can calculate NF in the following expression [7]:

\[ \text{NF}_{J,\text{PIA}} = 1 + \left( \frac{n_{\text{th}}}{2} + (1 + 2n_{\text{th}}) \right) - 2 - \left( \frac{\mu_j}{2} \right) \left( \frac{\nu_j}{2} \right), \]  

(2)

where \( n_{\text{th}} = [\exp(h\Omega/kT) - 1]^{-1} \) is the mean number of optical phonons at detuning \( \Omega \) and temperature \( T \); here \( h \) is Planck’s constant over 2\( \pi \); \( k \) is Boltzmann’s constant; \( \Omega = \omega_a - \omega_p = \omega_p - \omega_s \) and \( \omega_j \) for \( j = p, s, a \) is the angular frequency of the pump, Stokes, and anti-Stokes fields, respectively. And \( \mu_j, \nu_j \) are defined in [10]. The assumption \( H(\Omega) = H(-\Omega)^* \) (i.e., its time-domain response is a real function) is usually valid for \( \Omega \) up to several terahertz in standard fibers [10]. This implies that the real part of the nonlinear response in the frequency domain is symmetric about the pump frequency, and the imaginary part in the frequency domain is antisymmetric about the pump frequency [11], \( \mu_j, \nu_j \) may be simplified to [7]

\[ \mu_a = \exp \left( \frac{-i(\Delta k - [2H(\Omega)]I_p) L}{2} \right) \times \left( \frac{ic}{2g} \sinh(gL) + \cos h(gL) \right), \]

\[ \mu_s = \exp \left( \frac{-i(\Delta k - [2H(\Omega)]I_p) L}{2} \right) \times \left( \frac{ic^*}{2g^*} \sinh(g^*L) + \cos h(g^*L) \right), \]

\[ \nu_a = \exp \left( \frac{-i(\Delta k - [2H(\Omega)]I_p) L}{2} \right) \times \frac{iH(\Omega)}{g} \sinh(gL), \]

\[ \nu_s = \exp \left( \frac{-i(\Delta k - [2H(\Omega)]I_p) L}{2} \right) \times \frac{iH(-\Omega)}{g^*} \sinh(g^*L), \]

\[ \kappa = \Delta k + 2H(\Omega)I_p, \]

\[ g = \sqrt{-(\kappa/2)^2 + (H(\Omega))^2 I_p^2}. \]  

(3)

Here \( I_p = |A_p(0)|^2 \) is the pump power in watts; the complex gain coefficient \( g \) is defined as

\[ g = \sqrt{-(\kappa/2)^2 + H(\Omega) H(-\Omega)^* I_p^2}, \]  

(4)

where

\[ \kappa = \Delta k + \left[ H(\Omega) + H(-\Omega)^* \right] I_p, \]  

(5)

\( \Delta k = \beta a \Omega^2 \) is the phase mismatch to second order caused by dispersion, where \( \beta a \) is the group-velocity dispersion coefficient. \( H(\Omega) \) is the frequency-domain Raman response function.

We build a mathematical model for the one pump FOPA with Raman Effect, which will later be applied in the WDM transmission system. Figure 1 shows its gain and NF spectra.
2.2. Design of a FOPA-Cascaded Long-Haul WDM Transmission System

2.2.1. System Configuration. Our major task is to design and numerically analyze a long-haul WDM optical transmission system employing FOPA cascades. The schematic configuration of the system is shown in Figure 2.

The system consists of eight 2.5 Gb/s externally modulated channels with 0.4 THz channel spacing (193.8–196.6 THz). Each transmitter consists of a Pseudo-Random Bit Sequence Generator, a NRZ Pulse Generator, a CW Laser, and a Mach-Zehnder Modulator. Total signal power is −3 dBm before multiplexing, that is, −12 dBm in each channel. The eight channels are then multiplexed, and the signals are transmitted over spans of conventional optical fiber with an attenuation factor of 0.2 dB/km. The fiber loss and excess losses in the system are compensated by FOPAs. The FOPAs are pumped by 1.5 W of 1537.6 nm pump light. The demultiplexer is preceded by a fiber preamplifier. The bit-error-rate (BER) calculations take into account intersymbol interference, signal–spontaneous beat noise, and postdetection Gaussian noise [12]. Photodetector PIN, Low Pass Bessel Filter, and 3R Generator are applied at each channel before BER Analyzer.

2.2.2. Features of the FOPA in the WDM Transmission System. We tested the performance of FOPA module operating in simulation transmission system. Equal input signal powers of −12 dBm are used in all eight channels. Figure 3 shows the signal powers emerging after 1-km long FOPA. Data in list are obtained in the WDM Analyzer connecting to the output of FOPA, displaying the output features. Note that the graph agrees perfectly to the corresponding spectrum in the mathematic model of FOPA (see Figure 1). Judging from the following features, we find the performance of a single FOPA quite ideal.

2.2.3. End-to-End Equalization. In [13], an end-to-end equalization scheme was described to equalize either the output powers or the SNR in WDM channels of EDFA-amplified systems. Neither new optical components nor upgrades or adjustments were required at inline amplifier areas. Equalization could be accomplished by adjusting transmitter powers with variable attenuators at the terminals based on information obtained at the output terminal.

To have the output powers equalized, we only need to adjust individual input signal powers with attenuators while keeping the total input power constant. The power in each channel is scaled by a factor inversely proportional to the gain in that channel. The new input signal power of the ith channel is adjusted to [13]

\[ P_{\text{new}}^i = P_{\text{Total}} \left[ \frac{1/G_i}{\sum_{i=1}^{8} 1/G_i} \right], \]

where \( P_{\text{Total}} \) is the total signal power before multiplexing (−3 dBm), \( G_i \) is the optical gain in the ith channel.

A similar adjustment algorithm is needed to equalize SNR. The transmitter power for the ith channel should be adjusted to [13]

\[ P_{\text{new}}^i = P_{\text{Total}} \left[ \frac{P_{\text{in}}^i / \text{SNR}_i}{\sum_{i=1}^{8} P_{\text{in}}^i / \text{SNR}_i} \right]. \]

An analysis has been presented to predict the performance of WDM lightwave transmission systems using power and SNR end-to-end equalization [13]. It was said that compared to power equalization, the relative performance of SNR equalization tends to improve with the increase of channel numbers, bit rate and receiver dynamic range and deteriorate with the increase of amplifier gain imbalance.

In the long-haul transmission system we designed for numerical analysis, although the output powers can be easily equalized by power equalization, this might lead to unacceptable BER in some channels due to low SNR. Therefore, we apply both equalization techniques in the simulation and choose the one that leads to better system performance in every individual case.

2.2.4. Long-Haul Transmission. We use Optical Spectrum Analyzer (OSA) to display the modulated optical signal in the frequency domain and WDM Analyzer to monitor the numerical results of signal and the noise power at each optical signal channel. In amplified WDM systems, SNR and BER are routinely monitored as a measure of system performance. In most cases, BER below 1 × 10^{-12} is considered acceptable, and the range of output powers should not exceed that allowed by receiver dynamic range (−30 dBm to 10 dBm in this case). Therefore, we adjust the length of fiber span and gradually increase the number of FOPAs to enhance transmission distance. Power or SNR end-to-end equalization is applied for better system performance. For each set of fiber length (from 30 km to 65 km with an increment of 5 km), we look for the largest number of amplifiers that can be employed in the transmission system within the performance constraints we mentioned above. By comparing the results with different spans, we finally come to the optimal span length to achieve the maximum transmission distance with ideal performance in the above-mentioned system.

30-km Fiber Span. The fiber span is firstly set to be 30-km long. We gradually increase the amplifiers to look for the
Figure 3: Output features of FOPA (described in Figure 1 caption) in the transmission system (described in Figure 2 caption). Equal input signal powers of −12 dBm. The list beside shows signal frequency, output signal powers, SNR and BER.

Figure 4: Output signal (red) and noise (green) powers after 90 km transmission using 30-km fiber span and equal input signal powers of −12 dBm. No equalization is applied. The list beside shows signal frequency, output signal powers, SNR and BER.

largest number in the system while the BER and output power features are within acceptable levels. Figure 4 shows the output signal (red) and noise (green) powers emerging after 3 loops of FOPA and 30-km fiber span with no equalization, the detailed features are denoted beside.

We find though BER features are good in all channels but some signal powers are overly high with an imbalance of 47 dB. We choose to apply power end-to-end equalization. Figure 5 shows the output powers when the input powers are adjusted according to (6). The output powers are nicely equalized. In this case, SNR equalization is not superior to power equalization, for SNR in all eight channels are quite decent already. After applying three iterations of SNR equalization algorithm, the output features are quite close to the result obtained by one-time power equalization, for in this case, noise in most channels has not been accumulated to a measurable level, equalizing SNR finally becomes equivalent to equalizing signal power.

When fiber span is set to 30-km long, the largest number of amplifiers we have found is 3. When we continue to increase to 4, though the SNR and BER are still good in all channels, but the signal powers remain 18 dBm after several iterations of end-to-end equalization algorithm.

We set fiber span from 30-km to 65-km long with an increment of 5 km, and repeat the simulation as above. The results of certain typical lengths are selected with graphs and data displayed as follows.

40-km Fiber Span. When fiber span is set to be 40-km long, the largest amplifiers number we have found is 6. After applying power end-to-end equalization, the system is optimized with equalized output powers and good BER in all channels; see Figure 6. When we continue to increase amplifier number to 7, power equalization is no longer applicable because it makes transmission power too low. But
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Figure 5: Same as Figure 4, except that the input power is adjusted according to power end-to-end equalization.

Figure 6: Output signal (red) and noise (green) powers after 240 km transmission using 40-km fiber span and employing power end-to-end equalization. The list beside shows signal frequency, output signal powers, SNR and BER.

even with several iterations of SNR equalization till SNR in all channels are equalized to 70 dB, signal powers in certain channels are not acceptable.

$L = 50\, \text{Km}$: When fiber span is 50-km long, we gradually increase the amplifiers number to 6. In this case, BER in channel 4 is found no longer good (only $1.62 \times 10^{-2}$) because the amplifier gain at that wavelength is not high enough to cover the larger attenuation experienced in longer fiber span. We then apply power end-to-end equalization. Figure 7 shows the optimized system with acceptable BER in all channels. When we continue to increase amplifier number to 7, power equalization is again no longer applicable for unacceptable low transmission power. Four iterations of SNR equalization leads to good BER features but signal powers in last 2 channels are a little above the constraint; see Figure 8.

$L = 55\, \text{km}$: We can increase the amplifiers number to 7 with 55-km long fiber spans, which is the largest number that we achieved with a group of fiber spans of different lengths. When the fiber length becomes longer, signals close to the pump frequency experience larger power loss which generates unacceptable BER. Figure 9 shows output features after three iterations of SNR equalization. Increasing amplifier number to 8, neither power equalization nor SNR equalization is able to optimize the system to a good level. Even with good SNR, BER features in the channels close to pump frequency are bad because of low signal power.

2.3. Comparison of the Results. In this section, we sum up the results and make a comparison based on the graphs below. Figure 10 shows the maximum transmission distance that can be achieved in the long-haul WDM transmission system employing cascaded FOPAs as we described before. The maximum transmission distance is determined by the fiber length and the number of amplifiers that could be supported in the system. End-to-end equalization is applied to optimize the system so as to afford more amplifiers but at the same time ensuring BER in all eight channels that are
Figure 7: Output signal (red) and noise (green) powers after 300 km transmission using 50-km fiber span and employing power end-to-end equalization. The list beside shows signal frequency, output signal powers, SNR and BER.

<table>
<thead>
<tr>
<th>Frequency (THz)</th>
<th>Signal power (dBm)</th>
<th>SNR (dB)</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>193.8</td>
<td>-16.21</td>
<td>39.50</td>
<td>3.13E-43</td>
</tr>
<tr>
<td>194.2</td>
<td>-16.21</td>
<td>42.04</td>
<td>6.39E-48</td>
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<tr>
<td>194.6</td>
<td>-16.21</td>
<td>47.29</td>
<td>6.60E-39</td>
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<tr>
<td>195</td>
<td>-16.21</td>
<td>60.81</td>
<td>5.65E-42</td>
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<tr>
<td>195.4</td>
<td>-16.21</td>
<td>53.29</td>
<td>3.65E-47</td>
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<tr>
<td>195.8</td>
<td>-16.21</td>
<td>44.05</td>
<td>3.29E-51</td>
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<tr>
<td>196.2</td>
<td>-16.21</td>
<td>38.96</td>
<td>8.33E-40</td>
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<tr>
<td>196.6</td>
<td>-16.21</td>
<td>36.57</td>
<td>1.98E-48</td>
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</table>

Figure 8: Output signal (red) and noise (green) powers after 350 km transmission using 50-km fiber span and employing 4 iterations of SNR equalization. The list beside shows signal frequency, output signal powers, SNR and BER.

<table>
<thead>
<tr>
<th>Frequency (THz)</th>
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<th>SNR (dB)</th>
<th>BER</th>
</tr>
</thead>
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<td>0.00E+00</td>
</tr>
<tr>
<td>196.2</td>
<td>15.80</td>
<td>42.50</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>196.6</td>
<td>19.60</td>
<td>42.55</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>

Figure 9: Output signal (red) and noise (green) powers after 385 km transmission using 55-km fiber span and employing 3 iterations of SNR equalization. The list beside shows signal frequency, output signal powers, SNR and BER.

<table>
<thead>
<tr>
<th>Frequency (THz)</th>
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<th>SNR (dB)</th>
<th>BER</th>
</tr>
</thead>
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<td>196.2</td>
<td>5.92</td>
<td>21.54</td>
<td>4.88E-98</td>
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<tr>
<td>196.6</td>
<td>10.15</td>
<td>21.63</td>
<td>3.19E-127</td>
</tr>
</tbody>
</table>
Figure 10: (a) Maximum transmission distance achieved in the long-haul WDM transmission system employing cascaded FOPAs and end-to-end equalization versus length of fiber span. (b) Constraints on number of amplifiers (with end-to-end equalization) ensuring BER below $1 \times 10^{-12}$ and signal powers between $-30$ dBm and $10$ dBm versus length of fiber span. The results are computed for $R_b = 2.5$ Gb/s, eight externally modulated channels with $0.4$ THz spacing (193.8–196.6 THz). Total signal power is $-3$ dBm before multiplexing. Optical fiber has the attenuation factor $0.2$ dB/km. The FOPAs are pumped by $1.5$ W of $1537.6$ nm pump light. FOPAs are made with $1$ km DSF and pumped at $1537.6$ nm with $1.5$ W power. The zero-dispersion wavelength is $1537$ nm, and the dispersion slope is $0.034$ ps nm$^{-2}$ km$^{-1}$. The nonlinear coupling coefficient is $1.8$ W$^{-1}$km$^{-1}$. Maximum value of Raman-gain coefficient for DSF is $0.8$ W$^{-1}$km$^{-1}$, at the temperature of $300$ K.

Figure 11 shows the average BER and SNR achieved in eight channels when employing the largest number of cascaded FOPAs in every individual case. We find average SNR decreases monotonously with fiber span length. This can be understood by realizing that the signal powers experience larger attenuation in longer fiber span while noise keeps growing in proportion to the product of gain and noise figure. From Figures 5 to 9, we can see with the increase of fiber length, the noise powers after experiencing the maximum transmission distance begin to overwhelm the signals, reduce SNR, and deteriorate BER. For fiber spans of $30$ to $45$-km long, BER in all channels are zero due to high SNR and signal power.

We further display in Figure 12 the SNR and BER features in individual channels after experiencing the achievable maximum transmission distance corresponding to different lengths of fiber span. We find that SNR in each channel decreases monotonously with fiber span length. It is interesting to notice the distribution of SNR in eight channels corresponding to different lengths of fiber span. For fiber length from $30$ km to $50$ km, power equalization is chosen to optimize system performance because in these cases SNR and BER features are in good levels even before equalization. Therefore, for $35$-to $50$-km fiber span, SNR is distributed in a similar shape that is approximately symmetrical about the center frequency. SNR is higher in the center because the gain in this frequency domain is small which leads to smaller accumulated noise while signal powers are equalized to the same. For fiber length from $55$ km to $60$ km, SNR equalization is chosen for optimization because in these cases SNR is acceptable but BER is bad because of small signal powers. Despite the signal powers could be equalized higher after power equalization, BER in some channels remains unacceptable. However, with SNR equalization, BER in all channels become decent and signal powers stay within the constraints. Therefore, for $55$-to $65$-km fiber span, SNR is approximately in uniform distribution. But we should point out that when SNR are equalized, there remain power differences in adjacent channels. However, such problems can be avoided if the channel spacing is reduced or the channels are not set in a domain of large gain variance. Moreover, the FOPA model employed in this paper is powered by one-pump, whose gain spectrum is not flat over the amplifier bandwidth—obviously depressed when close to pump frequency. This large gain dip gets more...
severe after going through several amplifiers, where the signal power at pump frequency is far smaller than that at large detuning area. Two-pump FOPA configuration could be used in later research, which provides more freedom to allow optimization of gain flatness. Last, for 30-km long fiber span, SNR is also uniformly distributed, for in this case, noises in most channels have not been accumulated to a measurable level, equalizing powers is equivalent to equalizing SNR.

Finally, we compare the optimal transmission system employing cascaded FOPAs with that employing cascaded EDFAs or FRAs. The transmission system configuration is ensured to remain the same other than using different inline amplifiers. Transmission distance is set to be 385 km by using seven spans of 55-km-long fibers. We gradually adjust the transmission powers in eight channels to obtain the corresponding BER features. To optimize the gain and SNR imbalance, end-to-end equalization is also applied in three long-haul systems employing FOPA, EDFA, or FRA so that BER in all channels are almost on the same level. Figure 14 shows the average BER in eight channels corresponding to the different signal transmission powers after experiencing 385-km transmission distance with seven 55-km-long fibers. FOPAs are made with 1 km DSF and pumped at 1537.6 nm with 1.5 W power, the zero-dispersion wavelength is 1537 nm and the dispersion slope is 0.034 ps nm$^{-1}$ km$^{-1}$, the nonlinear coupling coefficient is 1.8 W$^{-1}$ km$^{-1}$. Maximum value of Raman-gain coefficient for DSF is 0.8 W$^{-1}$ km$^{-1}$, EDFA parameters are: core radius 2.2 μm, erbium doping radius 2.2 μm, erbium metastable lifetime 10 milliseconds, numerical aperture 0.24, erbium ion density $10^{25}$ m$^{-3}$, 0.1 dB/m loss at 1550 nm, 0.15 dB/m loss at 980 nm, length 5 m, 100 mW forward pump power at 980 nm. FRA Parameters are: Polarization factor 2, Rayleigh back scattering $2.349 \times 10^{-25}$ /km, pumped with 1500 mW power at 1450 nm, length 25 km. Results achieved with different inline amplifiers are identified with corresponding signs denoted in the graph text.
We come to find and to achieve the same level of BER that is acceptable (less than $1 \times 10^{-12}$); FOPA requires the least signal transmission power comparing with the other two types of amplifiers.

3. Conclusion

In this paper, we present a numerical analysis on the long-haul WDM transmission system employing FOPA cascades. FOPA is modeled as one-pump and with Raman Effect. End-to-end equalization scheme is applied to optimize the system features. The numerical results show that—through adjusting the fiber spans along with the number of FOPA, and the channel powers at the terminals in a prescribed way—the transmission distance and system performance can be optimized. In our project, the WDM system is operated at $R_b = 2.5$ Gb/s with eight externally modulated channels (193.8–196.6 THz, 0.4 THz spacing), total signal power $-3$ dBm before multiplexing, employing cascaded FOPAs pumped by 1.5 W of 1537.6 nm pump light. The optimal fiber span length we find is 55 km to achieve maximum transmission distance of 385 km by employing seven amplifiers. The system has an average SNR 21.735 dB and an average BER $6.85 \times 10^{-83}$.

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