# Transmission performance improvement using random DFB laser based Raman amplification and bidirectional second-order pumping

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**Abstract:** We demonstrate that a distributed Raman amplification scheme based on random distributed feedback (DFB) fiber laser enables bidirectional second-order Raman pumping without increasing relative intensity noise (RIN) of the signal. This extends the reach of 10×116 Gb/s DP-QPSK WDM transmission up to 7915 km, compared with conventional Raman amplification schemes. Moreover, this scheme gives the longest maximum transmission distance among all the Raman amplification schemes presented in this paper, whilst maintaining relatively uniform and symmetric signal power distribution, and is also adjustable in order to be highly compatible with different nonlinearity compensation techniques, including mid-link optical phase conjugation (OPC) and nonlinear Fourier transform (NFT).

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## 1. Introduction

It is well known that distributed Raman amplification improves the transmission performance, compared with lumped amplification such as EDFA. To minimize the noise generation, distributed Raman amplification would exactly counteract the fiber attenuation along the length of the transmission path, maintaining the signal power level at a near constant value [1]. In addition, recent work has shown that a constant and/or symmetric signal power distribution is advantageous for some techniques used to compensate nonlinear transmission effects [2-5].

We have previously reported an ultra-long Raman fiber laser (URFL) based amplification technique with second-order pump and two fiber Bragg gratings (FBGs) [1]. This technique can give an almost negligible (+/- 0.8 dB) signal power variation (SPV) over an 80 km span. However, this requires symmetrical bidirectional pumping with equal forward (FW) and backward (BW) pump powers to minimize the SPV and amplifier noise [6]. Unfortunately, the use of forward pumping is problematic in long-haul transmission systems, as the penalty associated with relative intensity noise (RIN) being transferred from noisy pumps to the signal is much greater than the performance improvement from low SPV and noise [6,7]. Therefore, using backward pumping only is more beneficial but at the expense of an increase in SPV and noise. Another interesting feature of using backward pumping only is that a random Rayleigh backscattering distributed feedback (DFB) fiber laser can be generated even in a closed cavity, as opposed to the usual Fabry-Perot lasing obtained when using bidirectional pumping [6]. The first work on random DFB fiber laser based amplification was demonstrated in [8] where the authors showed a transmission performance improvement using third-order backward pumping. Bidirectional pumping using similar scheme can be also used in unrepeatered transmission in which the RIN-induced penalty on the signal is significantly low [7,9].

In this paper, we report second-order bi-directionally/backward pumped Raman amplification schemes based on a random distributed feedback fiber laser configuration, and compare them with conventional Raman amplification schemes. In 10×116 Gb/s DP-QPSK WDM transmission, we demonstrate that bi-directionally pumped random DFB fiber laser based amplification scheme can achieve low SPV and improves transmission performance. Using the proposed random DFB laser based scheme with an SPV of ~4 dB, an extended reach of 7915 km in a recirculating loop experiment is achieved, compared to 4999 km using backward first-order Raman pumping, and 7082 km using other amplification schemes. More importantly, there is no RIN increase on the signal using this scheme even with bidirectional pumping. Therefore, the scheme can be further optimized to satisfy the link requirement for different nonlinearity techniques [2-5]. We also show a random DFB laser scheme with backward pumping which uses only one pump but has comparable performance to conventional dual-order scheme (two pumps wavelengths).

## 2. Experimental setup and characterizations of different Raman amplification schemes

To evaluate the transmission performance, a recirculating loop experiment was conducted using the setup shown in Fig. 1(a). Ten DFB lasers with 100 GHz spacing ranging from 1542.14 nm to 1549.32 nm were combined with a 100 kHz linewidth tunable laser used as a “channel under test” through a polarization maintaining (PM) coupler while the corresponding DFB laser was switched off. The combined signals were QPSK modulated at 29 Gbaud.

Normal and inverse $2^{31}$-1 PRBS patterns were used for I & Q with a relative delay of 18 bits. An EDFA was used to amplify the signal. The resultant 10×116 Gb/s DP-QPSK signals were generated by a polarization multiplexer with a 290-symbol delay between two polarization states before launching into the recirculating loop. The noise loaded back to back transmitter performances (both single channel and WDM) are shown in Fig. 1(b). The Q factor is plotted as a function of optical signal to noise ratio (OSNR) measured in a 0.1 nm noise bandwidth, for the central channel at 1545.32 nm. At the hard decision forward error correction (FEC) threshold corresponding to $3.8\times10^{-3}$ in bit error rate (8.5 dB in Q factor), the required OSNR was ~13.7 dB.

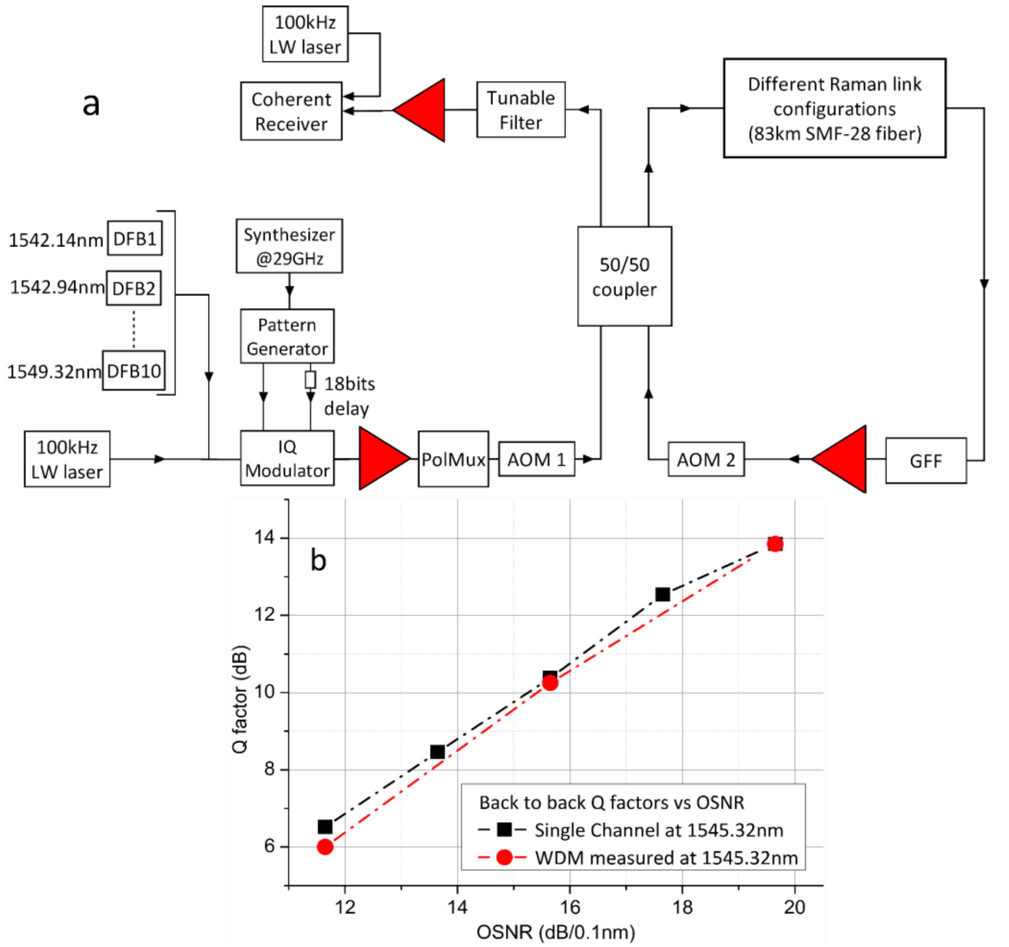


Fig. 1. (a). Experimental setup of long-haul transmission system. (b). Back to back Q factors versus OSNR of the central channel at 1545.32 nm of DP-QPSK WDM transmitter.

The transmission span in the recirculating loop was 83.32 km G.652 standard telecoms fiber. The total loss was ~17.6 dB, including ~16.5 dB from the fiber and ~1.1 dB from 1366/1455/1550 filter WDMs. The 1455 nm path of the WDM was not used and the end was angle-cleaved to prevent back reflections. To equalize channel powers, a gain flattening filter (GFF) was used after the Raman link. The ~12 dB loss from the GFF, 50/50 coupler, acousto-optic modulator (AOM), and Raman components was compensated using a single stage EDFA in the loop. The output signal was de-multiplexed by a tunable filter and amplified by an EDFA before the receiver. The receiver was a standard dual polarization coherent detection set-up, and the signals were captured with four photo-detectors using an 80 GSa/s, 25 GHz bandwidth oscilloscope for analogue to digital conversion. DSP was used offline with standard algorithm for signal recovery and linear impairments compensation. Q factors were calculated from bit-wise error counting, and averaged over two million bits.

Schematic diagrams and pump powers for the Raman configurations tested are shown in Fig. 2(a). For all configurations the Raman gain was set to counterbalance the ~16.5 dB attenuation of the fiber. The 1366 nm backward pumping configuration with a Fabry-Perot cavity (a pair of FBG at each end of the span) was used (scheme R1). The FBGs used were centered at 1455 nm with ~0.5 nm 3 dB bandwidth and 95% reflectivity. As demonstrated in [6], in this configuration with a pair of FBGs, backward pumping only gave the best transmission performance. In random DFB fiber laser based amplifiers (R2, R3 & R4), a single FBG was used at the output end of the span. First-order random DFB laser at 1455 nm was generated by the resonant mode reaching the lasing threshold in a distributed cavity formed by a distributed feedback (Rayleigh scattering) and an FBG [10-11]. Three pump power combinations were used in this configuration, as forward pumping at 1366 nm could amplify the signal near the input section of the fiber by amplifying the forward-propagated random DFB lasing. For comparison, backward first-order and dual-order pumping with no FBGs (R5 & R6) were also tested. For all configurations, the 1366 nm second-order and 1455 nm first-order pumps were highly depolarized and coupled into the span through WDM couplers. Signal power distributions along the transmission fiber measured at 1545.32 nm using a modified optical time-domain reflectometer (OTDR) are shown in Fig. 2(b), and confirmed with simulations (dotted lines) in Figs. 2(b) and 2(c) [1,4,12].

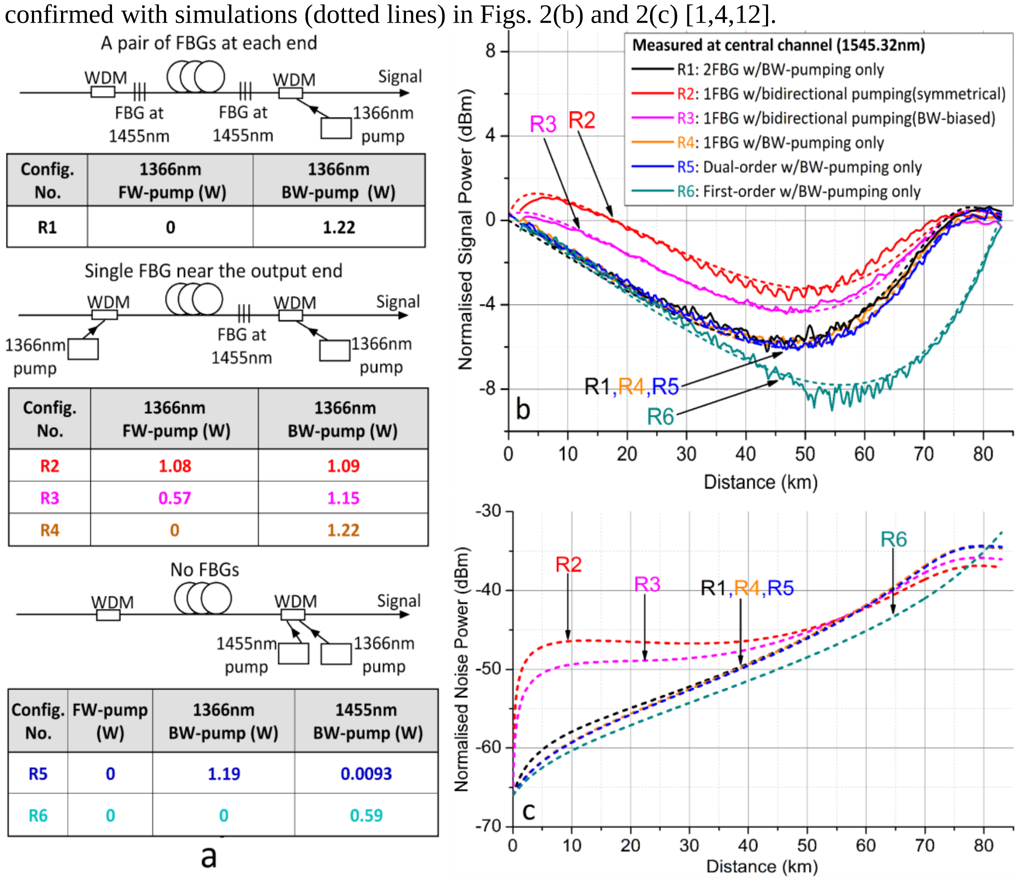


Fig. 2. (a). Schematic diagrams and pump powers of different Raman schemes. (b). Simulations (dotted lines) and experimental data (solid lines) of SPVs using different Raman configurations. (c) Simulations of noise distributions using different Raman configurations .

For scheme R1, the SPV was ~6 dB. Using bi-directionally pumped random DFB fiber laser, the SPVs were reduced to ~4 dB in R2 (symmetrical pumping) & R3 (BW-biased pumping). The performance of backward only pumped random DFB laser based scheme (R4) was identical to the Fabry-Perot backward only pumping (R1). This indicates, in scheme R1, the FBG at the input end of the span didn't actually contribute to the fiber laser generation, showing that the FBG at the input end was superfluous at this span length [10]. As shown in Fig. 2(c), the noise level was reduced with higher forward pump power, because the use of forward pump could reduce the SPV, and the noise figure corresponded to the SPV in linear units [6]. With no FBG, backward dual-order pumping scheme R5 (1366 nm and 1455 nm) could be used to give the same SPV as R1 and R4 only if using similar second-order pump power and very low first-order pump power (only ~9.3 mW) [1,13]. This did however require two pump wavelengths and careful control of first-order pump power (otherwise the SPV similar to backward pumped random DFB laser scheme could not be achieved), which made the simplicity of R4 attractive [1]. Scheme R6 used only backward first-order pumping and gave the highest SPV of ~9 dB and the highest noise at the output end.

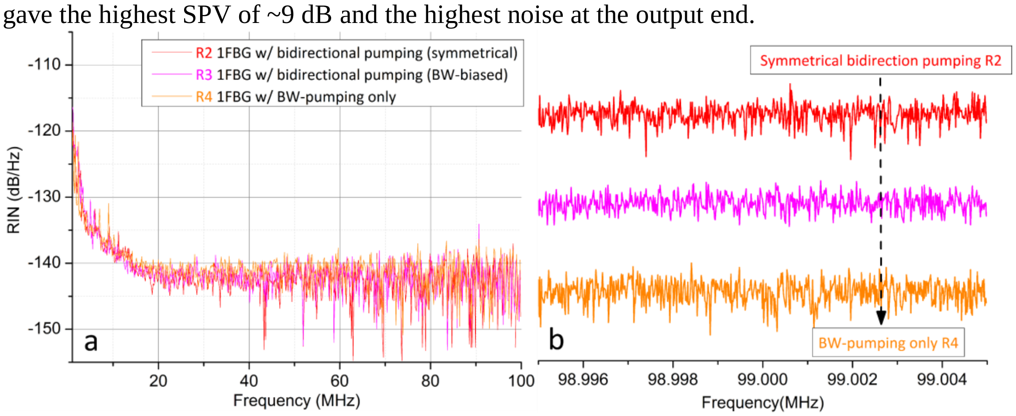


Fig. 3. (a). RIN of the output signal using three different random laser based amplification schemes. (b). Mode structures of forward-propagated random fiber lasers

In ultra-long Fabry-Perot fiber laser configuration, the RIN of the signal could have significant impact on the long-haul transmission performance and the Q factor penalty could be up to 4.15 dB [6,7]. In the random DFB laser configuration, we measured the relative intensity noise (RIN) of the output signal after one span using schemes R2, R3, and R4 [6]. The input signal was -6 dBm at 1545.32 nm from a CW low RIN (~-145 dB/Hz) laser. The setup for RIN measurement was based on an ultra-low-noise photo-receiver and an electrical spectrum analyzer (ESA) ranging from 1 to 100 MHz [6]. In Fig. 3(a), the RIN of the output signal stayed the same over the whole frequency range for all the pumping schemes, which indicates there might be no RIN-induced impact on the transmission using this amplification scheme [7]. In Fig. 3(b), the electrical spectra of FW-propagated fiber lasers at 1455 nm are shown. We can see that there was no mode structure, which confirms the laser was operating in the random DFB lasing regime [8-11]. The reason why the RIN of the signal didn't increase was that the minimized reflectivity near the input end led to the reduced efficiency of the Stokes shift (from second order pump to first order fiber laser) in forward-propagated direction. This resulted in the majority of signal amplification that came from the backward-propagated short-cavity random DFB laser, which significantly reduced the RIN transfer, compared to the bidirectional-propagated long-cavity Fabry-Perot laser with two reflectors on both sides [6,14].

### 3. Transmission results and discussions

The simulated and experimental Q factors versus launch power at 3333 km for all Raman configurations are compared in Fig. 4(a), showing a good agreement. The simulations used the same 10×29 Gbaud DP-QPSK channel, 100 GHz grid as the experiment and the transmission was 40×83 km fiber spans. Due to the large number of simulated channels, the length of the random sequence was reduced to $2^{17}$-1, compared with PRBS length of $2^{31}$-1 adopted in the experiment. Independent and uncorrelated data were transmitted among all the channels. The generated signal was oversampled 4 times providing a total simulation bandwidth of ~4 THz. The OSNR at the transmitter was set to 25 dB. The linewidths of both transmitter laser and local oscillator were set to 100 kHz. The propagation of the signal in the fiber link was simulated by solving numerically the Manakov system using the well-known split-step Fourier method, with the simulated signal power profiles (shown in Fig. 2(b)) providing a step size of 1 km. The Raman noise was modelled as Gaussian noise, which was added to the signal after each step (1 km), following the simulated noise profiles (shown in Fig. 2(c)). In this simulation, the same power and noise profiles were used for all the channels.

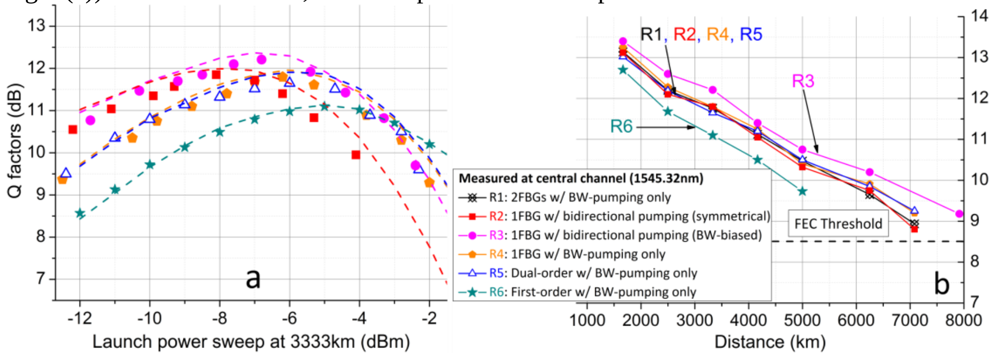


Fig. 4. (a). Simulated (dashed lines) and experimental (dots) Q factors versus launch power per channel at 3333 km; (b). Experimental Q factors versus transmission distances.

As RIN-induced impact was not included in the simulation, there is a strong indication that there was no RIN-induced penalty in the transmission performance using bi-directionally pumped random DFB laser scheme [7]. This is crucial because if the system performance is limited only by ASE noise and nonlinearity without suffering from RIN-induced penalty signal power profiles can be modified to meet different link requirements.

Figure. 4(b) shows Q factors versus transmission distances. The random DFB laser scheme R3 (bidirectional pumping with less forward pump power) gave the best performance at 3333 km and consequently the longest transmission distance of 7915 km. As expected from signal/noise power profiles in Figs. 2(b) and 2(c), the impact of nonlinear impairments in R2 (symmetrical pumping) degraded transmission performance. The SPVs of R3 and R2 were similar (~4 dB), but for R2 there was a sharp increase of signal power near the input section. This led to a lower optimum launch power and a reduced maximum reach of 7082 km. The random DFB laser scheme R4 (BW-pumping only) had a higher SPV value of ~6 dB which led to a higher optimum launch power and a reduction in reach to 7082 km. Figs. 2(b) and 2(c) show that dual-order pumping scheme R5 with no FBG gave the same signal and noise profiles as R1&R4. Consequently all three schemes show the same transmission performance in Fig. 4. With first-order backward pumping R6, the optimum launch power was highest at -5 dBm, but the reach was decreased to 4999 km due to higher accumulated ASE noise level.

Figure. 5 shows OSNRs, Q factors, and received spectra at maximum transmission distances using random DFB laser based schemes R2 (symmetrical bidirectional pumping), R3 (BW-biased bidirectional pumping), R4 (BW-pumping only), and R6 (first-order BW-pumping). All the measured channels were above the Q factor threshold.

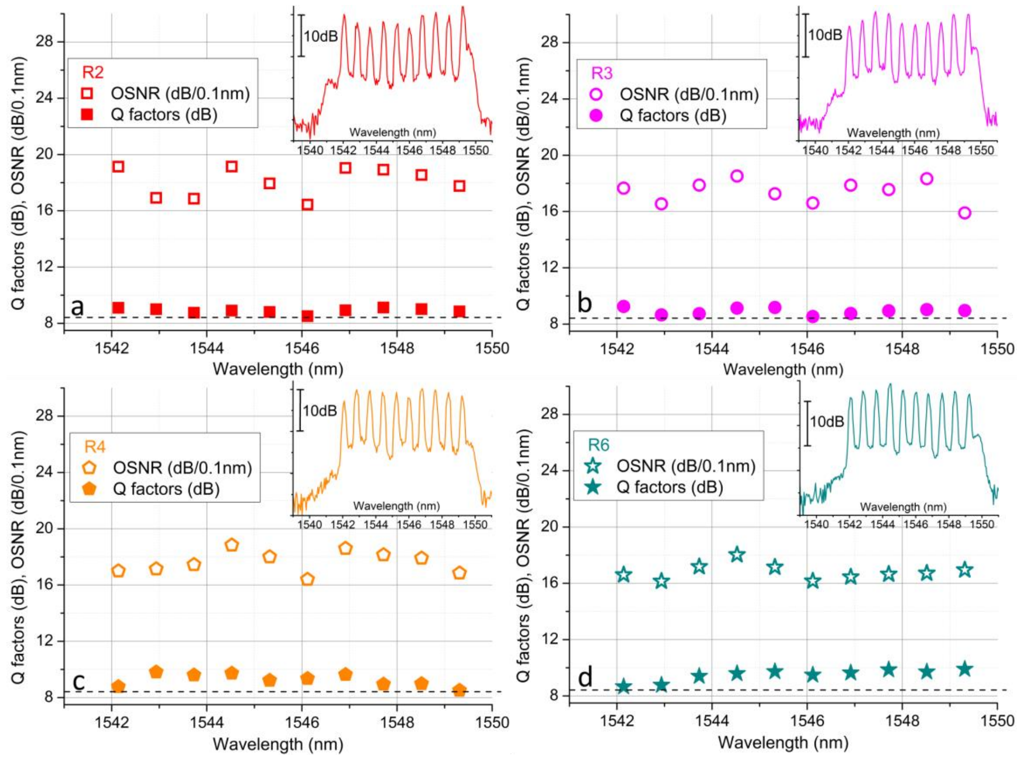

Fig. 5. OSNRs, Q factors, and received spectra measured at its maximum reach: (a). Symmetrical bidirectional pumped random laser scheme R2 at 7082 km; (b). BW-biased bidirectional pumped random laser scheme R3 at 7915 km; (c). BW-pumped random laser scheme R4 at 7082 km; (d). BW-pumped first-order scheme R6 at 4999 km.

## 4. Conclusion

We have demonstrated a novel use of random DFB fiber laser based Raman amplification scheme which enables bidirectional second-order pumping. A detailed investigation of 10×116 Gb/s DP-QPSK long-haul transmission using different Raman amplification techniques is presented. The best performance (7915 km) was achieved with a random DFB fiber laser based configuration which included bidirectional pumping. Further studies showed that there was no increase of signal RIN even with symmetrical bidirectional pumping. This scheme offers the best transmission performance and maintains a low signal power variation simultaneously. In addition, the scheme is able to provide a symmetric link which maximizes the benefit of nonlinearity compensation using mid-link OPC [2-4], or a low signal power variation which is critical for nonlinear Fourier transform based transmitter [5].

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