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Performance analysis of distributed fiber Raman amplifiers employing higher order pumping schemes in optical transmission systems

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Abstract: Performance of fiber Raman amplifier is explored with special emphasis on higher order pumping configurations for wavelength division multiplexed optical transmission systems. The amplification analysis is done in terms of equivalent noise figure (ENF), optical signal-to-noise ratio (OSNR), and double Rayleigh backscattering (DRBS) noise powers. The investigations reveal that at 36 dB on–off gain, ENF improvement of 1 dB (using second order pumping) and of 2 dB (using third order pumping configuration) can be achieved. On similar lines, by varying input optical power and fiber length, OSNR and DRBS are reported for the higher order of pumping configurations. Overall, the work presents improvements of about 1 dB in ENF and 0.03 dB in OSNR. These investigations are produced at lower input signal powers.

Key words: Higher order pumping (HOP), Raman on–off gain, equivalent noise figure (ENF), optical signal-to-ratio (OSNR), double Rayleigh backscattering (DRBS) noise

1. Introduction

The demand for broad bandwidth and flat gain optical amplifiers has increased rapidly due to worldwide implementation of WDM light wave transmission systems. Distributed fiber Raman amplifiers (DFRAs) are the preferred candidates in comparison to erbium-doped fiber amplifiers (EDFAs) for modern long-haul and ultralong-haul optical transmission applications. The conventional first order counter pumping configuration is generally employed in DFRAs because it suppress pump to signal relative intensity (RIN) noise. Recently, bidirectional and higher order pumping configurations of DRFAs have been put to use to enhance its performance [1–8]. In higher order pumping (HOP), especially the second and third order pump waves are 2 and 3 Stoke's shifts respectively away from signal waves and they directly do not amplify the signals. By principle, the shorter pump waves amplify long wavelength pump waves by stimulated Raman scattering (SRS) process, which in turn amplifies the signals.

In dual order bidirectional configuration, the first order pump is generally counter propagating and second order is copropagating with respect to the signals [7]. Among the various higher order configurations, second and third orders are very much beneficial in terms of optical signal-to-noise ratio (OSNR) and effective noise figure with fiber Raman amplifiers [8]. Higher order configurations provide benefits in terms of maximum unrepeated system reach and improvement in the optical equivalent noise figure. Second order pumping can produce flat power distribution and lower amplified spontaneous emission (ASE) noise with some nonlinearity [9]. Moreover,

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keeping the nonlinearity under control, second order pumping configuration improves the effective noise figure and increases the bandwidth by adjusting the second to first order pump powers ratio [10].

Important issues requiring careful considerations include signal double Rayleigh backscattering (DRBS) noise, which can induce transmission penalties at high counter propagating on–off Raman gains and pump-to-signal RIN transfer, which is critical when considering copumping configurations. Moreover, HOP configurations, mainly third order, are more affected by DRBS noise, whereas comparatively fourth and fifth order pumping have less noise implications [8,11–13]. Although signal DRBS noise enhancement with higher order counter pumping configurations has been studied, much less transmission work has been reported to evaluate DRBS-noise-induced transmission penalties at high on–off Raman gain. Thus, there is still scope of further analysis for performance improvement of Raman amplifier's HOP pumping configurations. Authors have numerically investigated the gain spectrum of the standard first order multipump fiber Raman amplifier in the WDM optical transmission system and it has been observed that an average net gain of 28 dB with 0.26 dB gain ripple in 50 km SMF fiber can be achieved with 1 mW input optical signal power [14].

Proceeding with the same, in this paper first, second, and third order backward pumping configurations of DFRAs are investigated in terms of their characteristic performance parameters such as effective NF, OSNR, and DRBS noise in WDM systems. Of the 4 sections below, Section 1 presents an introduction of recent work reported in the literature on higher order pumping configurations and performance tradeoffs of fiber Raman amplifiers. Section 2 provides details of the simulative system setup and parameters used in its investigations. Section 3 discusses the results and compares the work done with the literature. In the last Section 4, results have been concluded with the proposed future scope.

2. Theoretical model and system setup

The theoretical model of distributed higher order pumped fiber Raman amplifier is studied using the coupled equations involving the effects of Raman interactions, the interdependence of ASE, temperature, and amplified multi Rayleigh scattering [9]. The basic differential equations can be reproduced as

$$\begin{aligned}\frac{dP^{\pm}}{dZ} &= \mp\alpha(\nu)P^{\pm}(z,\nu) \pm R_s(\nu)P^{\pm}(z,\nu) \pm P^{\pm}(z,\nu)\sum_{\xi\succ\nu}\frac{g_r(\nu-\xi)}{K_{eff}A_{eff}(\xi)}\left[P^{\pm}(z,\xi)+P\mp(z,\xi)\right]\\ &\pm h\nu\sum_{\xi\succ\nu}\frac{g_r(\nu-\xi)}{K_{eff}A_{eff}(\xi)}\cdot\left[P^{\pm}(z,\xi)+P\mp(z,\xi)\right].\left[1+\frac{1}{e^{h(\xi-\nu)/kT}+1}\right]\Delta\nu\\ &\mp P^{\pm}(z,\nu)\cdot\sum_{\xi\prec\nu}\frac{\nu}{\xi}\cdot\frac{g_r(\nu-\xi)}{K_{eff}A_{eff}(\xi)}\cdot\left[P^{\pm}(z,\xi)+P\mp(z,\xi)\right]\\ &\mp 2h\nu P^{\pm}\sum_{\xi\prec\nu}\frac{g_r(\nu-\xi)}{K_{eff}A_{eff}(\xi)}\left[P^{\pm}(z,\xi)+P^{\mp}(z,\xi)\right].\left[1+\frac{1}{e^{h(\xi-\nu)/kT}+1}\right]\Delta\nu \end{aligned} \tag{1}$$

where ν and ξ denote optical frequencies, $P^{+}(z,\nu)$ and $P^{-}(z,\nu)$ are the forward and backward propagating optical power, respectively, within infinitesimal bandwidth about ν, and $\alpha(\nu)$ and $R_s(\nu)$ are the fiber attenuation and the backward Rayleigh scattering coefficient, respectively at frequency ν. The symbols h, k, and T are Plank's constant, Boltzmann's constant, and temperature in degree Kelvin respectively. Additionally K_{eff} is the polarization constant of numerical range 1–2. Finally, $g_r(\nu-\xi)$ represents the Raman gain coefficient from a higher pump frequency ν to a lower the Stoke's frequency ξ; A_{eff} represents the effective area of optical fiber at frequency ν. The OSNR as used in [9]

$$OSNR = \frac{P_s(0).G_{Raman}.\alpha_S L}{P_{ASE}(L) + P_{DRBS}(L)}, \tag{2}$$

where P_s is input optical signal power signal, P_{ASE} and P_{DRBS} denote ASE, and DRBS noise powers generated during distributed Raman amplification, respectively.

Concerned with the theoretical model discussed, Figure 1 shows a schematic diagram of an 8-channel WDM based simulated system having DFRAs employing higher order pumping. The optical transmitter of each channel consists of a pseudorandom bit sequence (PRBS) data source at 10 Gb/s, NRZ pulse generators, and Mach–Zehnder optical modulators with CW laser lights of C band wavelengths ranging from 1550 nm to 1557 nm with 1 nm channel spacing. The 8 channels are WDM multiplexed by an optical multiplexer and launched in 100 km standard single mode fiber (SMF) with 5 dBm optical power per channel. The fiber parameters selected in the setup are as follows: fiber loss (α = 0.2 dB/km), fiber effective core area (A_{eff} = 72 μm^2), Rayleigh scattering coefficient (γ = 5 $\times$ 10^{-5} km^{-1}), peak Raman gain coefficient (g_R = 1 $\times$ 10^{-13} m/W). The pump wavelength of the conventional first order pump is selected as 1451 nm, because the Raman gain coefficient has a peak at Stoke's shift of around 100 nm (13.2 THz) for 1550 nm signal channels. The second order pump, which is 2 Stoke shifts away from signal channels, has wavelength of 1351 nm and similarly the third order pump, which is 3 Stoke shifts from signals, has wavelength of 1271 nm. These 3 pumps are WDM multiplexed and launched in backward direction to signal waves in SMF fiber by pump and signal WDM coupler.

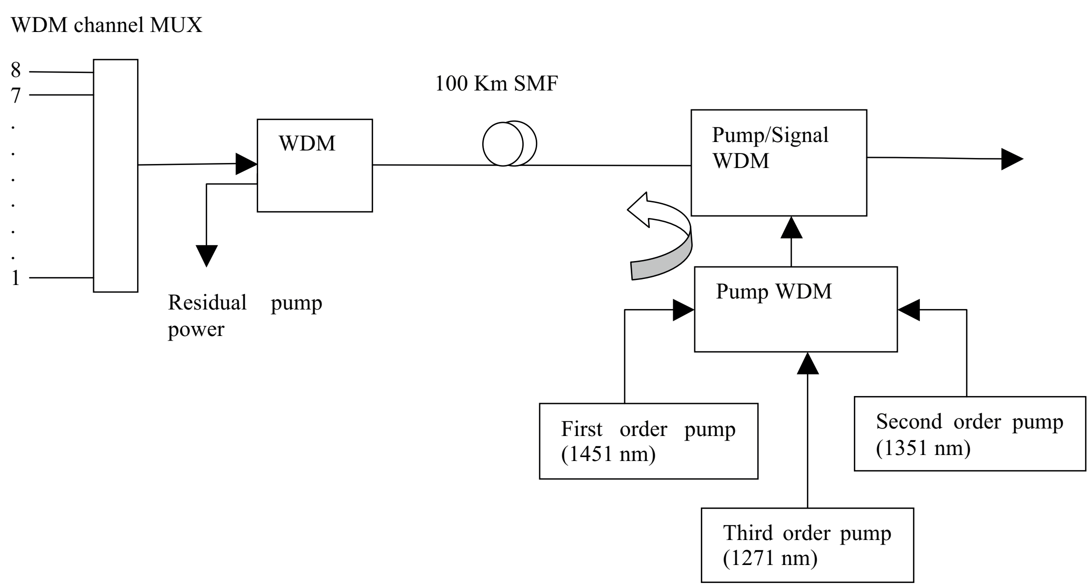

Figure 1. System setup of distributed fiber Raman amplification employing higher order configurations in 8-channel optical transmission system.

The performance of the setup as shown in Figure 1 is analyzed at various pump powers and at varied fiber length. First of all, ENF and OSNR are observed by varying on–off gain of first, second, and third order pumping configurations as shown in Figure 2. Particularly, for the conventional first order pumping, i.e. 1451 nm, first order pump power is varied in the range of 400 to 1800 mW and the resulting Raman on–off, ENF, and OSNR of the signal channels are observed. Further, for the analysis of second order pumping configuration, first order pump power is kept constant at 50 mW and second order power is varied from 100 to 1500 mW. Similarly, for third order configuration, first order and second order powers are kept constant at 10 mW and 50 mW, respectively, and third order power is varied from 1000 to 2400 mW, and the resulting above performance parameters are observed at signal channels. This configuration of pump power variation for first, second, and third order pumping configurations is in accordance with Ref. [7].

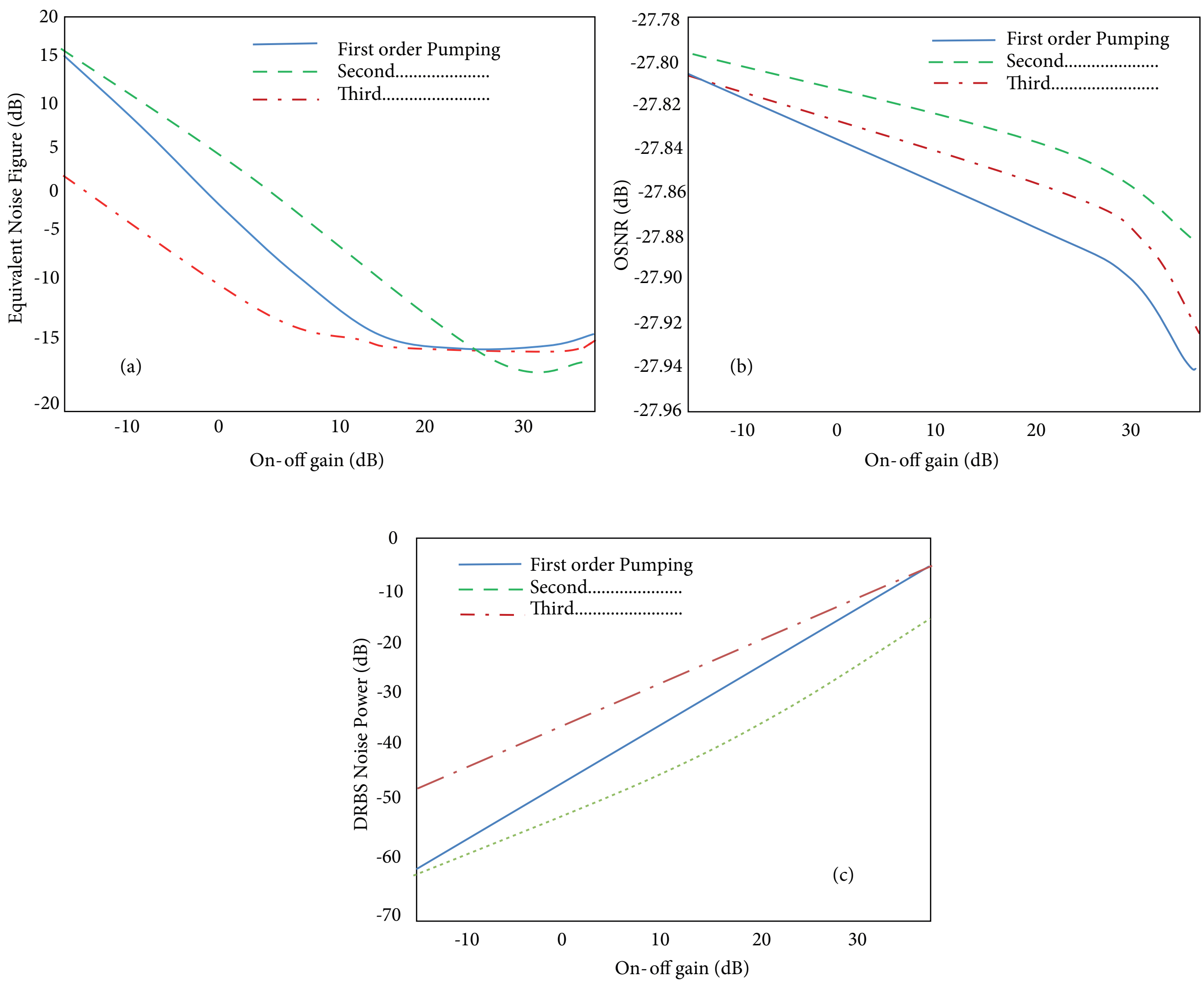

Figure 2. First, second, and third order pumping configurations plots for (a) equivalent noise figure (dB), (b) OSNR (dB), (c) DRBS noise power (dB) versus Raman on–off gain (dB).

3. Results and discussion

The setup shown in Figure 1 is investigated, with 8 WDM signal channels of C band with wavelengths (1550–1557 nm), whereas observation of 1 channel (1551 nm) at output of the Raman amplifier is discussed. The pump powers of first, second, and third order pumps are varied in the specified ranges (mentioned in the previous section). The resulting on–off gains at the amplifier's output are observed and compared in terms of its characteristics parameters.

Initially, on–off gain is plotted for 3 cases: equivalent noise figure, OSNR, and DRBS noise power and shown in Figures 2a–2c, respectively. Each part of the figure (a–c) indicates 3 cases of pumping configurations of amplifier, namely: first, second, and third order. The figures indicate 3 different curves by solid (blue), dashed (green), and dash-dot (red) corresponding to pumping configurations: first, second, and third respectively.

Figure 2a indicates that as the on–off gain increases ENF improves for all 3 order pumping configurations. Apparently, for 28 dB and higher on–off gain, second order pumping results less ENF compare to first and third order pumping. The main noticeable observation is that at 32 dB on–off gain the amplifier's ENF is –12,–15, and –13 dB with first, second, and third order pumping respectively. This is an ENF improvement of 3 dB in the case of second order and 1 dB in the case of third order in comparison to standard first order at high on–off gain. Thus it is useful and more effective in long-haul, unrepeated systems for applications in undersea Raman amplified transmission links [8]. As a result, the second order pumping configuration is advantageous. These results are in agreement with the results presented in Ref. [7,13].

Further, Figure 2b shows a graph of OSNR vs. on–off gain for the signal channel with first, second, and third order pumping configurations of the Raman amplifier. Here, it is observed that second order pumping provides 0.02 dB higher OSNR as compared to first and third order pumping. This small OSNR improvement helps to adjust the power budgeting of long-haul Raman amplified optical transmission fiber links.

Similarly, Figure 2c shows that DRBS noise generated is 2 dB lower by second order pumping as compared to first order pumping configuration. However, it can be observed that third order pumping configuration is severely deteriorated by DRBS noise source at high on–off gain in Raman amplified optical transmission systems. The result is on the lines of [11], that third and higher order pumping configurations improve the performance but these are also more affected by DRBS, RIN, and ASE noise sources.

In modern Raman amplified based optical fiber transmission systems, performance depends critically on input optical power launched per channel due to ASE and DRBS noise mechanisms [7]. To reinvestigate this fact, Figures 3a–3c present ENF, OSNR, and DRBS noise power performance for the varied input optical launched power per channel (range of 1 to 15 dBm) for the cases of first, second, and third order pumping Raman amplifier configurations, respectively. It may be observed in Figure 3a that second order pumping presents 1 dB lower ENF as compared to other pumping configurations for the investigated range of input optical power. One can see there is also a tradeoff between OSNR and DRBS noise. It is exhibited in Figure 3c, i.e. second order pumping has around 4 dB higher DRBS noise generated than first order configuration.

Figure 3b shows OSNR vs. varied input optical power for the pumping configurations. It indicates OSNR offered by second order pumping is 1 dB higher than first order pumping. At higher input power, beyond 14 dBm, OSNR starts declining sharply. The degradation is due to fiber nonlinearities and amplifier saturation behavior.

Additionally, another plot in Figure 3d indicates OSNR vs. transmission fiber length (in a range of 1 to 100 km) investigations of first, second, and third order pumping configurations of the system at 1550 nm. It shows that standard first order pumping provides 1 dB higher OSNR up to 40 km down the fiber compared to second and third order pumping configurations, whereas for link length greater than 40 km third order provides better OSNR compared to the first order. Similarly, second order has 2 dB greater OSNR compared to first order at 100 km fiber length. However, at 90 km and beyond it gives a constant OSNR of 43 dB because the pump signal gets depleted due to higher transmission losses at its wavelength (i.e. 1351 nm). These increased OSNR at a long length with higher order pumping (second, third) of Raman amplifier configurations are advantageous to cope with sensitivity degradations of optical receivers [8,13].

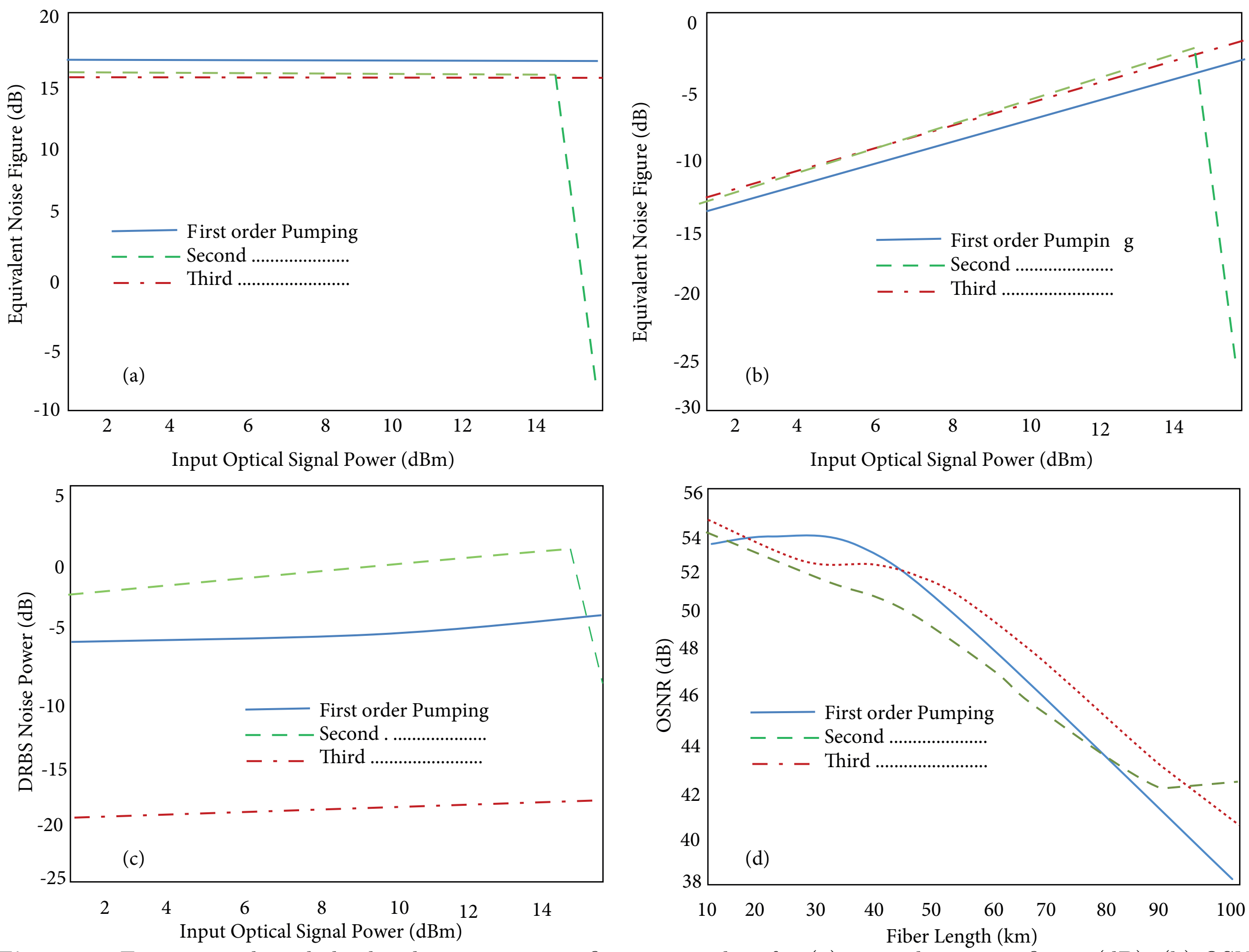

Figure 3. First, second, and third order pumping configurations plots for (a) equivalent noise figure (dB), (b) OSNR (dB), (c) DRBS noise power (dB) vs. input optical signal power (dBm), and (d) OSNR (dB) vs. fiber length (km).

Lastly, the investigations recommend that second order pumping of DFRA is more beneficial as compared to other configurations. The performance improvement is found at lower range on–off gains, whereas at the higher gains it starts degrading due to DRBS and RIN noise mechanisms. Consequently, the results are compared with the references [7,13] displayed in the Table. It shows improvement in ENF and OSNR found in the investigated system.

4. Conclusion

In this work, higher order pumping configurations, namely second and third orders, in comparison to standard first order, are investigated for fiber Raman amplifier in the WDM transmission system. The investigations reveal that second order pumping configurations of the distributed Raman amplifier showed improvement in overall performance of the transmission system. Quantitatively, the results indicate that the second order pumping configuration employed exhibits reduction of 2 dB in ENF at 36 dB and higher on–off gain. Near this gain, the conventional first order configuration performance starts deteriorating. Moreover, 2 dB OSNR improvements at 1 dB input optical power over the investigated fiber length is obtained. The results showed that the higher order pumping configuration is useful because only 50 mW of conventional first order pump power

Table. Comparison of the purposed work.

Parameter	Ref. [7]	Ref. [13]	Purposed work
Number of transmitted channels and their spacing	Single channel at 1551 nm	Seven channels from 1550.1 to 1554.9 nm with 100 GHz spacing	Eight channels 1550 to 1557 nm with 100 GHz spacing
Range input signal power variation per channel	–1 to 7 dBm	1 dBm	1–14 dBm
Improvement in ENF at on–off gain	1.8 dB and 2.9 dB with second and third order pumping respectively at 33 dB	2 dB with third order pumping at 35 dB	3 dB and 1.1 dB with second order and third order pumping respectively at 33 dB gain
OSNR at specified on–off gain/Input power/fiber distance.	Degradation 0.1 dB and 0.2 dB at 20 dB gain with second order and third order respectively.	Degradation 0.5 dB at 30 dB with third order pumping.	OSNR improvement of 1 dB at input optical and 2 dB at 100 km fiber distance with second order pumping.

is deployed. It is a considerable reduction of pump power achieved and suggests that first order lasers pumps of this power range can be easily integrated on chip for multipumping in Raman amplification applications.

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