Table 1. Amplification Schemes and Associated Pparameters

	Scheme	Total power (W)	**Wavelength/power (nm/W)**	**Gain flatness Δ G(dB)**	**OSNR (dB)**	δG **(dB)**
1	1st-order backward pumping (k1 = 0.2817, k2 = 0.5275, k3 = 0.1170	0.55	**1420.0 1457.1 1480.0** 0.31 0.064 0.175	2.29	37.8	5.2
2	1st-order bi-directional pumping (k1 = 0, k2 = 0.34, k3 = 0.24)	0.56	**1420.0 1440.0 1480.0** 0.1 0.068 0.1	1.9	39.87	2.16
3	Hybrid bi-directional pumping (k1 = 0.1, k2 = 0.63, k3 = 0.7)	0.1	**1369.0 1420.0 1480.0 (FBG at 1458 nm)** 0.35 0.08 0.066	1.45	39.9	1.80

The signal evolution in the spectral range from 1520 nm to 1594 nm is shown in Fig. 3 for the three configurations described in Table 1. Note that we also improved performance of the both 1st-order schemes using the described numerical algorithm to determine a location of pump wavelengths and pump powers, that is an important result itself. All the systems under consideration have 125 GHz channel spacing.

It is seen from the Table 1 that a hybrid bi-directional pumping scheme (lower figure in the centre in Fig. 3) shows the smallest signal power excursion along the propagation distance in comparison with conventional 1st-order backward pumping (Fig. 3 left upper corner) and (also optimized) 1st-order bi-directional pumping(right upper figure) schemes. We believe that further optimization and application of various methods in distributed Raman amplification [9–19], [1–5] will make it realistic to approach within a reasonable accuracy a cross-domain transparency in optical fiber spans.

3. Conclusions

In conclusion, a novel design of hybrid (combining 1st and 2nd-order pumping) bi-directional Raman amplification scheme is proposed for simultaneous reduction of the power excursion over propagation distance and improving gain flatness. The proposed scheme was compared to other distributed Raman amplification schemes and has shown the best signal power variation and gain flatness.

Acknowledgments

Authors would like to acknowledge the support of the EPSRC project UNLOC (Unlocking the capacity of optical communications) EP/J017582/1 and the Ministry of Education and Science of the Russian Federation (grant No. 14.B25.31.0003)