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1.28 Tbps DWDM optical network design using a dispersion compensating distributed Raman amplifier over S-band

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Abstract

A 100 km long dense wavelength division multiplexed optical network design with a capacity of 1.28 Tbps is proposed in this paper. The novelty of this work is the use of a dispersion compensating fibre as a Raman amplifier in the S-band for a high-capacity dense wavelength division multiplexing network. The transmission is accomplished auspiciously in the wavelength range from 196 THz to 202. 35THz. The coupling of a Raman amplifier made the realisation of the S-band possible in the network, as the erbium-doped fibre amplifier is competent for amplification in C- and L-bands only. Further, a pump coupler is used for multiple pumping to enlarge the gain spectrum for a high-capacity optical network. The performance analysis of the network is carried out systematically in terms of bit error rate (BER), eye diagram, Q-factor, and optical signal to noise ratio (OSNR). The results demonstrate that the proposed set-up shows adequately low BER, sufficient Q-factor values, wide eye-opening, and commendable OSNR for all receiving channels.

1. Introduction

Dense wavelength division multiplexing (DWDM) is currently the most effective technique for increasing the capacity of optical transmission systems. The DWDM technique multiplexes multiple signals through a single fibre, making a high-capacity system possible by multiplying the bandwidth of a single optical fibre channel [1]. There are three substantial limitations to optical fibre: attenuation, dispersion, and non-linear effects [2]. While the attenuation issue can be resolved by adopting a suitable amplifier like an erbium-doped fibre amplifier (EDFA), Raman amplifier, etc., the dispersion issue is the prime limiting factor in optical communication [1, 3]. It becomes elevated in the DWDM technique by introducing cross-talk between consecutive channels [4]. For dispersion compensation, dispersion compensating fibre (DCF) is one of the efficient techniques, offering uniform dispersion compensation to multiple spectral components and upgradability to already installed links [5, 6]. However, in addition to dispersion compensation, data communication development demands throughput increment in DWDM networks [7], for which multiple bands use or band swapping becomes an admirable approach.

The low loss window comprises S-, C-, and L-bands. Although the attenuation in all these bands is almost equivalent, C- and L-bands are the most often used bands as the EDFA is competent for amplification in these bands only [7]. Most optical systems use EDFA for amplification purposes, which can use only half of the low-loss window and hence limit the number of channels that can propagate through the optical transmission system simultaneously [8]. However, Raman amplifiers exhibit a broad gain spectrum and work well in the S-band, which resolves the issue of limited transmission capacity by using S-band. Using S-band in an optical network increases the throughput gains by 65% [9]. Also, the chromatic dispersion in S-band is smaller compared to C- and L-bands.

The current work investigates the performance of a DCF as a Raman amplifier for a high-capacity DWDM optical network. Multiple pump lasers coupling is used to instigate the stimulated Raman scattering (SRS) process in DCF. The DCF used simultaneously employs dispersion compensation and amplification for the signal propagating down the link. Thus, instead of adding further losses, DCF itself acts as an amplifier. S-band is launched in the channel

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for optical transmission as it gives better dispersion characteristics. However, the successful propagation of the S-band is made possible by coupling the Raman amplifier in the network. The scheme has shown a cost-effective approach to dispersion compensation.

The paper is catalogued as follows. The theory with the principle of operation is described systematically in section 2. Section 3 represents the simulation set-up of the proposed system model in detail. Results (with discussion) are reported rigorously in section 4. The conclusion is summarised in section 5.

2. Raman amplifier

The Raman amplifier works on the principle of a distributed Raman amplification, wherein the signal amplification is initiated within the transmission fibre itself but driven externally. Raman amplification relies on SRS, which uses laser pumps to transfer the energy from high-power pump signals to lower-frequency and lower-power optical signals [8, 10]. For practical implementation, Raman gain requires complete pump power control for which backward pumping is of assistance, as it is associated with less noise [10]. When the pump is ON, the extra gain [G (dB)] provided by the Raman amplifier corresponds to the rise in signal power and is expressed by Ref. 11 as follows:

$$G\ (\mathrm{dB}) = \frac{10}{\ln 10}\left(\frac{g_R}{A_{eff}}\right)\left(\frac{P_p(1-e^{-\alpha_P \cdot L})}{\alpha_P}\right), \tag{1}$$

where P_p (mW) is the pump power, L is the Raman amplifier length, α_P is the pump attenuation coefficient, A_{eff} is the interaction area of the Raman amplifier, and g_R is the Raman gain coefficient.

The Raman amplifier provides the gain over a frequency range of 40 THz, with a peak near 13 THz (100 nm) [8] and, hence, to get a gain band around any X (nm) wavelength component, pumping should be around X-100 (nm). For broadband amplification, a multiple-pump Raman amplifier is the finest choice in which the multiplexing of multiple pump signals of different wavelengths produces a high gain and flat spectrum [8]. Firstly, pumping two wavelength components separated by a 15 nm to 20 nm wavelength difference can enlarge the gain band approximately two times. Secondly, the multiplexing of two pump lasers of the same wavelength doubles the pump power and reduces the polarization dependence of Raman gain [10]. However, the pump power needs to be optimized carefully to realise a uniform gain spectrum besides keeping nonlinear effects low. Although the optimization for a Raman amplifier is more cumbersome, Raman amplification is more pliable comparatively by providing control over pump powers, gain, and gain shape [10].

2.1. *DCF as Raman amplifier*

The small core and long length are required to induce SRS in the fibre, for which DCF is the finest option. DCF having the lowest effective area gives the highest Raman gain efficiency [8, 11]. Hence, in Raman amplifiers, dispersion compensation and amplification simultaneously can be combined through a single fibre length. By using DCF as a Raman amplifier instead of adding further losses, DCF itself acts as an amplifier.

DCF is coupled in succession with the conventional single mode fibre (CSMF) to compensate for the dispersion. According to Ref. 12, the DCF length required for dispersion compensation in an optical link can be determined easily using the equation given below:

$$L_1 \cdot D_1 + L_2 \cdot D_2 = 0, \tag{2}$$

where L_1 is the CSMF length, L_2 is the DCF length, and D_1 and D_2 symbolise the group velocity dispersion (GVD) of the CSMF and DCF, respectively. By launching the S-band in an optical network, less chromatic dispersion is produced in CSMF and, hence, demands a shorter DCF length in cascade for dispersion compensation. Shortening DCF by a few km cuts the system price by a very high percentage.

2.2. *S-band*

S-, C-, and L-bands constitute the low-loss window for optical fibre communication, ranging from 1460 nm to 1625 nm, where the S-band extends from 1460 nm to 1530 nm, followed by the C-band up to 1565 nm and then the L-band up to 1625 nm. In optical networks, the S-band comparably shows better attenuation characteristics and is less prone to bending losses [8]. The chromatic dispersion arising in CSMF by launching S-band lies in the range of 12 to 16 ps/nm/km [13], which is approximately 10–30% less dispersion than the other two bands.

2.3. *Principle of operation*

The optical bandwidth required for the 128-channel DWDM optical network with a frequency spacing of 50 GHz is more than 5 THz. However, the total optical bandwidth of the C-band is just 4.38 THz, hence, it is not sufficient to accommodate all channels simultaneously. The C- and L- bands are preferred bands usually because EDFA works well in them. However, the use of S-band offers flexibility in attenuation and dispersion, and the optical bandwidth provided by S-band is comparatively larger. However, the use of S-band requires the installation of a Raman amplifier. DWDM systems require amplifiers that can provide uniform gain over a broad wavelength range efficiently [14]. The Raman amplifier offers a broadband amplification with a bandwidth > 5 THz and a flat gain over a wide wavelength range.

Furthermore, the instigation of the SRS process requires a long-length fibre with a small core, and a DCF with the least effective core area offers the best option. When generally used for dispersion compensation, DCF introduces losses and requires further amplification. By instigating the SRS process in a DCF, instead of accounting for additional losses to the system, DCF itself works as an amplifier.

2.4. *Mathematical analysis*

The extra gain provided by the Raman amplifier in decibels, as defined in (1), solves as

$$G\ (\mathrm{dB}) = 4.34\left(\frac{g_R}{A_{eff}}\right)\left(\frac{P_p(1-e^{-\alpha_P \cdot L})}{\alpha_P}\right). \tag{3}$$

The term g_R/A_{eff} is known as Raman gain efficiency, symbolised as

$$\gamma_R = \frac{g_R}{A_{eff}}. \tag{4}$$

Further, the term $\{(1-\exp(-\alpha_P \cdot L))/\alpha_P)\}$ represents the effective length (L_{eff}).

According to Ref. 11, if the interaction length of the amplifier is much higher than the effective length, the equation $(1-\exp(-\alpha_P \cdot L))/\alpha_P)$ can be approximated by $1/\alpha_P$.
In the proposed system, $L = 10$ km. So, the L_{eff} approximately becomes 2.857. Hence, the extra gain becomes

$$G\text{ (dB)} = 4.34\frac{g_R}{A_{eff}}\left(\frac{P_p}{\alpha_P}\right). \tag{5}$$

The parameters P_p and α_P are constant for the proposed system, defined in the simulation setup. However, the Raman efficiency gain spectrum is always dependent on fibre characteristics. Reference 15 reports on page 38 that the Raman gain efficiency spectrum for a DCF is approximately 5–9 times higher than non-zero dispersion shifted fibre (NZDSF) and CSMF. Hence, equation (5) reflects that the extra gain provided by the Raman amplifier depends on DCF characteristics, especially the least effective area of DCF, which should be kept as low as possible.

3. Simulation setup

The current work proposes the design of a 128 × 10 Gbps DWDM optical network working in the S-band, simulated using the OptiSystem software. The block diagram of the simulation set-up is presented in Fig. 1. The transmitter section comprises 128 channels, working in the wavelength range from 196 THz to 202.35 THz with a frequency spacing of 50 GHz. Each signal is modulated using the return-to-zero (RZ) technique and transmitted at a bit rate of 10 Gbps. The RZ signal has a shorter pulse duration and greater peak power compared to other modulation techniques and can transmit data at higher speeds without significant distortion or loss.

In succession there is a channel comprising a 90 km long CSMF and a 10 km long Raman amplifier. The Raman amplifier is purposely designed over a DCF with an effective area of 35.3 μm^2. Beside amplification, the Raman amplifier compensates for dispersion. The use of DCF as a Raman amplifier avoids the need for an additional amplifier to compensate for DCF losses, which would otherwise occur.

Furthermore, to produce a high-gain and flat spectrum for a high-capacity DWDM network, the Raman amplifier is pumped by dual pump lines using a coupler. The pump lasers generate the pump signals at wavelengths of 1406 nm and 1425 nm with a power of 1 W each. At the receiver end, BER analysers are coupled for the performance evaluation of the network. The additional simulation parameters are listed in an orderly manner in Table 1.

Table 1.
Simulation parameters of the proposed model.

	Components/Parameters	SMF	DCF
Channel	Total length	90 km	10 km
	Attenuation	0.2 dB/km	0.35 dB/km
	Dispersion (ps/nm/km)	16.75	−80
	Dispersion-slope (ps/nm^2/km)	0.075	0.38
	Noise figure	4 dB	10 dB
	Effective core area	80 μm^2	35 μm^2
Raman amplifier	Raman gain type	Raman gain	
	Raman gain peak	10^{-13}	
	Raman gain-reference pump	1000 nm	
	Rayleigh backscattering	$5 \cdot 10^{-5}$ km^{-1}	
	Polarization factor	2	
Receiver	Photodetector	PIN diode with 1 A/W responsivity & 10 nA dark current value.	
	Low pass filter cut-off frequency	0.75 × bit rate	

*SMF – single mode fibre

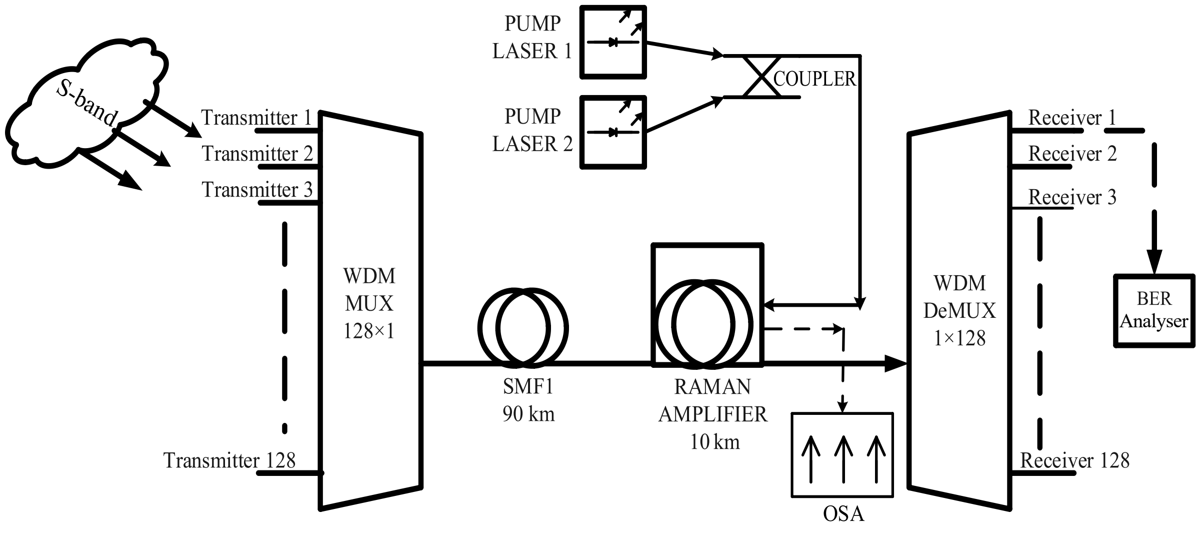

Fig 1. Block diagram of the simulation set-up.

4. Results and discussion

The proposed high-capacity system design requires an optical bandwidth of 6.35 THz, which can be efficiently provided by the S-band. However, transmission in the S-band requires coupling of a Raman amplifier in the channel section. The distributed amplification process, which uses multiple pumping sources, produces a high gain and a flat spectrum that has been thoroughly optimized using an optical spectrum analyser (OSA), as shown in Fig. 2, where the gain spectrum is enclosed by points marked ‘A’ and ‘B’. While the signal is well amplified, there are also discretised noise and unwanted wavelength parameters that arise due to dispersion. These unwanted wavelength components can act as false reproductions of the signal, while the noise can affect the OSNR of the system. High OSNR is a standard performance parameter for long-haul optical networks. However, achieving an acceptable signal-to-noise-ratio (SNR) requires a high-enough input power [16], and the optical power at the channel output must match the receiver sensitivity criteria. High input power, though, can cause non-linear effects in fibre links, making the installation of an amplifier in the link the only alternative solution. However, amplifiers introduce amplified spontaneous emission (ASE) noise, as shown in Fig. 2, which can become the primary cause of the reduced OSNR in the system. The Raman amplifier has the main advantage of producing less noise and less OSNR degradation than the EDFA. The minimum acceptable OSNR defined for RZ 10-Gb/s RZ-OOK is 12 dB [10], and to maintain a high-OSNR performance, the OSNR retrieved signal must be higher than the required one. The OSNR values observed for each output channel are more than 26 dB, indicating that the proposed design has provided an adequate OSNR for all receiving stations and the noise does not degrade the signal.

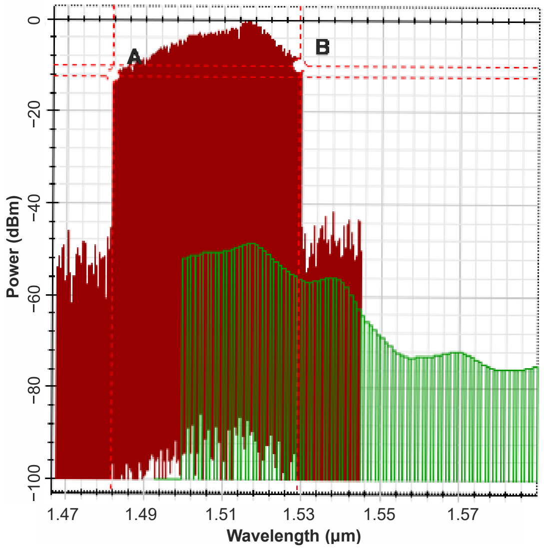

Fig 2. Spectrum of the pumped signals.

The performance of the proposed system design was further investigated using Q-factor, BER, and eye-diagram. The BER parameter defines the channel quality, which gives the probability of a bit being in error [17]. Reference 10 reports the maximum acceptable BER as 10^{-9} to receive the quality signal from the receiver side. However, it is always preferable to have BER less than 10^{-13}. Table 2 tabulates the BER observed for some randomly selected channels in the proposed design, which shows that the BER for all observed channels is adequately low.

Table 2.
Result parameters.

Channel no	BER	Q-factor	Eye-height
1	$5.16 \cdot 10^{-15}$	7.736	0.000248
30	$5.51 \cdot 10^{-20}$	9.06	0.001603
64	$5.17 \cdot 10^{-14}$	7.43	0.000927
101	$9.81 \cdot 10^{-19}$	8.75	0.000315
128	$6.47 \cdot 10^{-18}$	8.54	0.000102

The system performance is strongly affected by timing jitter and amplitude noise, and the BER measure cannot differentiate the influence of the two effects. However, the eye diagram helps examine both, especially timing jitter. The eye diagram also measures the extinction ratio and computes the Q-factor of the receiving signal. To have a successful optical transmission, the minimum acceptable Q-factor reported by Ref. 1 is 6.8. Table 2 orderly mentions the Q-factor value and eye height observed for the randomly chosen channels, alongside the BER. The observations show that all Q-factor values are higher than the acceptable value, and the eye heights are good enough, making the system practically feasible.

Moreover, for C-band propagation, the chromatic dispersion arising in the channel is approximately 16 to 18 ps/nm/km. Therefore, the DCF length required to compensate for the dispersion in an optical link with a 90 km long CMSF is longer than 20 km, as calculated using (2). By launching S-band, the present work uses a 10 km long DCF only, reducing the DCF cost by more than 50%. Although a slightly longer DCF in the proposed design would have improved dispersion compensation, it would have induced higher non-linear effects due to the high pump power of the Raman amplifier. Therefore, the least workable DCF length is chosen to strike a balance between dispersion compensation and non-linear effects while keeping the system cost-effective. Moreover, using DCF as a Raman amplifier eliminates the need for an additional amplifier in the design, reducing the complexity.

5. Conclusions

The approach used in the current work to tackle throughput demand in DWDM networks is by launching the S-band, which allows to keep a good-enough frequency spacing between the consecutive channels while increasing the network capacity. The high-frequency spacing makes the system less prone to cross-talk and lessens the probability of a bit being in error. However, the S-band transmission is made possible by the coupling of the dispersion compensating Raman amplifier, which beside dispersion compensation is also used for amplification. The proposed design offers a cost-effective approach for a high-capacity system design by using less than 50% of the required DCF length. The results demonstrate that the proposed set-up shows adequately low BER, sufficient Q-factor values, and commendable OSNR for all receiving channels.

Authors' statement

Both authors contributed equally.

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