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An Approach to Flatten the Gain of Fiber Raman Amplifiers with Multi-Pumping

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***Abstract*—**The effects of the pumping wavelength and their power on the gain flattening of a fiber Raman amplifier (FRA) are investigated. The multi-wavelength pumping scheme is utilized to achieve gain flatness in FRA. It is proposed that gain flatness becomes better with increase in number of pumping wavelengths applied. We have achieved flat gain with 0.27 dB fluctuation in a spectral range of 1475-1600 nm for a Raman fiber length of 10 km by using six pumps with wavelengths with in the 1385-1495 nm interval. The effect of multi-wavelength pumping scheme on gain saturation in FRA is also studied. It is proposed that gain saturation condition gets improved by using this scheme and this scheme is more useful for higher spans of Raman fiber length.

***Keywords*—**FRA, gain, pumping, WDM.

I. Introduction

In a multiple wavelength system, it is important that all signal wavelengths have similar optical powers. The demand of today network also moves towards ultrahigh speed of operation with suppression of nonlinearities [1]-[3]. The variation in the gain provided to different wavelengths after passing through an amplifier is referred to as the gain flatness. If the signal at one wavelength is disproportionately amplified, as it passes through several amplifiers, it will grow super linearly relative to the other channels reducing the gain to the other channels. The net result will be that the system will be limited by the channel with the lowest gain [4]. Raman amplifiers can be used to achieve gain flatness over a wide range of wavelength. In Raman amplification, a flat spectral profile can be obtained by using multiple pump wavelengths [5], [6]-[9]. The use of multi-wavelength-pump silica fiber Raman amplifiers make it possible to considerably widen the overall gain-bandwidth while simultaneously reducing its spectral non-uniformity [10]. In order to obtain a flat-top gain profile, two symmetrically opposite slopes are necessary, but a single-wavelength pumped Raman gain spectra is asymmetric around the gain peak. Therefore many gain profiles are shifted and superposed on the shorter wavelength side so as to create a broadband gain slope [11]. Shorter wavelength pump channels transfer power to the longer wavelength channels and decay more rapidly. This is compensated for by a substantial tilt in input pump power distribution. With multiple pumps, the gain profile can be adjusted by appropriately choosing the relative positions and powers of the pump waves. It can allow for the design of amplifiers with any required gain spectra [12].

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In this paper, we have proposed the design of a multi-wavelength pumped Raman amplifier with gain flatness close to the optimum. A gain flattened Raman amplifier using multiple pump wavelengths is demonstrated. We carried out our work by using six pump wavelengths with in the 1385-1495 nm intervals in a FRA and then studied their effect on gain flattening for a Raman fiber of length 10 km with different spans. The gain saturation in FRA is also investigated for two cases; one with single pumping and the other with multi-pumping for different input powers and different spans of Raman fiber length.

This paper reports the gain flattening simulation for Raman amplifiers. Introduction to FRA related to flattening is present in Section I. The Section II discusses the simulation set up used for analysis of fiber Raman amplifier. Multiple pumping schemes are discussed in Section III. The Section IV and V represent the simulation results discussion and effect of multi-wavelength pumping on fain of fiber Raman amplifier. Finally, conclusions are made in Section VI.

II. Set Up

A silica FRA of length 10 km pumped at a wavelength of 1451 nm is designed. The pump power is kept at 1000 mW and it is used in counter propagating mode. Data source at 10 Gb/s is used. This data source is applied to a driver with NRZ format. The bit rate is kept at 10 Gb/s for a -5 dBm input signal source. A continuous wave (CW) laser with a 50 MHz amplitude modulation is used. The simulation is carried out by varying the laser wavelength from 1475 nm to 1600 nm with pump attenuation of 0.2 dB/km. The gain spectrum of a single pump is not very wide and it is flat only over a few nanometers. The peak of the Raman gain is located where pump-signal frequency difference (Stokes shift) is 13.2 THz. So, in order to make gain spectrum broad, multiple pumping wavelengths are used. For a given fiber, the location of the Raman gain is only dependent on the wavelength of the pump, the magnitude of the gain is proportional to the pump power, and the shape of the gain curve is independent of the pump wavelength. Therefore, if multiple pumps are used, a flat spectral gain profile can be obtained. The required pump wavelengths and the gain required at each wavelength can be predicted by summing the logarithmic gain profiles at the individual pump wavelength [13]. Fig. 1 shows the individual pump gain profile of different pump wavelengths (1385, 1407,1429,1451,1473, and 1495 nm).

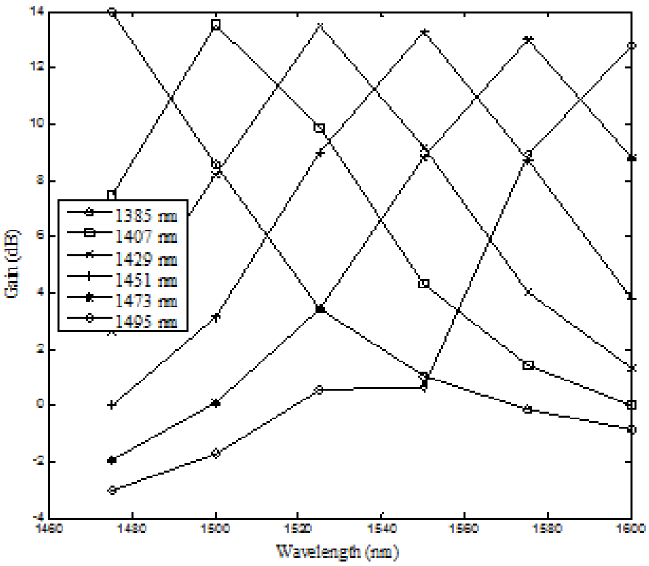

Fig. 1 Gain contribution from individual pump wavelengths

From Fig. 1, it is seen that the peak of the Raman gain for individual wavelengths is different for different pump wavelengths. Each pump creates its own gain profile. Superposition of several such spectra can produce relatively constant gain over a wide spectral region when pump wavelengths and their power levels are suitably chosen.

III. Multiple Pumping Wavelength Schemes

Here, we have used six pump wavelengths (1385, 1407, 1429, 1451, 1473, and 1495 nm) to make an optimized multi-wavelength pumping arrangement with their individual pump powers as 390, 200, 100, 65, 70, and 165 mW respectively and the total pump power is approximately 1000 mW. These pumps are applied to a Raman fiber of length 10 km to study their effect on gain flatness. Pump powers are larger for shorter wavelength pumps because all pumps interact through stimulated Raman scattering (SRS), and some power is transferred to longer wavelength pumps within the amplifier.

In order to have flat gain profile, simulation is carried out by using the above multiple pumping-wavelength scheme by varying signal input wavelengths keeping all other parameters same. Fig. 2 shows the Raman gain thus obtained for a single span of Raman fiber length of 10 km for both, single pumping as well as multi-pumping.

In the above figure, it can be seen that there is significant amount of flattening of gain if multiple pumping is used. The gain fluctuation is of the order of 0.27 dB in the bandwidth of 125 nm (1475 to 1600 nm) with peak gain at 1.84 dB. So, with this scheme, the gain fluctuation is minimized and also we obtain gain flatness in the large bandwidth range. But as the net small signal gain for a single span of Raman fiber length is very small, so to obtain high gain with significant gain flatness, the work is carried out further by increasing number of spans of Raman fiber length by taking; first the single pumping at 1451 nm and then by applying multiple pump wavelengths with the same values as used in Fig. 2. Figs. 3-5 show the Raman gain spectrum for five, eight, and ten spans respectively for both single pump and six pumps with each span corresponding to the Raman fiber length of 10 km.

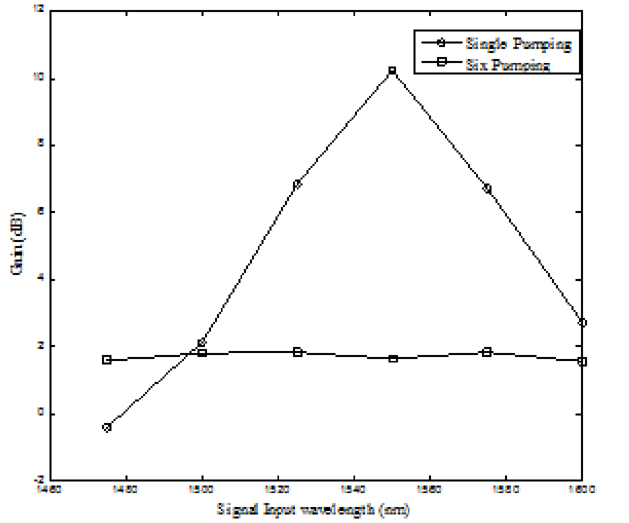

Fig. 2 Variation of Raman gain for single span of Raman fiber length of 10 km

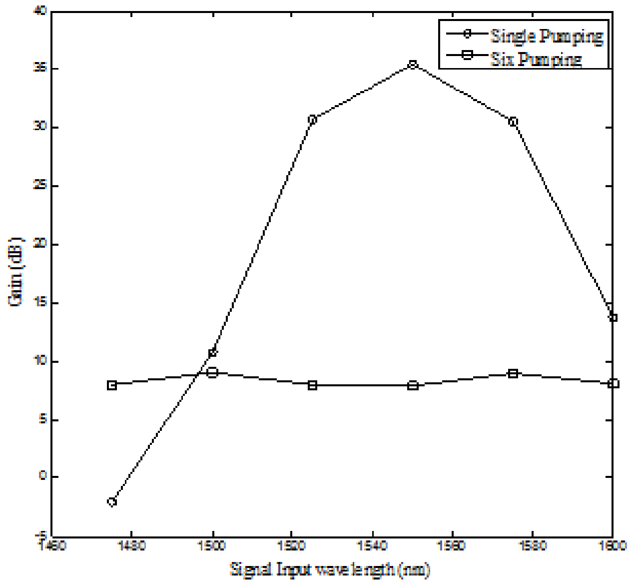

Fig. 3 Variation of Raman gain for five spans of Raman fiber length of 10 km

IV. Simulation Results and Discussions

From the above figure, if we take first the case of single pumping, it can be seen that, the peak of gain is 10.24 dB corresponding to signal wave length of 1550 nm at Stokes shift of 13.2 THz for single span (Fig. 2). At higher spans of Raman fiber length, we do not see the significant increase in this gain. For five spans of Raman fiber length, the peak of this gain lies at 35.42 dB and it is only 37.8 dB and 38.06 dB for eight and ten spans respectively. If we take the case of shortest wavelength signal (1475 nm), its gain is -0.4 dB for single span and it is -2 dB, -3.2 dB and -4 dB for five, eight

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and ten spans respectively. It means for higher spans, the net gain for this signal wavelength is reduced. So it can be clearly seen that for higher spans of Raman fiber length, single pumping scheme cannot be used to obtain high values of gain and also gain flatness is not there in this scheme as there is huge difference in gain for different signal wavelengths.

Now if we take the case of multi-pumping, there is significant improvement in the overall performance of the system. For five spans of Raman fiber length, the gain fluctuation is only 1.24 dB in the bandwidth of 125 nm (1475 to 1600 nm) with peak gain at the value of 9.11 dB. This situation doesn't get worsened even at higher spans. For eight and ten spans of Raman fiber length, the gain fluctuation is 1.87 and 2.3 dB with peak gain at the value of 14.47 and 17.85 dB respectively.

To justify the above statement, the quality factor of the signals at different spans (each span is of 10 km) for single and multi-pumping is also obtained. Table I shows the value of quality factor for all these cases.

The eye diagrams for both single and multi-wavelength pumping schemes at different span lengths are also obtained. We have taken eye diagrams corresponding to two wavelengths, 1550 nm and 1575 nm by taking first single pump and then by using six pump wavelengths for different spans of Raman fiber length of 10 km. Figs. 6 and 7 show the eye diagrams for single pump and Figs. 8 and 9 for six pumps respectively.

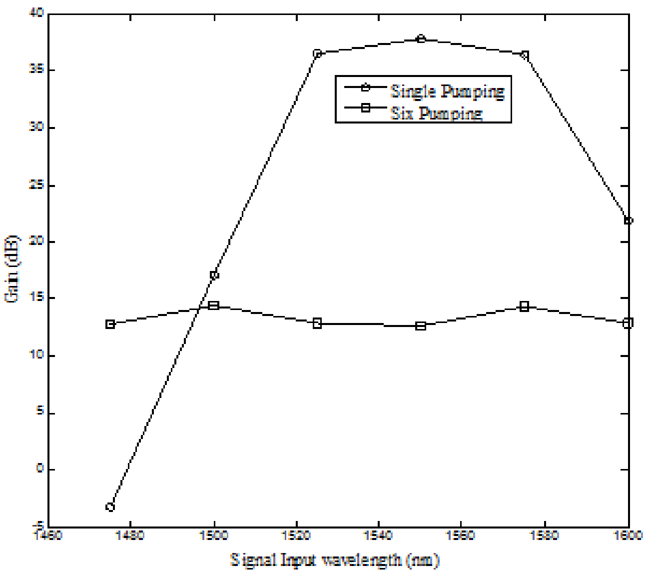

Fig. 4 Variation of Raman gain for eight spans of Raman fiber length of 10 km

From the table and eye diagrams, it is clear that for single pumping scheme, signal cannot propagate through higher spans of Raman fiber length. Its quality deteriorates considerably. As shown, for eight spans, the quality factor of two signal wavelengths (1550 and 1575 nm) is only 6 dB and when spans are increase to a value of ten, then quality factor of four signal wavelengths (1525-1600 nm) is below 20 dB. But if six pump wavelengths are used, we can clearly see from the table that all signal wavelengths (1475-1600 nm) show a good quality factor (more than 20 dB) even at ten spans of Raman fiber length. So we can have a very important conclusion, that a wide band of signal wavelengths can be transmitted through a single Raman fiber for long haul wavelength division multiplexed (WDM) systems with multi-wavelength pumping scheme.

TABLE I
COMPARISONS OF SINGLE AND MULTI-PUMPING AT DIFFERENT WAVELENGTH

Signal input Wavelength (nm)	Q at Single Pump Wavelength (dB)			
	1 Span	*5 Spans*	*8 Spans*	*10 Spans*
1475	40	32.8	27.8	25
1500	40	36.4	33	27.7
1525	40	40	31	6.8
1550	40	22.3	6	6
1575	40	39.7	6	6
1600	39.5	29.4	25.8	18
	Q at Six Pump Wavelengths (dB)			
1475	40	33	28.3	24.7
1500	40	36.6	33.9	31.7
1525	40	37	35	35
1550	37.9	37	35.5	32.8
1575	40	32.8	27.9	27
1600	39.5	29.4	26	22.5

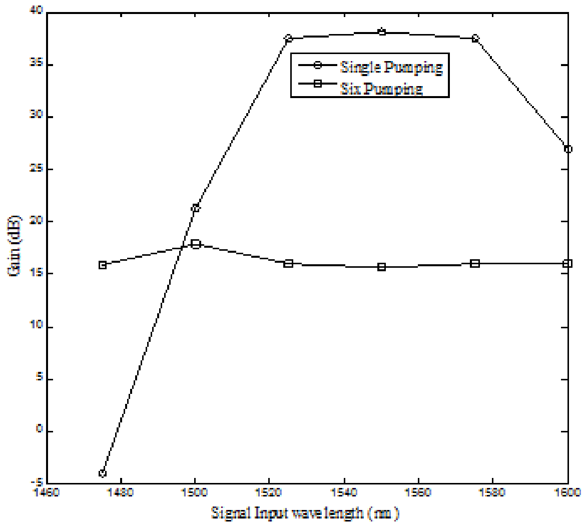

Fig. 5 Variation of Raman gain for ten spans of Raman fiber length of 10 km

V. EFFECT OF MULTI-WAVELENGTH PUMPING ON GAIN SATURATION

The gain saturation is defined as the decrease in gain exponentially with the applied pump power. The saturation of gain is due to depletion of the pump light by power transfer to the signal. The gain saturates differently for different pumping configurations. For the fixed pumped power, gain saturation condition is more. The gain saturation is defined as the decrease in gain exponentially with the applied pump power. The saturation of gain is due to depletion of the pump light by power transfer to the signal. The gain saturates differently for different pumping configurations. For the fixed pumped

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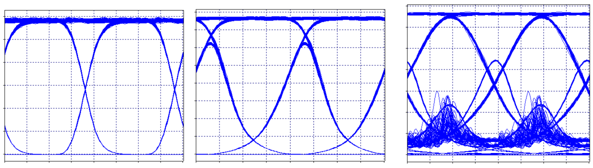
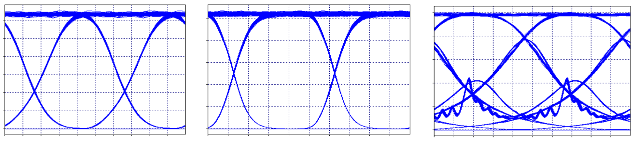
power, gain saturation condition is more pronounced for high input powers. So it is a big challenge to design a system which provides high small pronounced for high input powers. Therefore, it is a big challenge to design a system that provides high small signal gain with optimum pump power and gain flattening should be there for high input powers. The rate of loss of this type of amplifier should be minimized to such an extent that saturated output power is of the order of the pump power [4], [14]-[19]. The gain saturation in FRA is investigated by taking two cases. First by using single pumping scheme, and then by using six pump wavelengths as used in Section III. For this a silica fiber Raman amplifier of length 10 km pumped at a wavelength of 1451 nm is designed. The pump power is kept at 1000 mW and it is used in counter propagating mode with pump attenuation of 0.2 dB/km.



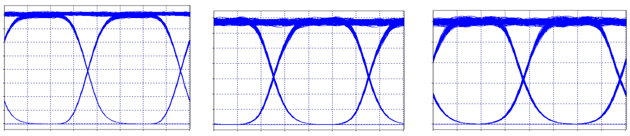
(a) Q = 40 dB (b) Q = 22.34 dB (c) Q = 6 dB

Fig. 6 Eye diagrams for single pumping input 1550 nm, (a) single span (b) 5 spans (c) 8 spans



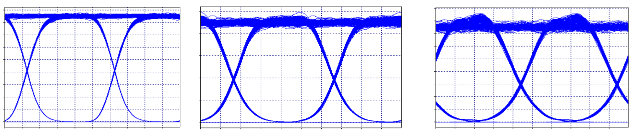
(a) Q = 40 dB (b) Q = 39.7 dB (c) Q = 6 dB

Fig. 7 Eye diagrams for single pumping input 1575 nm, (a) single span (b) 5 spans (c) 8 spans



(a) Q = 38 dB (b) Q = 37 dB (c) Q = 35.53 dB

Fig. 8 Eye diagrams for six pumping input 1550 nm, (a) single span (b) 5 spans (c) 8 spans



(a) Q = 38 dB (b) Q = 37 dB (c) Q = 35.53 dB

Fig. 9 Eye diagrams for six pumping input 1575 nm, (a) single span (b) 5 spans (c) 8 spans

A CW laser with wavelength 1550 nm and central frequency of 193.41 THz with a 50 MHz amplitude modulation is used. The simulations are carried out for different input powers ranging from -30 to 30 dBm by taking different spans of Raman fiber length with each span is of 10 km. The variation of gain for both, single pumping and multi-pumping arrangement for different input powers thus obtained is shown in Figs. 10-12.

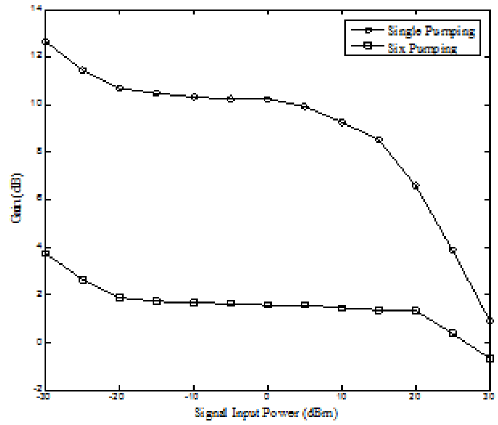


Fig. 10 Variation of Raman gain for single span of Raman fiber length of 10 km

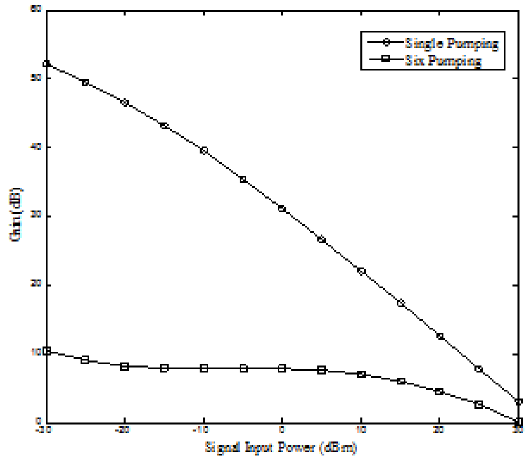


Fig. 11 Variation of Raman gain for five spans of Raman fiber length of 10 km

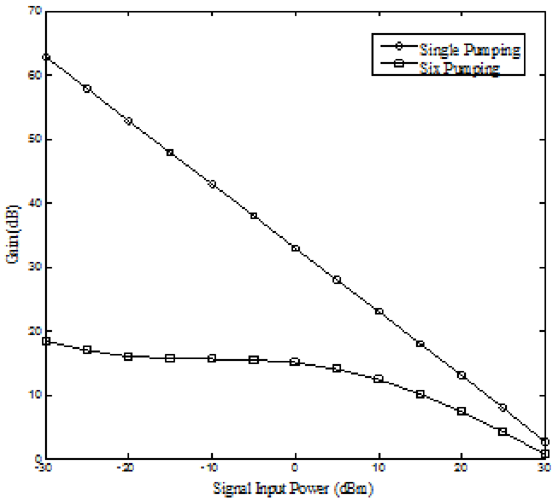
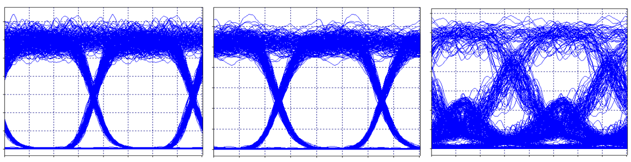


Fig. 12 Variation of Raman gain for ten spans of Raman fiber length of 10 km

Results clearly indicate that gain saturation condition is better in case of multi-pumping scheme. For single span of Raman fiber length, if we consider the case of single pumping, the maximum small signal gain has highest value of 12.65 dB at signal input power of -30 dBm and 3 dB gain compression in this case occurs at input power of 5 dBm. At the same time in the case of multi-pumping, the maximum small signal gain is 3.75 dB and 3 dB gain compression occurs at input power of 25 dBm. But small signal gain in this case is very less. So the work has been carried out by taking five and ten spans of Raman fiber length. From Fig. 11, it can be seen that in case of single pumping, the maximum small signal gain has highest value of 52.13 dB at signal input power of -30 dBm and 3 dB gain compression in this case occurs at input power of -25 dBm showing deterioration in gain saturation condition. If we consider the case of multi-pumping, for this span, the maximum small signal gain is 10.41 dB and 3 dB gain compression occurs at input power of 10 dBm. Finally, for ten spans, the maximum small signal gain in single pumping is 62.9 dB and gain saturation condition gets worsened and it occurs even before input power of -25 dBm, whereas if six pump wavelengths are used, the maximum small signal gain is 18.45 dB with gain saturation occurring at 0 dBm. So, it can be concluded that gain saturation condition gets worsened for higher spans of Raman fiber length in single pumping and we should go for multi-pumping arrangement to get flat gain profile.

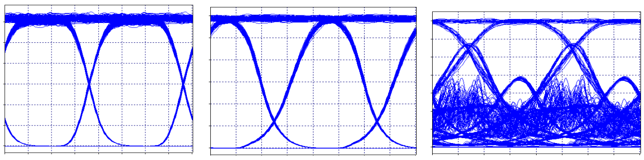
To make the results more clear, the quality factor of the output signal is also obtained by observing eye diagrams as shown in Figs. 13-18.

From these eye diagrams, it is clear that for single pumping scheme, quality factor of the signal becomes poor when signal is made to propagate through higher spans of Raman fiber length. Its quality deteriorates considerably, particularly for higher signal input powers. In the above case, if we take the case of single pumping, the quality factor of all signal input powers: -30 dBm, -15 dBm and 0 dBm reduces largely. For ten spans of Raman fiber length, its value is only 6 dB. At signal input power of 0 dBm, the quality factor is even poorer.



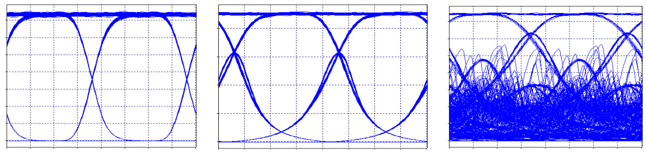
(a) Q = 23.8 dB (b) Q = 23.85 dB (c) Q = 6 dB

Fig. 13 Eye diagrams for signal input power of -30 dBm using single pumping, (a) single span (b) 5 spans (c) 10 spans



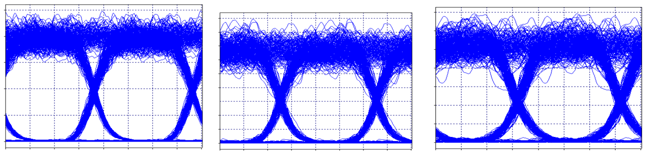
(a) Q = 34.6 dB (b) Q = 38.4 dB (c) Q = 6 dB

Fig. 14 Eye diagrams for signal input power of -15 dBm using single pumping, (a) single span (b) 5 spans (c) 10 spans



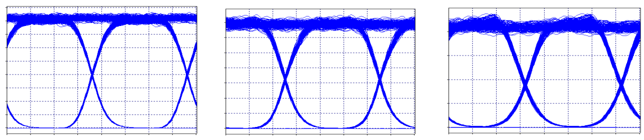
(a) Q = 40 dB (b) Q = 15.2 dB (c) Q = 6 dB

Fig. 15 Eye diagrams for signal input power of 0 dBm using single pumping, (a) single span (b) 5 spans (c) 10 spans



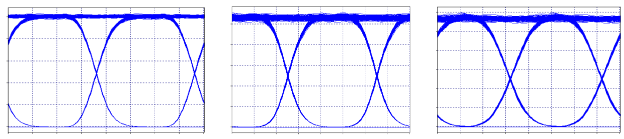
(a) Q = 23 dB (b) Q = 21 dB (c) Q = 19.8 dB

Fig. 16 Eye diagrams for signal input power of -30 dBm using six pump wavelengths, (a) single span (b) 5 spans (c) 10 spans



(a) Q = 34 dB (b) Q = 32.8 dB (c) Q = 30 dB

Fig. 17 Eye diagrams for signal input power of -15 dBm using six pump wavelengths, (a) single span (b) 5 spans (c) 10 spans



(a) Q = 40 dB (b) Q = 38 dB (c) Q = 36.6 dB

Fig. 18 Eye diagrams for signal input power of 0 dBm using six pump wavelengths, (a) single span (b) 5 spans (c) 10 spans

For five spans of Raman fiber length, its value reduces to only 15.2 dB. At the same time, if we look into the eye diagrams obtained using six pumps, the quality factor for higher spans of Raman fiber length is good. Its value is 19.8 dB for signal input power of -30 dBm if ten spans are used. For the same spans, if signal input power is increased, even then we obtain good quality factor. For signal input power of 0 dBm, the quality is 36.6 dB. So it is suggested that at higher spans of Raman fiber length, single pumping cannot be used due to high pump depletion and so multi-pump wavelength scheme is the best choice. By using it, gain saturation condition improves a lot and that too with a very good quality factor even at high input powers. So it again justifies our statement given in previous of this article that a wide band of signal wavelengths with high signal input powers can be transmitted through a single Raman fiber for long haul WDM systems with multi wavelength-pumping scheme.

VI. Conclusion

It has been concluded that with multiple pumps, the gain profile of a fiber Raman amplifier can be broadened by appropriately choosing the relative positions and powers of the pump waves applied to the fiber. Also with more number of pump wavelengths, the gain fluctuations are reduced and gain flatness can be achieved in the larger bandwidth window. Further, higher spans of Raman fiber length cannot be used with single pumping scheme due to high pump noise transfer to the signal resulting in gain saturation. So, by using multi-pumps, almost flat spectral gain profile is obtained with good quality factor for a wide band of signal wavelengths. We are able to achieve the gain fluctuation of the order of 1.87 and 2.3 dB for eight and ten spans of Raman fiber length, with peak gain at the value of 14.47 and 17.85 dB respectively. Also the gain saturation condition is improved a lot for high signal input powers with multi-pumping arrangement, particularly for higher spans of Raman fiber length.

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