Raman tilt and non-ideal tilt control function of C-band Erbium-doped fiber amplifiers

Yihong Chen, Leda Lunardi, Daniel Al-Salameh, Stan Lumish

JDS Uniphase Corporation, 625 Industrial Way, Eatontown, NJ 07724, USA
Phone (732) 380-2306, fax: (732) 380-3217, e-mail: yihong.chen@jdsu.com

ABSTRACT

Due to stimulated Raman scattering, shorter wavelength channels will pump longer wavelength channels, and so transfer their energy to longer wavelength channels. A tilt occurs when a flat DWDM signals travel through transmission fiber. We characterized the Raman tilt for 100 km SSMF and LEAF fiber at composite input powers ranging from 13 dBm to 22 dBm with a 40-channel laser source with 100 GHz spacing. Raman tilt with different fiber length at different composite launch power for SSMF is fully studied.

In order to compensate the positive Raman gain tilt generated in the transmission fiber, a negative tilt is required. A tilt control function is available in some EDFAs. The mechanism of this tilt control is to use a tunable attenuator to change the internal loss of the amplifier. Unfortunately, the negatively tilted gain spectrum achieved by this mechanism is not a straight line. From the simulation result, the tilted gain curve actually can be regarded as two straight lines with a junction at about 1538 nm in good approximation. By combining the Raman output spectrum with the EDFA output spectrum, tilt is eliminated, but a non-flat spectral shape is generated with a dip at 1538 nm. This combined spectral shape agrees quite well with the measured spectral shape in actual system. This study reveals imperfection with this tilt compensation mechanism. A new tilt compensation solution is proposed and tested. Test results shown significant flatness improvement.

Keywords: Erbium doped fiber amplifier, stimulated Raman scattering, WDM transmission, optical fiber

INTRODUCTION

Dense wavelength division multiplexing (DWDM) optical system provides an attractive solution to the demand for high capacity. One of the key components for DWDM transmission is a gain-flattened optical amplifier, which is required to achieving uniform channel performance across the operational band. The typical achievable gain flatness for a single inline EDFA in a long haul transmission link is about 1 dB over C-band or L-band. More stringent requirements are needed sometimes but that will result in significant increase of manufacturing cost and lead-time of EDFAs. In addition to imperfection of amplifier gain spectrum, other factors also need to be considered to ensure uniformity across the band. One of them is the Raman tilt of the DWDM signal, which could reach a few dB in a single span. It needs to be compensated in the transmission link. Several tilt compensation methods have been proposed [1-6], such as using a variable attenuator, a variable gain equalizer, thulium-doped fiber, etc. Among them the middle-stage variable attenuator approach is the most popular method in use.

In this work, we characterized Raman tilt in standard single mode fiber (SSMF) and LEAF fiber. The tilt control function of C-band EDFA has been examined in DWDM transmission environment. This study reveals imperfection with this tilt compensation mechanism, which must be considered in the system-driven design of EDFAs for optimum transmission performance. A new tilt compensation solution is proposed and tested

RAMAN TILT

Due to stimulated Raman scattering, shorter wavelength channels will pump longer wavelength channels, and so transfer their energy to longer wavelength channels. A tilt occurs when a flat DWDM signals travel through transmission fiber. We measured the Raman tilt for 100 km SSMF and LEAF fiber at composite input powers ranging from 13 dBm to 22 dBm with a 40-channel laser source with 100 GHz spacing. They are shown in the Fig. 1 and Fig. 2 respectively. Table 1 lists the tilt values for both fibers at different composite input power levels. At 22 dBm composite input power, both SSMD and LEAF generate about 2.7 dB Raman tilt in positive slope. The tilt decreases with increasing input power. At 13 dBm input power, the Raman tilt is below 1 dB for LEAF, and 1.26 dB for SMF with 100 km fiber length.

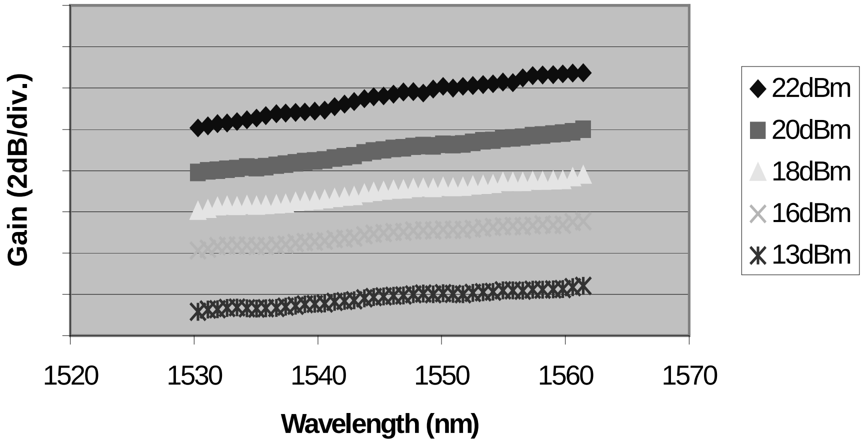

Fig. 1. Raman tilt for different input power through 100 km SSMF

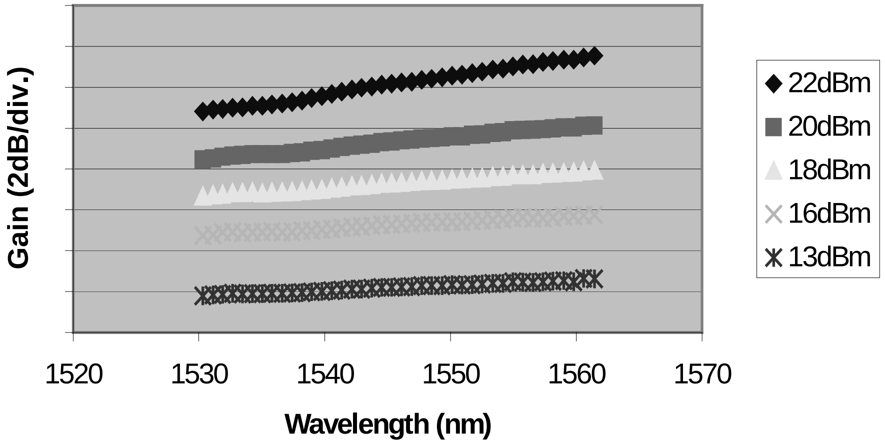

Fig. 2. Raman tilt for different input power through 100 km LEAF

Table 1. Tilt in 100 km SSMF and LEAF at different composite input power

Composite input power (dBm)	Tilt in 100 km SSMF (dB)	Tilt in 100 km LEAF (dB)
22	2.75	2.73
20	2.08	1.66
18	1.74	1.24
16	1.41	1.03
13	1.26	0.84

We also measured Raman tilt verses fiber length at different composite launch power for SSMF; the results were demonstrated in Fig. 3. First 80 km fiber generates most tilt because of higher signal power in the section. After that, the signal power has been reduced significantly due to fiber loss, and so the stimulated Raman scattering is weaker.

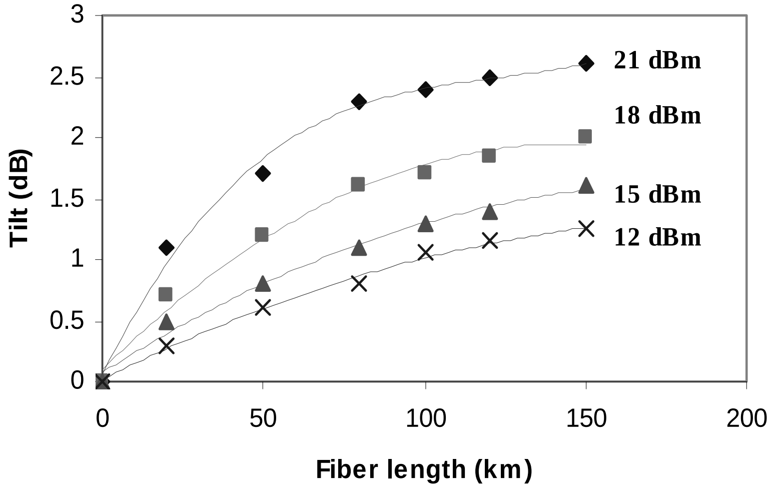

Fig 3. Raman tilt for different composite input power through SSMF

THE IMPACT OF DISPERSION COMPENSATION FIBER (DCF)

After considering the Raman tilt in transmission fiber, another factor we might need to consider is the tilt generated in the DCF that is plugged to the midstage of the EDFA. For the amplifiers used in this test, the total power going into the DCF module is between 13.5 dBm and 16.5 dBm. Although this is much less than the power launched into the transmission fiber, DCF has a smaller modal diameter, leading to lower threshold powers for non-linearity. The DCF module associating with the amplifier is DK-80 (for compensating dispersion of 80 km SMF fiber) which is about 14 km in length. We measured the loss spectrum of the DCF module using low power broadband source at about –20 dBm composite input power, assuming that the Raman tilt at this power level is negligible. The loss spectrum is shown in Fig. 4. There is a 0.4 dB tilt shown in this spectrum, which should represent the tilt in linear loss of the DCF. A DWDM signal source was used to measure the Raman tilts at input power 10 dBm, 13 dBm, and 16 dBm. As seen in the Fig. 5, 0.6 dB, 0.8 dB, and 1.2 dB tilt were associated with the input powers respectively. If we subtract the tilt caused by the DCF loss, the stimulated Raman scattering caused spectral tilts are 0.2 dB, 0.4 dB and 0.8 dB for 10 dBm, 13 dBm and 16 dBm composite input powers. Although this tilt caused by DCF is smaller than that in transmission fiber due to lower input power and shorter fiber, it still must be compensated for by adjusting VOA in the amplifier.

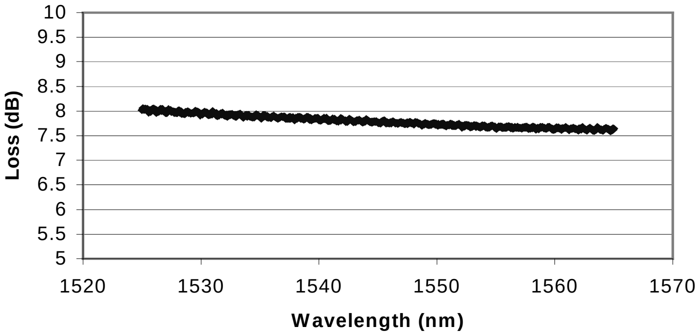

Fig. 4. DCF module DK-80 loss spectrum measured using broadband source with –20 dBm composite power

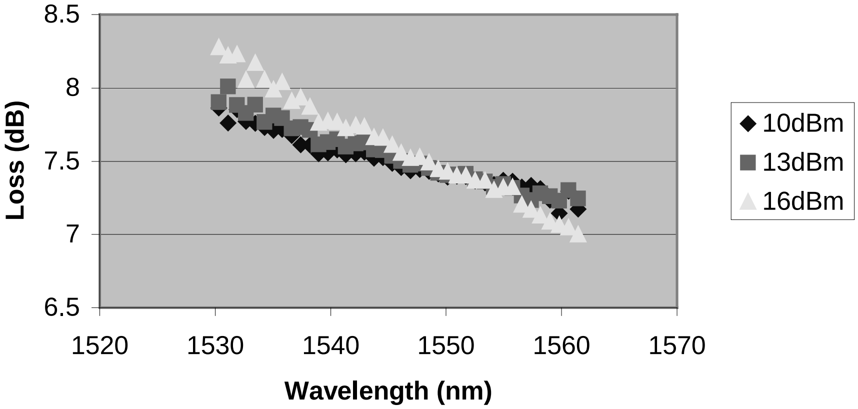

Fig. 5. Loss spectra of a DK-80 module measured with DWDM laser source with different input powers

EDFA GAIN TILT BEHAVIOR AND TILT COMPENSATION

In order to compensate the positive Raman tilt generated in the transmission fiber, a negative tilt is required. Tilt control function is available in the EDFAs we used in the experiment. The mechanism of this tilt control is to use a tunable attenuator to change the internal loss of the amplifier. In this way, a negative gain tilt can be generated to compensate the positive spectral tilt generated in the transmission fiber and DCF. Unfortunately, the negative gain tilt achieved by this mechanism is not a perfect straight line. It actually can be regarded as two straight lines with a junction at about 1538 nm in very good approximation, as shown in Fig. 6.

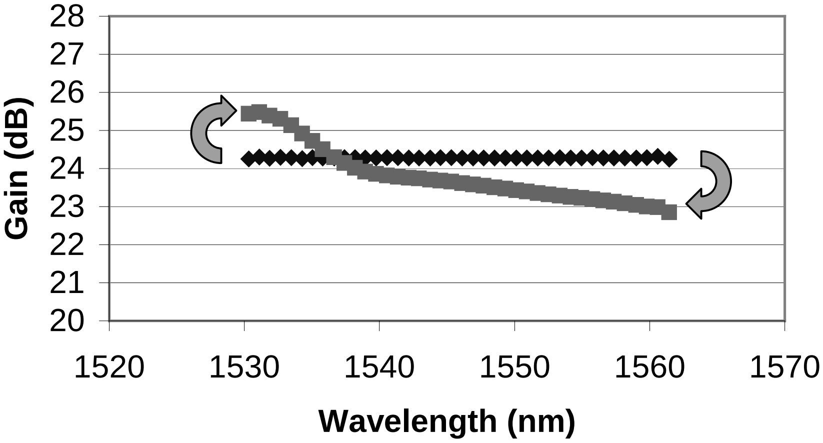

Fig. 6. EDFA tilt behavior

By combining the positive Raman tilt with the negative EDFA tilt, a spectral shape with a dip at 1538 nm is generated, see fig. 7. This combined spectral shape agrees quite well with the spectral shape observed in our experiments.

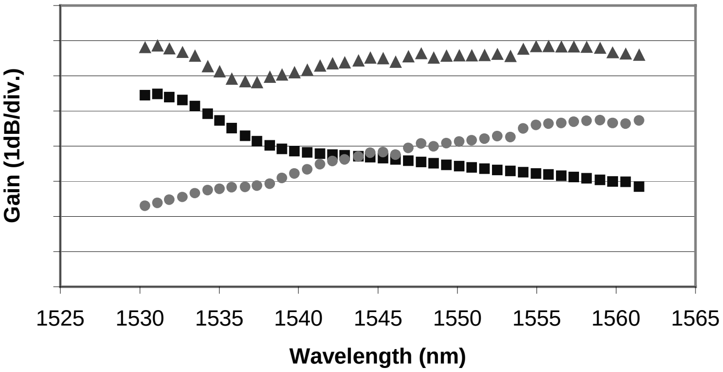

Fig. 7. Tilt compensation. ● Raman tilt spectrum, ■ EDFA tilt spectrum, ▲ Combined spectrum

TRANSMISSION PERFORMANCE DEGRADATION

In the transmission test, gain flattened EDFAs manufactured by JDSU were used. The amplifiers include gain tilt control function realized by a variable optical attenuator between the EDF stages, which can be used to adjust power difference between the longest and shortest channels. The amplifiers were operated with output power approximately 22.5 dBm and gain flatness better than 0.7 dB over the 32 nm C-band. The measured gain shape for each individual amplifier does not show obvious systematic features, so when they are cascaded, there should not be any significant accumulation of amplifier gain ripple with certain pattern. In stead it should be a randomly distributed variation. Standard single mode fiber (SSMF) was used in the transmission test and the span length is 100 km.

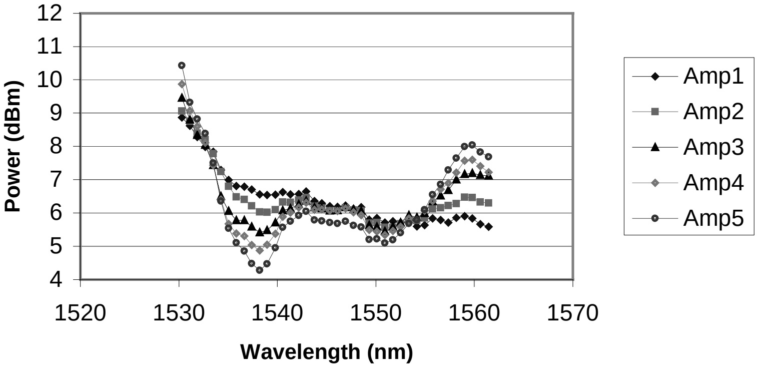

Figure 8. Spectral shapes at the outputs of different amplifiers

With the understanding of the signal flatness degradation in a single span, we can now explore spectral flatness degradation in a multi-span long haul transmission link. To ensure that the signal to be tilt free at the end of each span so the tilt will not be accumulated along the link, the tilt at the output of each amplifier needs to be adjusted to negative 2.5 dB measured by the difference of the shortest wavelength and longest wavelength, That is, the power launched into the fiber at the shortest wavelength is 2.5 dB greater than the power launched at the longest wavelength. Figure 8 shows the measured output spectra of the first 5 amplifiers, which correspond to the power spectra launched into the first 5 fiber spans. The channel power evolution shown in Figure 8 indicates that as more spans are added, the channels in the central region, especially around 1538 nm, get less and less power. While the total output power from the amplifiers keeps constant, the channels at the both ends, especially short wavelength side because of the required tilt, get more and more power. This high launch channel power leads to non-linearities in the transmission fiber that is responsible for the transmission degradation.

At the end of each span, which is after fiber span and at the input of the next amplifier, the spectra are adjusted to be tilt free. The evolution of the channel power spectrum at the ends of spans in a 5-span system is shown in Figure 9. The degradation of each span shows a similar pattern and it accumulates along the transmission link. The biggest dip is at 1538 nm. Each span causes about 1 dB dip at this wavelength.

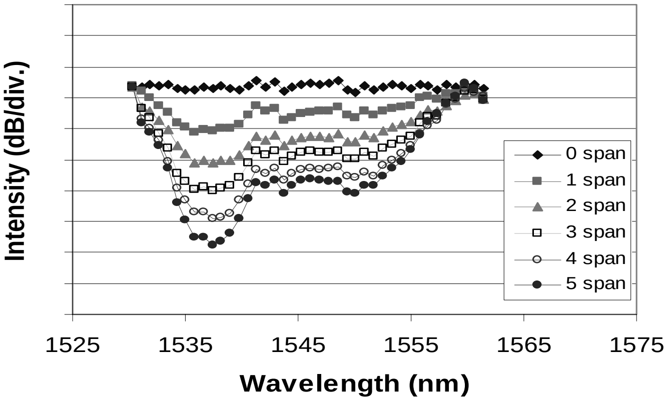

Figure 9. Spectral shapes at the ends of different spans

Along with the flatness degradation, we observed significant error-rate variation across the band of channels, especially for the short wavelength channels from 1530 nm to 1540 nm, as displayed in Fig. 10. The Q-factor plotted here is a quantitative measure of the signal eye quality which is defined as: Q= $|\mu_1-\mu_0| / (\sigma_1+\sigma_0)$. μ_1, μ_0 are the on/off level average values and σ_1, σ_0 are the noise standard deviations for the two levels. After 3 spans, the Q-value for the first channel (at 1530.3 nm) is 4 dB below that for the best channels. The Q-factor difference we observed is directly related to the spectral flatness degradation shown in Fig. 8 and Fig. 9.

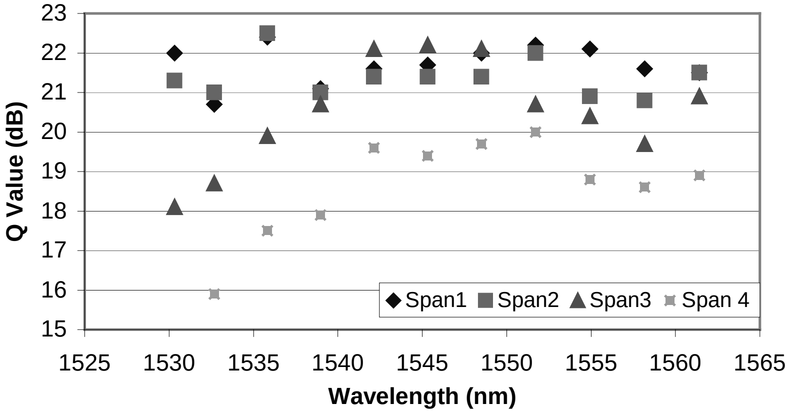

Figure 10. Q-values at selected wavelengths for the first 4 spans

A SIMPLE TILT COMPENSATION SOLUTION

To improve the flatness in the EDFA amplified link, we proposed and implemented a simple device to compensate the Raman tilt. This new device is a fiber coil with a small radius. Due to the wavelength dependence of the bend loss, a fiber coil has a larger attenuation at longer wavelength than at shorter wavelength. Fig. 11 shows the loss spectra of different fiber coils. By changing the number of turns, different loss tilts can be achieved. An excess loss of 3 dB is associated with a 2.2 dB tilt device. The maximum deviation of the spectrum from an ideal linear spectrum is about 0.3 dB for such a device. This deviation, along with excess loss, will decrease if less tilt is required, as shown in Fig 11. A tunable tilt compensator can be made using this mechanism.

By introducing the fiber coil tilt compensators into the transmission link, significant flatness improvement was achieved. For a link with 7x100km SSMF spans, about 3 dB channel-to-channel power variation was achieved at the end of the link, comparing to about 7 dB variation when using tilt control function of the amplifiers.

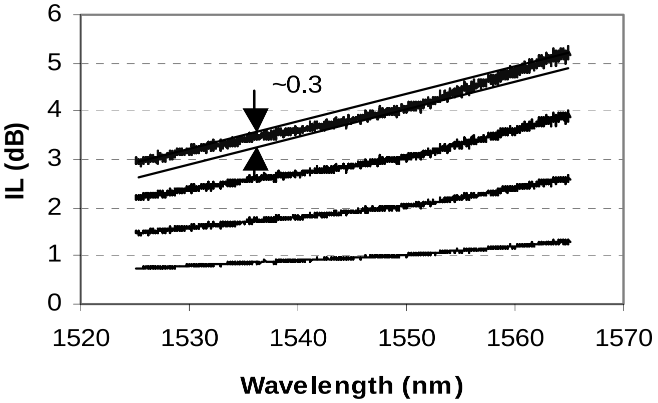

Fig 11. Loss spectra of fiber coil tilt compensators with different tilt

CONCLUSION

Raman tilt in SSMF and LEAF were characterized. Test on EDFA amplified C-band transmission link revealed imperfection of tilt compensation mechanism associated with the amplifiers. A new and simple mechanism was proposed for tilt compensation. Test results shown significant flatness improvement.

REFERENCE

[1] T. Kitabayashi, T. Sakai, T. Aizawa, T. Kashima and A. Wada, “Active gain tilt compensation of EDFA using thulium doped fiber as saturable absorber”ECOC’2000

[2] S. Kinoshita et al., “Low noise and wide dynamic range erbium doped fiber amplifiers with automatic level control for WDM transmission system” Tech. Dig. OAA’96, paper SaA5, pp211-214 (1996)

[3] Y. Sugaya, et al. OAA’95, FC3, 1995

[4] T. Naito, et al. OAA’99, WC5, 1999

[5] M. J. Yadlowsky, OAA’98 Tech. Dig. Pp24-27, 1998

[6] T. Kawazawa, et al. OAA’01 Tech. Dig. OMD3, 2001