INVESTIGATION OF THE EFFECTS OF FIBRE AGING AND DIFFERENT INPUT POWER DISTRIBUTION ON SRS INDUCED SPECTRAL TILT IN C+L WDM SUBMARINE CABLE SYSTEMS

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Abstract: C+L-band optical transmission has been expected to realize larger capacity than C-band only in WDM submarine cable systems. Compared with C-only systems, however, such dual-band systems may suffer from more limitations imposed by the SRS-induced spectral tilt due to the increasing optical signal bandwidth and fibre input power. In this paper we experimentally and theoretically investigate the effects of fibre aging and different fibre input power distributions on the Raman-induced spectral tilt for the C+L transmission. The variation of fibre input power distribution in the C- and L-bands may be caused by the accumulated imbalance between repeater gain and span loss, pre-emphasis, fibre aging and cable repair, and the decrease of repeater output power resulting from pump failures and component degradation. It is shown that the significant change in spectral flatness as well as tilt can be introduced due to the variation of SRS tilt. Therefore, for C+L transmission systems additional shape and tilt equalization has to be taken into account in system design to compensate for the power spectrum variation caused by the SRS effect. The solutions to maintain the transmission performance over the lifetime of submarine cable systems will be discussed.

1. INTRODUCTION

C+L-band optical transmission has been expected to realize larger capacity than C-band only in WDM submarine cable systems. Compared with C-only systems, however, such dual-band systems may suffer from more limitations imposed by stimulated Raman scattering (SRS) effect. The SRS effect between WDM channels behaves as a transfer of optical power from the shorter wavelengths to the longer ones, whereby a spectral tilt is generated. As the optical signal bandwidth and fibre input power increase, the SRS-induced spectral tilt becomes more pronounced and may degrade the optical signal to noise ratio (OSNR) and performance of the system. Therefore, for C+L-band WDM systems with a large total input power, the gain flattening filter (GFF) of the repeaters should be designed in consideration of the Raman gain/loss profile of the transmission fibre, so that a flat net gain over C+L-band is yielded for each transmission span.

In a real system, if SRS gain/loss deviates from the nominal design profile, the gain shape of each fibre span will be negatively influenced. Finally this may translate into end-to-end system spectral distortions. To include sufficient performance margin for these degradations, it is crucial to study the factors which affect SRS gain/loss profile. The previous works primarily focus on the dependence of SRS tilt on the fibre characteristics and total launched power.[1]-[3] In this paper we experimentally and theoretically investigate the effects of fibre aging and different fibre input power distributions on the Raman-induced spectral tilt for the C+L transmission. The variation of fibre input power distribution in the C- and L-bands may be caused by the accumulated imbalance between repeater gain and span loss, pre-emphasis, fibre aging and cable repair, and the decrease of repeater output power resulting from pump failures and component degradation. It is shown that the significant change in spectral flatness as well as tilt can be introduced due to the variation of SRS tilt.

2. MEASUREMENT OF SRS-INDUCED SPECTRAL TILT IN A SINGLE FIBRE SPAN

The gain/loss through SRS can be represented in decibel as

$$\mathrm{Loss}_{\mathrm{SRS,i}} = \mathrm{P}_{\mathrm{in,i}} - \mathrm{P}_{\mathrm{out,i}} - \mathrm{Loss}_{\mathrm{linear,i}} \quad (1)$$

where $P_{in,i}$, $P_{out,i}$, and $Loss_{linear,i}$ are the fibre input power, fibre output power, and background loss of the fibre in decibel scale for the i-th channel, respectively. From Eqn. (1) Raman gain/loss can be simply acquired from the measurement of the linear loss of the optical fibre and the total insertion loss at specified optical power levels.

Firstly, we experimentally investigated the SRS-induced spectral tilt in a single transmission span for various input power distributions. Our experimental setup is shown in **Figure 1**. The transmitter includes 49 and 47 channels at 100-GHz channel spacing (except for the longest wavelength channel of C-band) in C and L bands, respectively. The wavelengths of C-band range from 1528.77 to 1566.72 nm and L-band from 1570.41 to 1609.19 nm. All channels in each band are multiplexed, amplified by each EDFA, and passed through an attenuator to adjust the injected power. After combined with a multiplexer both bands are fed into a 74.9 km G.654D fibre with an effective area of 150 μm^2 and a typical attenuation of 0.151 dB/km at 1550 nm. The SRS-induced tilt was evaluated by measuring the optical power spectra with an optical spectrum analyzer (OSA) at the input and output ends of the fibre. Three cases were investigated:

i. Spectrally flat input power of 19.7 dBm for each band

ii. Input power level is 16.7 dBm and 19.7 dBm for C and L bands, respectively; equal channel loading for each band

iii. Input power level is 19.7 dBm and 16.7 dBm for C and L bands, respectively; equal channel loading for each band

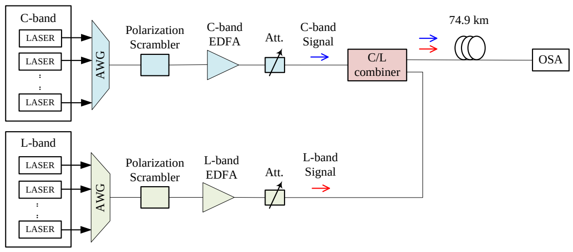


Figure 1: Experimental setup for SRS tilt measurement.

Cases ii and iii represent there is a pump failure in C and L bands amplifiers, respectively. In submarine applications pump laser sparing approaches are generally employed to maximize repeater reliability, in which two shared lasers pump both amplifiers in a fibre pair through a 3-dB coupler.[4] With this design if a single pump laser fails, the typical output power drop of a amplifier is equal to 3 dB.

Figure 2 shows the SRS gain/loss profiles for these three cases, respectively. The symbols indicate measured data and the solid lines through the symbols are calculated results. We can see that for the same input power per band (triangles in **Figure 2**), the L-band channels get net gains at the expenses of net losses of all the C-band channels. The relationship of SRS-induced power tilt to the wavelength is linear over the two bands. For 74.9 km fibre, the overall intra-band SRS spectral tilt over the C and L band can reach about 1.16 dB and 1.14 dB under 19.7-dBm input power per band.

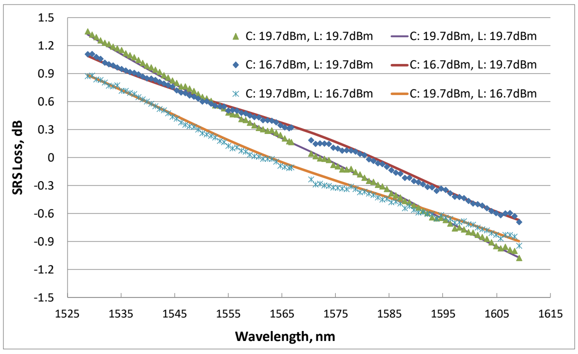


Figure 2: Comparison of measured and simulated SRS loss/gain for single span transmission (symbols: experiment, solid line: simulation).

As **Figure 2** shows, when a pump failure occurs in any band, there exists a SRS loss deviation from the linearity at the boundary of C and L band. The average SRS loss and intra-band spectral tilt is influenced for both bands. Taking example for a pump failure in C-band amplifier (diamonds in **Figure 2**), only the spectral tilt of C-band is decreased from 1.16 dB to 0.75 dB and the average SRS loss is nearly unchanged. However, for L-band the average SRS gain and the spectral tilt is reduced by 0.3 dB and 0.2 dB, respectively. For a pump failure in L-band amplifier (stars in **Figure 2**), situation is similar.

The numerical simulation was carried out by using VPI transmission maker™ v8.6. As seen in Figure 2, the experimental and simulation results agreed very closely, and thus the quantitative validity of the evaluation in the following section is assured.

3. NUMERICAL EXAMPLES AND DISCUSSION

In this section we utilized VPI simulation to investigate the effects of fibre aging and different fibre input power distributions on the SRS gain/loss profile for C+L-band WDM transmission.

3.1 SRS Loss Variation due to Fibre Aging

To evaluate the system impact of SRS tilt variation due to fibre aging, the SRS loss was simulated with the assumption: the fibre loss increase is 0.005 dB/km over 25 years. Other fibre parameters are the same as described in section 2. The optical spectrum injected into the fibre is flat and the total power is 19.7 dBm/band. These results were compared to the results before fibre aging.

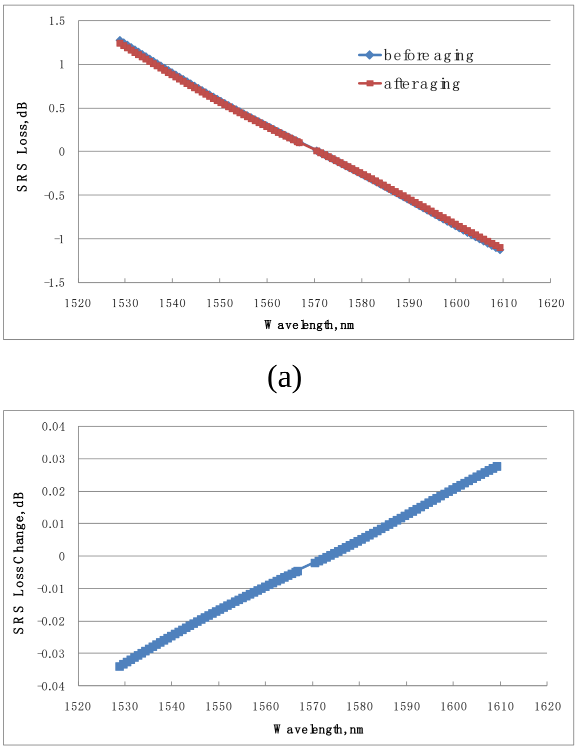


Figure 3: (a) Simulated single span SRS loss shape after fibre aging. (b) SRS loss shape change caused by fibre aging.

Figure 3(a) shows the SRS loss profiles before and after fibre aging. **Figure 3**(b) illustrates the change in the SRS loss profile caused by fibre aging. From **Figure 3**, we can see the SRS loss profile is spun around central wavelength channel due to fibre aging. As a result, the SRS spectral tilt is reduced by 0.029 dB and 0.03 dB over C and L bands, respectively. In turn, the total span loss spectrum including fibre attenuation and SRS effect is positively tilted by the same amount. Finally this variation in the SRS loss profile will be translated into an opposing net gain tilt (-0.03 dB) for each span.

Although this per-span negative net gain tilt is slight, it does occur in all spans and will be accumulated more than 3 dB after a long-haul transmission with hundred spans. This negative net gain tilt may adversely affect the transmission system OSNR, and may consume dynamic range in pre-emphasis. In particular, when a tens of dB negative gain tilt has occurred due to an average span loss increase induced by fibre aging and cable repairs, the pre-emphasis may be not enough to compensate for this additional net gain tilt caused by SRS loss change. Thus the fibre aging induced SRS loss tilt need be taken into consideration during the system design phase.

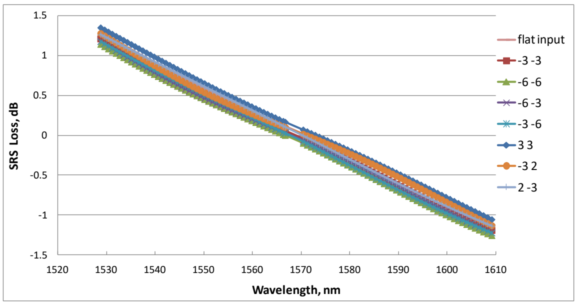
3.2 Dependence of SRS Loss on Fibre Input Power Distributions

For WDM transmission systems, channel power profile may vary with different effects, such as the accumulated imbalance between repeater gain and span loss, pre-emphasis, fibre aging and cable repair, and the decrease of repeater output power resulting from pump failures and component degradation. In this work, we only take into consideration the case:

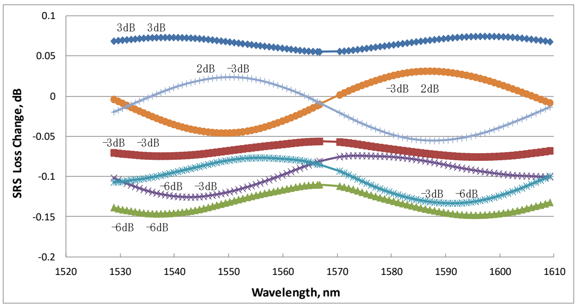
- The C and L-band channel input spectrum are tilted positively (with higher power level at longer wavelength and lower power level at shorter wavelength) or negatively (with higher power level at shorter wavelength and lower power level at longer wavelength).

- The total optical power level launched into the transmission fibre is 19.7 dBm for each band independent of the spectral tilt changes. This is based on the fact that the output power of the undersea amplifiers can remain approximately constant by the natural gain saturation of the EDFAs.

We simulated the single span WDM transmission for various input spectral tilts over C and L bands and a group of SRS loss profiles were acquired. Figure 4(a) shows the SRS loss profiles when the C and L band input spectrum are flat or tilt with the various spectral slope combinations. Figure 5 (b) illustrates the changes of the SRS loss profiles of tilted inputs against the flat input.



(a)



(b)

Figure 6: (a) SRS loss profiles simulated for different input spectral tilts. (b) SRS loss shape changes against the flat input.

It is clearly seen from Figure 7 that the Raman gain/loss profile depends on the input spectral slope. The SRS loss will increase when input spectral shapes of both bands have a positive slope, and will decrease when two input spectral shapes have a negative slope. As the input spectral tilt of -3dB per band induce a 0.07dB decrease in average SRS loss (squares in Figure 8 (b)), the tilt of 3 dB per band lead to a 0.07 dB SRS loss increase (diamonds in Figure 9 (b)). Moreover, the amount of change in the SRS loss increases with the input spectral tilt. The change of average SRS loss is increased from 0.07dB to 0.13dB when the input spectral tilt increases from -3 dB to -6 dB for each band (squares vs. up triangles in Figure 10 (b)). Consequently, the amount of increase or decrease in SRS loss depends on the magnitude of input spectral tilt and is regardless of positive or negative input tilt.

From Figure 11 it can also be noted, the SRS loss change is more wavelength-dependent with the increasing of input spectral tilt. For instance, the peak-to-peak variation of intra-band SRS loss is increased from 0.018dB to 0.036dB when the input spectral tilt increases from -3 dB to -6 dB for each band. Moreover, the wavelength-dependence of SRS loss variation is enhanced when C and L bands tilt in different directions. As a example, the peak-to-peak variation of C-band SRS loss is increased from 0.018dB to 0.042dB while the C-band input spectral tilt remains -3dB and the L-band spectral tilt changes from -3dB to 2dB.

All these impacts of input spectral tilt on the SRS loss profile will be translated into additional net gain excursion and tilt. The resulting change of the net gain spectrum may be insignificant for an individual span, but can accumulate over multiple spans. This may result in unacceptable channel performance variation, especially for systems susceptible to nonlinear propagation impairments.

Given the above, in order to achieve effective gain-shape management for the full system lifetime, the influence of the fibre aging and input power distribution on SRS gain/loss needs to be taken into account, especially in C+L-band long-haul systems. A passive equalizer (GFF, shape equalizer or tilt equalizer) is not enough to combat the accumulation of the SRS gain/loss variation, unless accurate control of both output power and spectral tilt of C and L band amplifiers as well as accurate control of the span loss between the repeaters can be implemented over a system lifetime. However, considering that the deployment of the undersea system is complex and fibre aging and cable repairs are inevitable, such tight control is impractical. Therefore, this compensation method is generally imperfect as far as counting the SRS loss variation. By contrast, an in-line dynamic gain equalizer (DGE) is more desirable to control the system gain shape and tilt variation due to SRS effect. The use of a wavelength selective switch (WSS), whether as a part of a reconfigurable optical add/drop multiplexer (ROADM) or in the form of a separate wet plant, can realize such equalization capabilities in the system. However, the cost may be the obstacle to use of WSS.

4. CONCLUSION

In this paper we show that fibre aging and input power distribution have an influence on the SRS loss profile in the C+L transmission. The impact on the average SRS loss, the SRS tilt magnitude and the flatness may be slight to a lesser extend for an individual transmission span, but the resulting accumulation across a long-haul system can be significant and result in unacceptable channel performance variation. Therefore, for C+L transmission systems additional shape and tilt equalization has to be taken into account in system design to compensate for the power spectrum variation caused by the SRS effect. The use of DGE is effective for the management of such variable SRS loss. However, the cost may be the obstacle to use of DGE.

5. REFERENCES

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