16.1. Introduction

In most chapters of this book, stimulated Raman scattering (SRS) is invoked intentionally. Pump radiation is coupled into the fiber carrying the signal radiation to generate Raman gain. The Raman gain can be used very advantageous, for example, to improve the optical signal-to-noise ratio (OSNR) budget by distributed amplification in the transmission fiber. However, SRS also occurs unintentionally in WDM transmission systems. Due to the large number of channels inside the Raman gain bandwidth, total power can add up to levels where considerable amounts of SRS are generated, with the signal channels acting as pumps. In contrast to the beneficial effects of intentional Raman pumping, the unintended generation of SRS usually degrades system performance.

This chapter addresses effects resulting from the unintended invocation of SRS and their impact on WDM signal transmission. Section 16.2 covers the generation of spontaneous emission and its effect on maximum channel launch powers. A number of system impairments result from the interaction between signal channels due to SRS. Effects with time scales well below the bit period affect the mean values of the individual channel powers. These slow interactions are discussed in Section 16.3, whereas Section 16.4 addresses fast interactions between individual bits. Such interactions change the variances of the respective channel powers and can be considered as noise. The last section (16.5) provides some selection criteria for transmission fibers with respect to Raman efficiency.

16.2. Raman Threshold

The Raman amplification process relies on stimulated emission of radiation. However, stimulated emission is inevitably linked to the generation of spontaneous emission [1, 2]. Consequently, launching signal radiation of WDM channels into an optical fiber leads to generation of new photons due to spontaneous Raman scattering. The peak intensity occurs at a frequency of one Stokes shift (approx. 13.2 Thz in silica
fibers, corresponding to a wavelength shift of 106 nm for a signal at 1550 nm) below the frequency of the signal radiation.

The initial number of spontaneously generated photons is rather small and usually negligible. It can grow considerably due to amplification by stimulated emission with the signal radiation acting as a pump. The stimulated emission converts signal photons into amplified spontaneous emission (ASE) photons, thus contributing an additional loss mechanism for the signal radiation. The conversion rate is proportional to the intensity of the ASE. Consequently, the additional loss of the signal radiation due to SRS is negligible compared to other loss mechanisms in the fiber as long as the ASE intensity is sufficiently small. If the signal launch power increases and ASE starts to experience a very strong growth, the additional loss due to SRS will eventually exceed the other loss mechanisms in the fiber. The depletion of the signal power due to SRS grows so strongly that further increase of the launch power above the level of equal loss contributions results in a decrease of the signal power at the fiber output. This limitation of reasonable signal launch powers is called the Raman threshold [3].

There are several options to define the Raman threshold or the critical launch power. One would be the minimum launch power resulting in an excess loss due to SRS that is equal to other loss mechanisms at some point along the signal propagation. Another option is the signal launch power that achieves the maximum signal power at the fiber output. The most commonly used definition for the critical power seems to be the launch power that results in a total ASE power equal to the signal power at the fiber output [3, 4].

The critical signal launch power \( P_{\text{crit}} \) in W according to the definition with equal signal and ASE power at the fiber output can be estimated using the following equation [4].

\[
P_{\text{crit}} = \frac{8 A_{\text{eff}} g_R}{1 - \exp(-\alpha_S L)},
\]

where \( A_{\text{eff}} \) denotes the effective mode field area in \( \text{m}^2 \), \( g_R \) the peak Raman coefficient in \( \text{m/W} \) for random polarizations, \( \alpha_S \) the loss coefficient at the signal wavelength in \( \text{1/m} \), and \( L \) the length of the fiber in m. For a section of standard single-mode fiber (SSMF) with a length of 100 km, an effective mode field area of 80 \( \mu \text{m}^2 \), a peak Raman coefficient of \( 2.3 \times 10^{-14} \text{ m/W} \), and a loss coefficient of 0.2 dB/km, this equation predicts a critical launch power of 1.3 W for a single signal with a center wavelength of 1550 nm.

According to Eq. (16.1), the critical launch power depends on the transmission fiber type and its characteristics. Experiments were carried out to determine the critical power for four different transmission fiber types [5]. Figure 16.1 shows the experimental setup. Eight continuous wave (CW) laser diode sources with different output wavelengths were employed to generate the signal radiation rather than a single one in order to reduce the impact of stimulated Brillouin scattering (SBS). The signal wavelengths were chosen on the ITU grid in the range from 1549.3 to 1560.6 nm with 200 GHz channel spacing and output powers of 2 dBm per channel at the input of the power combiner. SBS was further suppressed by applying a triangular amplitude modulation with a frequency of 15 kHz and a modulation index around 10% to