Suppression of stimulated Raman scattering in high power fiber laser systems by lumped spectral filters

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ABSTRACT

We present a systematic study on the inhibition of stimulated Raman scattering by lumped spectral filters both in passive optical transport fibers and in fiber amplifiers. This study reveals the parameters that have the strongest influence on the suppression of the Raman scattering (such as the attenuation at the Raman wavelength and the insertion losses at the signal wavelength). These parameters have to be optimized in order to achieve the desired Raman inhibition and/or to minimize the loss in amplifier efficiency. The study is concluded with realistic predictions on the use of spectral filtering elements for Raman scattering inhibition in real-world high power fiber amplifiers.

Thus, using for example 10 lumped spectral filters with 20 dB effective Raman attenuation and less than 0.25 dB insertion losses, a maximum Raman threshold increase by a factor of 3 is expected. In this context, long period gratings are proposed as promising filtering elements for Raman inhibition in high power fiber amplifiers.

In order to experimentally verify the theoretical predictions and the suitability of long period gratings, a fiber amplifier consisting of 2 m active Ytterbium doped fiber was built. Three long period gratings were consecutively inserted at different positions along the fiber, and the Raman threshold was determined for each situation. It is shown that, with three long period gratings, the Raman threshold (defined as the 20 dB ratio of Raman to signal output power) was increased by about 60%, which offers a good agreement with the theoretical predictions.

Keywords: long period grating, fiber laser, fiber amplifier, spectral filtering, stimulated Raman scattering, Raman suppression

1. INTRODUCTION

In a pristine fiber (Fig.1), the Raman scattering transfers energy to longer wavelengths and, thus, limits the power scalability of high power fiber laser systems.

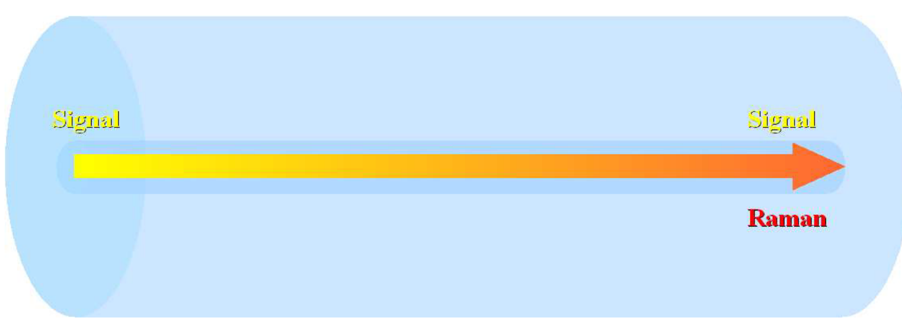

Figure 1. Stimulated Raman scattering transfers energy to longer wavelength when a certain threshold is reached.

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1.1 Techniques of stimulated Raman suppression

Stimulated Raman scattering in optical fibers can be inhibited by different techniques. Some of the most popular include the use of special fiber designs that work as distributed spectral filters [1, 2, 5] or the use of lumped filtering elements [3, 4]. The most widespread distributed filter concepts, w-type [1] and hole-assisted fibers [2], introduce a fundamental mode cut-off at a wavelength shorter than that of the Raman scattering, thereby forbidding its propagation in the fiber. In [1] an Yb-doped fiber amplifier consisting of 23 m of active w-type fiber with 7µm core diameter was demonstrated to suppress Raman. This was achieved by decreasing the fiber cut-off wavelength through bending until the losses at the Raman wavelength amounted to about 5dB/m (20dB/m theoretically) while the insertion losses remained below 1dB/m. The Raman threshold was increased approximately by a factor of 2.4 to ~13kW peak power.

Another SRS suppression technique that has been explored is the ring-type fiber, in which the Raman scattering is resonantly coupled from the fiber core into a core-ring mode. This fiber type was demonstrated to suppress SRS in an amplifier setup with a 10µm core diameter fiber [5].

Yet another concept to suppress Raman scattering is the use of photonic bandgap fibers, with potentially very high losses per meter as demonstrated for a core diameter of 10µm [6].

However, these special fiber designs are in general limited in the maximum fiber core size that can be employed and usually provide Raman attenuations of only a few dB/m. These characteristics imply that these special fiber designs are not suitable for high power fiber amplifiers and lasers, where typically large core diameters and short fiber lengths are employed. Hence, for these applications lumped filters could provide a better and more flexible solution. Their main advantages are their inherent Raman inhibition scalability and adaptability to any fiber type. With lumped filters, the Raman inhibition factor can be easily controlled by the number of filters inserted in the fiber and their attenuation at the Raman wavelength.

1.2 Functional principle of long period gratings as lumped filters

Lumped spectral filters work as band rejection filters for the Raman scattered light and thereby inhibit the stimulated process (Fig.2). In real laser systems, however, the subsequent integration of lumped filters always leads to insertions losses that decrease the signal power. In this way, both the influence of the total attenuation introduced by the filters at the Raman scattering wavelength and the impact of their insertion losses are theoretically studied in this paper.

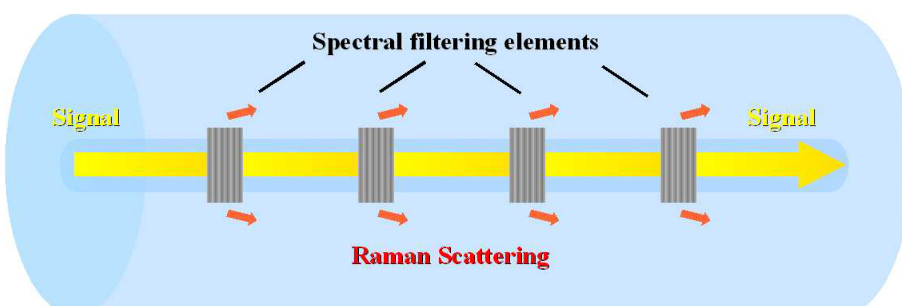

Figure 2. Fiber spectral filtering elements mitigate stimulated Raman scattering by removing the Raman scattered light from the fiber core.

In this work, lumped filters are evaluated (both theoretically and experimentally) as Raman suppression elements in passive fibers as well as in active Yb-doped fibers for amplifier applications. The influence of both the number of equidistant discrete filters in various setups and the impact of their insertion losses are theoretically studied. As an experimental proof of principle, a counter-propagating amplifier was set up and several long period gratings were implemented as lumped spectral filters to achieve an increase in the Raman threshold.

2. SIMULATIONS

2.1 Simulation technique

The theoretical study [7] is based on simulations carried out using a continuous wave (cw) model. This model solves the rate equations and incorporates the effects of spontaneous and stimulated Raman scattering as well as amplified spontaneous emission (ASE) (that can act as a seed for the Raman process). Despite it being a cw model, its predictions could be used for the pulsed regime as long as there is no significant pulse walk-off, the Raman response can be considered instantaneous in comparison with the pulse duration (i.e. pulses > 1 ps) and the pulse repetition rate is much shorter than the average lifetime of the excited ions (~1 ms). The simulations enable the determination of the Raman threshold for different fiber lengths in passive fibers, as well as in fiber amplifiers and lasers. Additionally, the spectral filter is modeled as a strong loss at the Raman wavelength with certain insertion losses at the signal wavelength of 1064 nm.

2.2 Raman threshold

In the literature [8] the Raman threshold is defined as the input power at which Raman and signal output power are equal. However, in the context of high power laser systems, this definition is not suitable because signal depletion would have already had taken place and this is contrary to the goals pursued in high power laser systems, namely reaching the highest possible output powers and clean spectra. Therefore, a new definition of the Raman threshold is required and has been recently proposed in [9]. Following the recommendations given in that paper, in this work the Raman threshold is also defined as the 20dB ratio of signal to Raman power at the fiber output. This value seems acceptable both for passive transport fibers and for active setups used in various applications.

2.3 Passive Fibers

When an ideal filter without insertion losses is considered, our simulations show that the Raman threshold increases linearly with the filter strength and the number of filters introduced in the fiber. However, incorporating the unavoidable insertion losses of the filters at the signal wavelength changes the picture. The linear growth of the Raman threshold disappears giving rise to a curve that exhibits a maximum, as shown in Fig.3. The optimum number of filters that provides the maximum increase of the Raman threshold depends exponentially on the filter insertion losses at the signal wavelength.

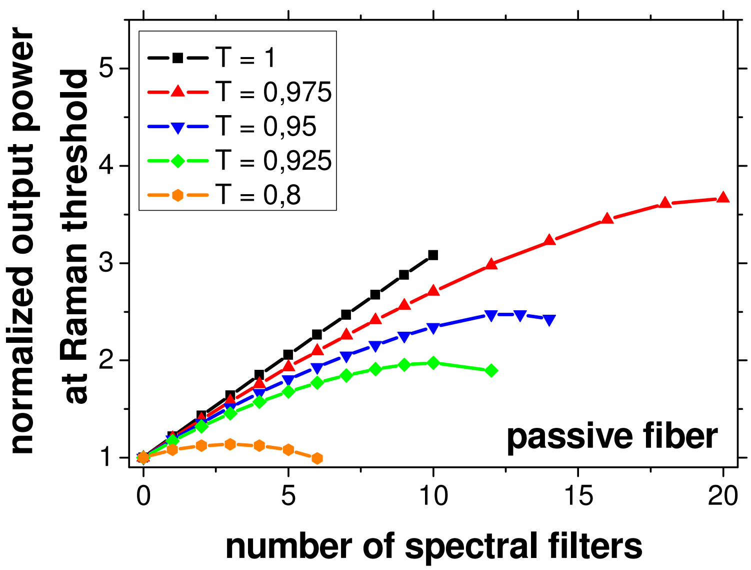

Figure 3. Simulated output signal power of a passive fiber at the Raman threshold normalized to the corresponding value for a fiber without spectral filtering. T denotes the filter transmittance at the signal wavelength.

The optimum arises from the fact that from this point on the overall signal losses exceed the signal gains obtained from the SRS inhibition. After this maximum, the curves discontinue because the Raman threshold cannot be reached any more. This is because beyond this point, the signal is so strongly attenuated by the overall insertion losses introduced by the filters that it cannot reach the Raman threshold power at any point along the fiber. On the other hand, it is also clearly visible in Fig.3 that this maximum of Raman threshold increase can be raised by reducing the filter insertion losses. However, a higher maximum implies that the number of filters required to achieve it increases.

2.4 Amplifiers

The simulations for active setups [7] have been carried out for a 2 m long Yb-doped double clad fiber with a core diameter of 10 µm and a cladding diameter of 125 µm. The ion concentration amounts to $8.5 \cdot 10^{25}$, the pump wavelength is 976 nm and the signal wavelength is 1064 nm. We have chosen this particular wavelength as representative of the longer wavelength region of the Ytterbium gain spectrum. In systems where SRS is a problem (as the ones under analysis in this paper), longer emission wavelengths should be preferred since for significantly shorter wavelengths, i.e. for example 1030 nm, the gain and ASE are much higher at the Raman wavelength, leading to an even smaller Raman threshold [9].

The fiber length of the co-propagating amplifier without filters was optimized to extract the highest possible power with the given pump power. As seen in Fig.4, the simulations of Raman inhibition by lumped spectral filters in a co-propagating amplifier show that the Raman threshold increase factor is still highly sensitive to the insertion losses of the filters (although less than in passive fibers).

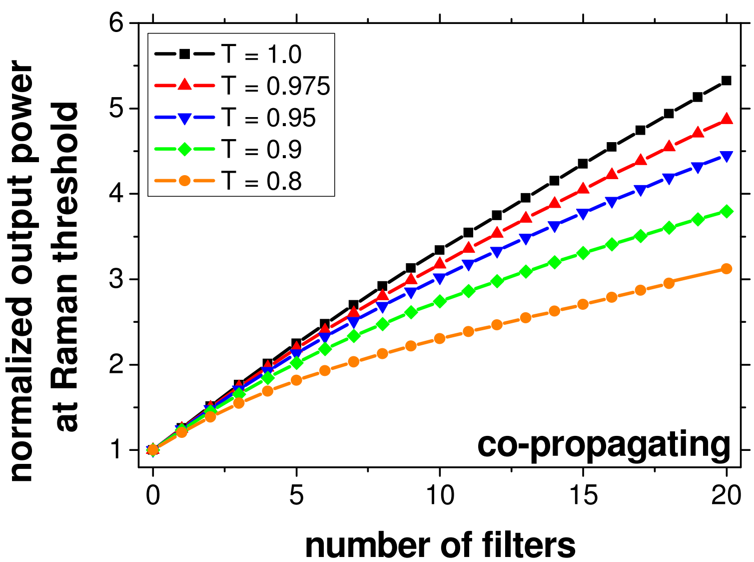

Figure 4. Simulated output signal power at the Raman threshold normalized to the corresponding value for a fiber without spectral filtering. T denotes the filter transmittance at the signal wavelength: For a co-propagating amplifier and 20dB average Raman attenuation per filter.

This is due to the fact that in the co-propagating setup the signal power grows very fast at the beginning of the fiber and then propagates over a longer fiber distance with a relative small growth (i.e. we have the situation of an almost constant power propagating along the fiber as in the passive case). This fact has a twofold effect. On the one hand it means that in the co-propagating case more Raman scattering should be generated than in the counter-propagating setup. On the other hand it also implies that each filter should have a stronger effect in Raman inhibition. Hence, compared to the counter-propagating amplifier, in principle higher Raman threshold increase factors should be expected in this configuration.

Additionally, in contrast to passive fibers, no maxima can be observed in Fig.4. Here instead, the slope efficiency decreases slowly with the number of filters towards a value defined by the insertion losses. Increasing the number of filters implies higher losses that are compensated by the amplifier gain. This is why no maxima appear, but the amplifier efficiency is reduced instead [7].

For the counter-propagating amplifier case, the simulations were carried out using the same fiber parameters as before. The results show that, contrary to the co-propagating case, the insertion losses at the signal wavelength have almost no influence on the Raman threshold increase factor (Fig.5). This is due to the fact that the signal losses can be exactly compensated simply by increasing the pump power. From Fig.5 it can be deduced that the Raman threshold increase per filter amounts to about an average value of 16%, although the behavior is not completely linear any longer. For more than 10 filters, the Raman inhibition per filter is reduced to about 14%.

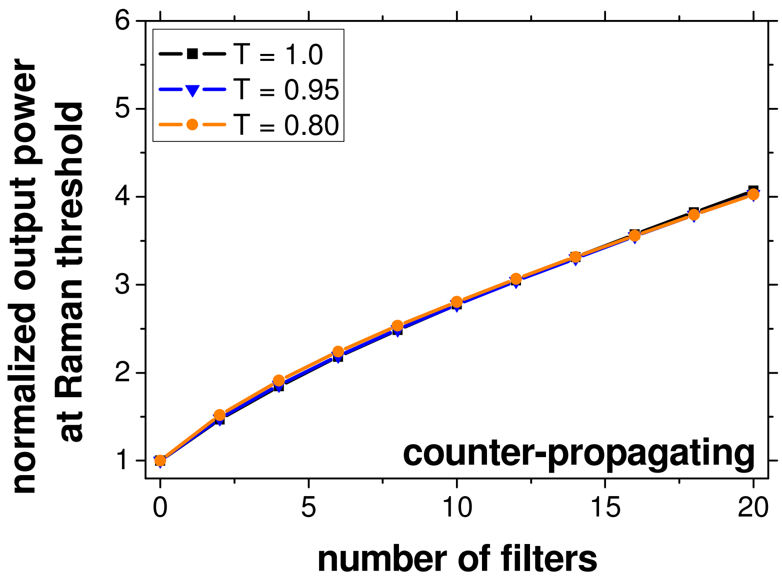

Figure 5. Simulated output signal power at the Raman threshold normalized to the corresponding value for a fiber without spectral filtering. T denotes the filter transmittance at the signal wavelength: For a counter-propagating amplifier and 20dB average Raman attenuation per filter.

This apparent immunity to the insertion losses of the filters comes at the cost of worsened amplifier efficiency. The amplifier efficiency increasingly drops with a larger number of filtering elements [7]. In any case, thanks to the fact that the main signal growth takes place near the fiber end, the total efficiency decrease is smaller in this setup than in the co-propagating case. In spite of it, this drop in amplifier efficiency is, as before, the factor that ultimately limits the maximum achievable Raman threshold increase factor. Hence, if the amplifier efficiency should not drop by more than 15% in high power laser systems, one can reach at most a Raman threshold increase factor of 3 with about 10 filters if their signal transmission is better than 0.95.

As mentioned before, in counter-propagating configurations the signal grows extremely fast towards the fiber output. This implies that high signal power only propagates over a short fiber distance. Therefore, as predicted in the previous subsection, this leads to much higher Raman thresholds in this configuration than in co-propagating amplifiers.

Until now, the available long period gratings could not exceed 15 dB average Raman suppression. Therefore, the preceding simulations were also performed for this attenuation value (Fig.6).

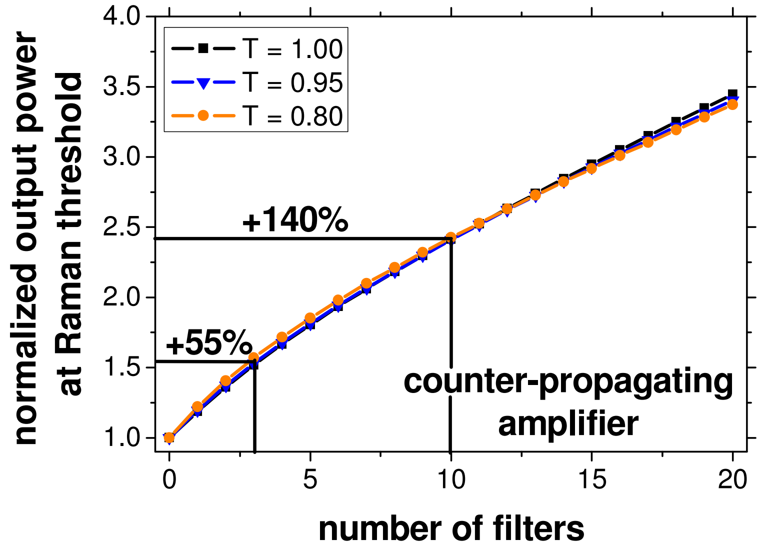

Figure 6. Simulated output signal power at the Raman threshold normalized to the corresponding value for a fiber without spectral filtering. T denotes the filter transmittance at the signal wavelength: For a counter-propagating amplifier and 15 dB average Raman attenuation per filter.

With 3 filters of 15dB average attenuation a 55 % increase of the Raman threshold can be expected. For as many as 10 filters, the Raman threshold can potentially be increased by 140% but, depending on the filter insertion losses, this can severely limit the amplifier efficiency.

3. EXPERIMENTS

In actual setups long period gratings (LPGs) that show low insertion losses combined with high peak attenuation [10-12] can be used as filtering elements [7].

In order to verify the predictions of the simulations, a counter-propagating Ytterbium doped fiber amplifier was built. The active fiber had a core diameter of 10 µm and a cladding diameter of 125 µm. The fiber amplifier was seeded by a pulsed source with 80 kHz repetition rate, 72 ps pulse duration and 18 mW average output power. To keep the amplifier fiber length fixed during the experiment, three 15 cm long pieces of passive fiber (with the same geometry as the active fiber) were spliced in-between the active fiber, thus splitting it in four sections of equal length. Subsequently the passive pieces were replaced by passive fibers with long period gratings. For each configuration the Raman threshold was determined. Fig.7 displays the obtained Raman output power versus signal output power for increasing pump powers. As can be seen the introduction of LPGs progressively increases the Raman threshold.

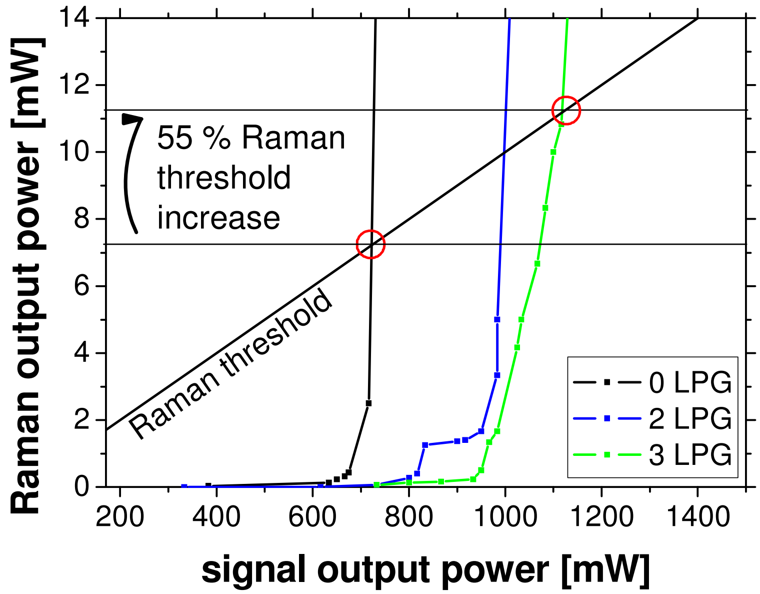

Figure 7. Raman output power vs. signal output power for three fiber configurations. Implementing long period gratings into the fiber increases the Raman threshold.

Thus, compared to the unmodified fiber, the Raman threshold of a fiber with three LPGs is reached at about 55% higher output powers. This value agrees very well with the theoretically predicted value of Fig.6.

4. CONCLUSIONS

The different behavior in co- and counter-propagating amplifiers in terms of Raman inhibition by lumped filters in Fig.4 to Fig.6 is caused by the very different inversion distributions along the fiber in both configurations. Where the inversion is high enough, the active fiber can compensate the losses introduced by the filter. On the other hand, if the inversion is not so high, these losses will have an appreciable effect on the output signal. In this context, in counter-propagating amplifiers the highest inversion (i.e. the strongest amplification) is found near the fiber end, i.e. the pump side. This section comes after the signal has gone through the majority of the filters. Thus, the fiber gain is able to compensate for these extra losses. On the other hand, in co-propagating amplifiers the highest inversion (i.e. the main amplification) is found near the front end of the fiber. After this section the inversion/amplification levels are not so high and, therefore the fiber gain cannot fully compensate for the insertion losses of the filters that come afterwards (i.e. the majority of the filters).

It can be concluded that Raman inhibition can potentially be more efficient in co-propagating amplifiers provided that the filter insertion losses are not too high. However co-propagating amplifiers have a much reduced Raman threshold to start with. This makes counter-propagating amplifiers the configuration of choice if the systems are limited by Raman scattering. An additional advantage of the counter-propagating setups is their higher tolerance with respect to the filter insertion losses.

To verify these predictions a counter-propagating amplifier was built up. As proposed in [7], long period gratings were implemented to increase the Raman threshold of this amplifier system. It was shown that 3 long period gratings could increase the Raman threshold and thus the achievable output power was increased by about 55%, which is in good agreement with the theoretically predicted values.

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