Gain Optimization of Germanosilicate Fiber Raman Amplifier and Its Applications in the Compensation of Raman-Induced Crosstalk Among Wavelength Division Multiplexing Channels

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Invited Paper

Abstract—Spectral characteristics of stimulated Raman scattering (SRS) process were theoretically investigated for step-index silica optical fibers with various GeO\textsubscript{2} concentrations. Optimal-fiber lengths and germanium concentration, where the first Stokes power reaches maximum, were calculated at various pump power levels for application in Raman amplifiers. Based on this analysis, we proposed and experimentally demonstrated a new channel-equalizing technique to simultaneously compensate Raman-induced crosstalk and amplify wavelength-division-multiplexing (WDM) signals using a discrete Raman amplifier in the 1.5-\textmu m range. As a further application of SRS in germanosilicate glass fibers, we introduce an all-optical variable attenuator for channel equalization that could be used in dynamic optical power tilt control in WDM systems.

Index Terms—Amplifier design, optical fiber, power equalization, Raman amplifier, variable optical attenuator (VOA).

I. INTRODUCTION

Raman fiber amplification has been extensively studied as a key device for wavelength division multiplexing (WDM) optical communication with the development of high-power semiconductor laser diodes [1]–[8]. Distributed amplification in transmission fibers has been recently demonstrated for dense WDM signals in long haul systems [7], [8]. Discrete amplifiers based on highly doped germanosilicate fibers have been also actively studied as an alternative direction of Raman amplifier development [1]–[6]. Compared with distributed Raman amplifiers based on transmission fibers, discrete Raman amplifiers could have additional useful functions, such as dispersion compensation or dynamic power control. With rapid development of dense WDM systems, various functions are required to deal with signal traffic and it would be highly desirable to design optical devices with multiple functions that can be scalable and reconfigurable with system evolutions. In this paper, the authors review their attempts to explore potentials in the stimulated Raman scattering (SRS) process for multi-functional optical devices.

Since SRS is not limited to resonant electronic radiative transitions as in rare-earth ions, in Raman amplifiers an arbitrary gain spectrum can be synthesized by using multiple pumps at different wavelengths. Furthermore, a gain of over 30 dB and a bandwidth over 80 nm have been demonstrated with stable characteristics useful for practical applications [1]–[6]. In order to achieve a significant gain, however, fiber length on the order of a few tens of kilometers and pump power over a few hundred miliwatts are required in Raman amplifiers to obtain a signal gain comparable to those of in-line erbium-doped fiber amplifiers (EDFA). The main reason for low efficiency is due to the fact that the Raman-gain efficiency in pure silica is inherently limited to about 1.2 × 10\textsuperscript{-14} cm/W [9], [10]. The Raman gain efficiency has been known to increase several folds by doping the core in germanium [10]. High germanium concentrations, however, induces the Rayleigh scattering loss in the fiber [11] such that balanced optimization of GeO\textsubscript{2} concentration is required to fully exploit the gain capability of germanosilicate fibers. Recently, the authors reported a theoretical analysis for optimization of the net gain in Raman amplifiers in the 1.3-\textmu m range, including the energy transfer to the second Stokes shift as well as the germanium-related optical properties [12]. The SRS process, the basis of Raman amplifiers, could limit the performance of dense WDM systems due to Raman-induced crosstalk among WDM channels. Especially in long-haul WDM systems, SRS—induced crosstalk could accumulate a significant amount of gain tilt, degrading system performance [13]. To prevent this excessive nonlinear penalty, equalization based on external filters [14] and spectral inversion method [15] were proposed. There have been attempts to use the SRS process to dynamically equalize the gain of EDFA placing a discrete Raman amplifier in front of an EDFA and varying the pump power [16]. Applying the idea of using a Raman medium as a power equalizer, the authors...
recently reported preliminary experimental results of a new technique to compensate for the SRS-induced crosstalk using a discrete Raman amplifier with a negative gain slope [17], [18].

In this paper, Raman medium parameters were analyzed for the small-signal gain optimization of Raman amplifiers in the 1.5-μm range. Applications based on the SRS process in optical fibers were also explored for all-optical dynamic-power-equalization fiber devices. In Section II, we characterized optimal parameters of germanosilicate fibers for 1.5-μm Raman amplifiers based on the authors’ previous analysis [12]. Using the Raman frequency modeling [19], [20], the fiber length and germanium-concentration dependencies of the small-signal gain at the first Stokes shift were theoretically investigated. In Section III, we introduce a new Raman amplifier with a negative gain slope that enables simultaneous amplification and equalization of tilted WDM channels, dynamically compensating for Raman-induced crosstalk in the 1.57- to 1.59-μm region. We theoretically predicted that a lumped Raman amplifier composed of high germanium concentration fiber could work for this purpose. Channel equalization and amplification is demonstrated experimentally: the crosstalk accumulated after 330 km of single-mode fiber (SMF) was compensated for without external devices. In Section IV, we introduce a new filtering device to equalize channel powers using SRS. The spectral response could be dynamically controlled by a pump at the first Stokes shift. Equalization of the power tilt among WDM channels due to Raman-induced crosstalk was proposed using this all-optical variable attenuator in the 1.5-μm range.

II. OPTIMIZATION OF GERMANOSILICATE FIBER FOR RAMAN AMPLIFIER

When a Raman medium is pumped, signals in the frequency range of the first Stokes are firstly amplified by the SRS process. If the signals are further amplified to exceed a certain threshold value, some energy at the first Stokes will be transferred to the second Stokes. This process continues until the power level is attenuated below the SRS threshold. In most Raman amplifiers, the gain bands are in the region of the first Stokes shift of the pump frequency. The energy transfer from first to second Stokes acts as a loss mechanism in the Raman amplifier operating in the wavelength region that is within the first Stokes shift of the pump. In order to optimize the gain of a Raman amplifier, it is thus critical to understand the energy transfer mechanism for various parameters such as GeO\textsubscript{2} concentration, fiber length, and pump power.

Raman amplifier gain characteristics were analyzed using Raman-frequency modeling initially developed by Stolen et al. [19]. The governing equations are

\[
\frac{dP_0}{dz} = -\alpha_0 P_0 - P_0 \sum_{k=1}^{n} g_{0k} P_k \frac{P_k}{A_{\text{eff}}} - \sum_{k=1}^{n-1} C_0 P_0 \frac{g_{0k}}{g_{0m}} \tag{1}
\]

\[
\frac{dP_i}{dz} = -\alpha_i P_i + P_i \sum_{j=0}^{i-1} g_{ij} P_j \frac{P_j}{A_{\text{eff}}} - P_i \sum_{k=i+1}^{n} g_{ik} P_k \frac{P_k}{A_{\text{eff}}} + \sum_{j=0}^{i-1} C_j P_j \frac{g_{ij}}{g_{jm}} \tag{2}
\]

where \(P\) represents the instantaneous power at distance \(z\) along the fiber, which travels at the group velocity of the propagating optical pulse. \(P_k\) is the power at frequency \(\nu_k\). The subscript \(n\) is the final frequency shift, fixed at 1000 cm\(^{-1}\) in these simulations. Parameters with the subscript ‘0’ correspond to variables at the pump wavelength of 1.472 μm. Forward pumping was assumed, as in [19] and [20]. \(g_{ij}/g_{jm}\) represents the normalized lineshape of the Raman gain curve, and \(C_j\) is the optical fiber loss [11]. The term \(C_j\) is related to the spontaneous Raman scattering coefficient, which actually varies according to the capture fraction of Raman scattered light and the effective area \(A_{\text{eff}}\) [19], [21]. In this simulation, \(C_j\) is assumed to be constant [12], [18], which has little affect on the final numerical results due to its small contribution in the Raman amplification process. We also assume that the polarization states for the pump and signal are parallel throughout the Raman medium. Effects of polarization, especially correlation between the signal and pump polarization states, would need further rigorous analysis including the effect of polarization mode dispersion, which is beyond the scope of this paper.

To further simplify the analysis, optical losses from external devices have not been considered. Detailed descriptions of other parameters are given in [12] and [18].

Fig. 2 shows the spectral evolution of optical power in the Stokes shifts. The Raman medium is a germanosilicate fiber with an index difference \(\Delta n\) of 0.01 and an optical loss of 0.191 dB/km. The pump power is 1.0 W. The input signals were assumed to be white noise with a power level of –60 dBm. In order to investigate the small-signal gain characteristics for the fiber length of 60 km, the first Stokes shift reaches its maximum with the peak power of 48.5 mW for the fiber length of 6.0 km. The peak power then gradually decreases, since it serves as a pump for the second Stokes. For fiber lengths longer than 10 km, the second Stokes signals grow prominently while the first Stokes decreases further. Due to this energy transfer between the Stokes shifts, there exists an optimal fiber length where the first Stokes power reaches its
maximum before the onset of conversion to higher Stokes. Fig. 3 shows the small-signal gain as a function of pump power at the optimal fiber length. The input signal at 1.57 μm was assumed to be −20 dBm. The small-signal gain increases linearly with pump power, then saturates due to energy transfer to the second Stokes shift. Nonlinear spectral broadening by self-phase modulation (SPM) can be induced for signal powers greater than 20 dBm. The dotted line in the figure indicates the calculated threshold where the optimum Raman medium length $L_{opt}$ exceeds the nonlinear medium length $L_{nl}$. $L_{nl}$ is defined as $L_{opt}/\int_0^{L_{opt}} \gamma P_{sgn}(L) dL$, where $\gamma$ is given as a function of GeO₂ concentration [22], [23]. A more detailed description of the nonlinear length in germanosilicate fibers has been published elsewhere by the authors [12].

In Fig. 4, the small-signal gains at optimal fiber lengths are shown for various index differences $\Delta n$ of the fiber. Here, the index difference was assumed to be due to GeO₂ doping only. Due to the tradeoff between Raman gain and Rayleigh scattering loss in germanosilicate fibers [10], [11], the small-signal gain reaches its maximum when the index difference is near 0.015 for all pump powers (0.05–0.2 W). This result is the same as that for the analysis of a Raman amplifier 1.3 μm [12]. As the index difference further increases to 0.04, the gain decreases rapidly due to excessive Rayleigh scattering loss. Therefore, it is found that the GeO₂ concentration has an optimal value corresponding to an index difference of about 0.015. Fig. 5 shows the optimum fiber length (where the first Stokes reaches maximum) as a function of pump power for various index differences. As long as the pump power is transferred only to the first Stokes, the optimal length increases with pump power. When the pump power exceeds a certain value where the energy starts to be transferred to the second Stokes, the optimal length abruptly decreases and results in signal gain saturation. The dotted curve is the threshold length $L_{th}$ where nonlinear spectral broadening induced by SPM begins to take place. SPM is dominant when the pump power exceeds 0.2 W.

Note that the criterion for optimization of Raman amplification used in this analysis does not satisfy all of diverse amplifier applications. In this work, optimization is specifically aimed at maximization of the net small-signal gain in terms of fiber length and germanium concentration. Optimization of the noise figure or output power would require different criteria. Consideration of the pumping directions, such as backward or co-directional, would also require a different optimization scheme.
III. APPLICATION OF RAMAN AMPLIFIER IN THE WDM SIGNAL POWER EQUALIZATION

Based on previous analysis of the SRS process along an optical fiber, we introduced a method to compensate the Raman-induced crosstalk accumulated along SMF among WDM channels in the EDFA L-band region [17]. The principal idea is schematically shown in Fig. 6. WDM channels undergo power tilt by Raman crosstalk, which transfers the power of shorter-wavelength channels to longer wavelengths. An amplifier with an appropriate negative gain slope would compensate for the power tilt as it amplifies the channels differentially. The Raman gain spectra of various germanium concentrations are shown in Fig. 1. The pump wavelength is assumed at 1.472 μm, which is the wavelength of the pump laser diode used in the experiments described below. Note that in conventional SMF with typical Δn = 0.005, the Raman gain shows a positive slope below 1.59 μm. However, as germanium concentration increases, the peak moves toward 440 cm⁻¹, which results in a gain band with a negative slope in the range of 440 cm⁻¹ to 505 cm⁻¹. This gain band with a negative slope could be used to compensate for the crosstalk-induced power tilt among the WDM channels (see Fig. 6). Fig. 7 shows the spectral evolution of 25 WDM channels between 1.571 and 1.591 μm with 0.8-nm spacing along a 330-km SMF without any pump. In this simulation, the optical loss we considered in the wavelength range from 1.571 to 1.591 μm is only the Rayleigh scattering loss of 0.12 dB/km, as given in [11]. The Rayleigh loss spectrum is almost uniform in the wavelength range. Germanium concentration dependent infrared absorption could be included in the analysis to result in a lower power level. Power tilt among channels due to Raman-induced crosstalk would be still dominant since both Rayleigh scattering and infrared absorption can be regarded as spectrally uniform in the given wavelength range. After propagating 330 km of SMF, initially uniform channels showed a power difference of 5 dB between channels at 1.571 and 1.591 μm. For channel equalization, we tested the feasibility of the Raman-gain band with a negative slope between 440 cm⁻¹ and 505 cm⁻¹ in the silica fibers doped with high GeO₂ concentration shown in Fig. 1. We assumed that the input signals for the proposed amplifier were the WDM channels with a power unbalance of 5 dB caused by Raman crosstalk after 330-km SMF transmission (see Fig. 7). Dispersion-compensating fiber (DCF) with a Δn of 0.02 and a length of about 2 km was used as a Raman medium. The spectral response of WDM channels for various pump powers is shown in Fig. 8. As the pump power increases, the signal power in the shorter-wavelength region increases more rapidly than that of the longer wavelength. This numerical analysis predicted that WDM channel power could be regulated to −27 dBm within 0.8 dBm without external filters for 200 mW of pump power. SPM could be ignored due to the low signal power (−27 dBm).
Fig. 10. Power equalization of two initially tilted channels, 1.571 μm at -39 dBm and 1.591 μm at -43 dBm, for a pump power of 250 mW.

Fig. 11. Variation of channel power versus pump power for the amplifier of Fig. 9.

Experimental demonstration of crosstalk compensation was performed with the setup described in Fig. 9. The DCF with a Δn of 0.02 was used as a Raman-gain medium; its length was about 7.7 km. The Raman medium was pumped bi-directionally through a specially fabricated WDM coupler to deliver maximum pump power. Two tunable laser sources were used at 1.571 and 1.591 μm with a spectral width below 0.2 nm. Using variable optical attenuators (VOAs), the signal at 1.571 μm was set at -39 dBm, while at 1.591 μm it was set to -34 dBm to simulate the crosstalk for propagation of 25 channels with 0.8-nm spacing through SMF 330 km, as in Fig. 7. The experimental results are shown in Fig. 10. The pump laser diodes generated a broad amplified spontaneous emission from 1.51 to 1.65 μm. The spectral region with a negative slope extended from 1.57 to 1.65 μm, which covers the entire EDFA L-band. The spectra of unbalanced input channels are represented by the dotted lines, -39 dBm at 1.571 μm and -34 dBm at 1.591 μm. The evolution of both signals was monitored as the pump power was varied, as shown in Fig. 11. The forward pump was turned on to 160 mW, and then the backward pump was turned on for further equalization. The power difference of the two channels decreased as the pump power increased, and the powers were equalized at the total pump power of 250 mW, as shown in the solid line of Fig. 10. When the backward pump power increased further, over-compensation of Raman-induced crosstalk was observed as predicted in Fig. 8.

It was found that the balance between the two pumps and the order of pumping, which determines the signal power distribution along the Raman medium, did influence the experimental results. Further optimization of the pumping scheme in terms of power balance between the forward and backward pumps could improve the pump efficiency.

The difference in Raman-medium length between simulation (2 km) and experiment (7.7 km) could be attributed to many factors. As mentioned before, in the numerical calculation only Rayleigh scattering was considered. In practice, infrared absorption will further increase the total loss in the fiber. Furthermore, we assumed that the polarization states of the pump and the signal were parallel. In experiments, both signals and pumps were partly polarized and were independently subject to statistical variation along the fiber. DCF and couplers could have polarization-dependent loss that would contribute to lower average gain. In addition, there were losses related to component insertion loss and SMF-DCF splicing loss. All of those factors contribute to the deviation of numerical simulations from experimental results. The broad linewidth and subsequently low peak power of the pump sources could also play a role in the difference between simulation and experiment. Narrow-linewidth depolarized pump sources, such as polarization-multiplexed fiber-grating Raman lasers, would give better agreement.

IV. ALL-OPTICAL VARIABLE ATTENUATOR USING SRS FOR THE CHANNEL EQUALIZATION

In Section III, the concept of equalization of tilted channels using the SRS process has been demonstrated. A detrimental effect, however, is that amplified spontaneous emission (ASE) was added to the signals and acted as a noise source (see Fig. 10). This will degrade the optical signal-to-noise ratio (OSNR), especially for the channels at shorter wavelengths. In this section, we propose another equalization technique based on SRS that would not degrade the OSNR of WDM channels. Its principle of operation is illustrated in Fig. 12. Once energy transfer from the pump to the first Stokes is initiated by the SRS process, the pump power along the fiber is very susceptible to the first Stokes power. Therefore, a light source (Stokes-shifted pump), whose spectral position lies within the first Stokes of the signal channels, will selectively depletes their energy by...
SRS instead of amplifying them. The physical principle can be found in the governing equation (2). The third term on the right-hand side describes the energy transfer, which will eventually deplete the signal power ($P_s$) if the Stokes-shifted pump power ($P_2$) is high enough. For example, the signal power at the longest wavelength, shown as the solid line in Fig. 12 is more depleted by the Stokes-shifted pump than those at shorter wavelengths, which results in spectral power equalization. Note that the amount of attenuation achieved in the figure cancels the power tilt generated by Raman-induced crosstalk among WDM channels. Based on this phenomenon, we propose an all-optical VOA based on SRS that selectively changes the signal power distribution by controlling the Stokes-shifted pump power and its spectral position. Channel power equalization to compensate for the Raman-induced crosstalk was analyzed theoretically, which could remove the degradation of the OSNR incurred by a negative-slope Raman amplifier.

For a detailed theoretical analysis of the VOA based on SRS, the governing equations (1)–(3) were used with different assumptions. We have assumed that the signal channels are distributed from 1.57 to 1.59 μm. Now the parameters with the subscript ‘0’ correspond to variables at the shortest wavelength (1.57 μm). The Raman gain values were kept the same as in the previous section. The Stokes-shifted pump power is located at the wavelength of 1.71 μm, which could be achieved with either a Tm-doped fiber laser or a cascaded fiber Raman laser. Other parameters, which are not mentioned in this section, were kept same as in the Section II. The governing equations (1)–(3) were solved using the fourth-order Runge–Kutta method. For numerical stability, the mesh size of the fiber length was chosen as 50 cm. The input signals for the VOA were the WDM channels with the power unbalance of 5 dB caused by Raman-induced crosstalk after 330 km of SMF transmission (see Fig. 7). Dispersion-compensating fiber with Δn of 0.02 and length of 1 km was used as the Raman medium for the proposed VOA and its application. Once again, the same assumptions were made as in the previous sections, including forward pumping and pump-signal polarization alignment.

The spectral response of WDM channels after the VOA is shown in Fig. 13 for various pump powers. As the pump power increases, the signal powers at longer wavelengths decreases more rapidly than that at shorter wavelengths. The channel power level could be regulated at −47 dBm to within 0.93 dB without external filters for the Stokes-shifted pump power of 270 mW. SPM was ignored due to the low signal power (−47 dBm). Note that this VOA reduces the overall power level of WDM channels, but it regulates the power tilt dynamically without the penalty of OSNR degradation. At a high level of signal power, however, the first Stokes of the signals and the Stokes-shifted pump photon could interact to degrade the power regulation. Thus this proposed VOA could be located in front of a gain flattened in-line EDFA in the transmission link that could boost the signal uniformly.

V. Conclusion

Considering the effects of GeO₂ both on Rayleigh scattering loss and Raman gain, we performed a rigorous numerical analysis on the evolution of the optical power of the first to the second Stokes in the fiber. For a small signal around 1.5 μm, it is found that the GeO₂ concentration has an optimal value corresponding to the index difference near 0.015 due to the tradeoff between Raman gain and Rayleigh-scattering loss. As an application of Raman amplifier, compensation of Raman-induced crosstalk was predicted using the inherent negative Raman-gain slope in the spectral range of 1.571 to 1.591 μm. Using this approach with dispersion compensating fiber and two counter-propagating pumps, a crosstalk of 5 dB accumulated over 330 km of SMF could be compensated without external devices. A new type of all-optical variable attenuator based on the stimulated Raman scattering process was also theoretically proposed to equalize the power imbalance induced by Raman crosstalk without degradation of the signal-to-noise ratio. When a germanium-doped Raman fiber medium is pumped with 270 mW at 1.71 μm, WDM channels tilted with initially 5 dB of power difference in the spectral range of 1.571–1.591 μm were equalized to within 0.93 dB.

REFERENCES


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