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Efficient Numerical Scheme for Simulating Complex Raman Amplifiers in Optical Telecommunication Systems

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〈概要〉

励起光源として従来のラマンポンプに加えて広いスペクトルを持つインコヒーレントポンプ（iPUMP）を用いるラマン増幅特性を高精度に計算するシミュレーション技術を開発した。このシミュレーション技術は，従来の狭スペクトル幅を持つFBG付きラマンポンプによる双方向の励起方式とiPUMPによる前方励起方式を取り入れたラマン増幅特性を計算する。光ファイバの伝搬損失や有効断面積の波長依存性や信号自体と信号間のラマン利得の周波数依存性を組み込むことで，波長分割多重（WDM）信号光の伝搬方向におけるパワー変動の正確な解析とラマン利得スペクトルを平坦にする励起光源の構成の最適化が可能となった。後方励起方式の計算においては固有の収束問題があるが，反復最適化法を採用し計算誤差が十分に小さくなることを確認した。

実測値と計算値の一致からこのシミュレーション技術の精度が実証され，前方励起方式と励起光源としてiPUMPを採用する光ファイバ通信システムに適用するラマン増幅の設計と最適化を行えることを確認した。

1. INTRODUCTION

Furukawa Electric Co., Ltd. has been a pioneer in Raman amplifier technology since 2000 actively contributing to its research, development, and implementation1), 2). Raman amplifiers can play a significant role in boosting signal power within long-haul optical telecommunication links. Unlike their rear-earth doped counterparts, Raman amplifiers offer several advantages: firstly, they can amplify signals across any telecommunication band with the selection of the appropriate pump wavelength. Secondly, they generate significantly less amplified spontaneous emission (ASE), minimizing signal noise. Moreover, various pump configurations, including the “WDM pump” scheme, can be employed to achieve a broad and flat gain profile for amplified signal channels, ensuring optimal performance in WDM systems1).

Designing and optimizing these amplifiers require accurate numerical simulations that can handle various pump configurations and the nonlinear Raman gain effect in that every propagating signal or pump channels affects every other signal or pump channels. This paper presents a novel approach and efficient numerical scheme for simulating Raman amplifiers with diverse pump scenarios, including Raman pumps in both forward and backward directions, and incoherent pumps with broad spectral regions in the forward direction.

Our proposed scheme addresses the challenges associated with these complex pump configurations. For backward-propagating Raman pumps, an iterative method tackles the inherent boundary value problem, ensuring accurate propagation calculations. Additionally, the software incorporates frequency-dependent loss and Raman gain coefficients, capturing the realistic behavior of various optical fibers. Furthermore, it accounts for inter-signal Raman gain, a critical factor for accurate gain prediction in densely spaced WDM systems.

This simulation tool excels in evaluating signal evolution and achieving flat gain for WDM signals, employing diverse combinations of Raman pumps. Its effectiveness is demonstrated through comparisons with actual measurements reported in our previous work3), showing excellent agreement between simulated and experimental results.

This paper presents a numerical scheme implemented in MATLAB that efficiently handles diverse pump configurations, including Raman pumps in both forward and backward directions and incoherent pumps with broad spectral regions in the forward direction. The scheme incorporates key nonlinearities such as frequency-dependent loss/gain and inter-signal Raman gain, enabling accurate prediction of WDM signal evolution and optimization for flat gain (i.e., minimizing gain variations across different signal channels) using various pump combinations. The scheme's accuracy is validated by comparing our simulations to published experimental results, dem-

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onstrating excellent agreement. This work provides a valuable tool for researchers and engineers involved in designing and optimizing Raman amplifiers for enhanced performance in optical telecommunication systems.

2. THEORY

Several prior studies[4)-8)] have simulated the stimulated Raman effect using various approaches, primarily differing in their handling of backward propagating signals and equation formulations. This work introduces frequency dependency of Raman gain by offering two approaches: Cordina's estimation[9)] and utilizing measured effective core area data to scale the Raman gain coefficient.

In our model, the power evolution is calculated by integrating Eq. (1), which contains the frequency dependent effective core area data in this description equivalently to Ref.[4)] except that we do not include backward Reyleigh scattering here.

$$\begin{aligned}\frac{dP^{\pm}(z,\nu)}{dz} &= \mp\,\alpha(\nu)\cdot P^{\pm}(z,\nu) \pm P^{\pm}(z,\nu)\cdot\sum_{\xi>\nu}\frac{C_R^0}{2}\cdot\frac{A_0}{A_{eff}(\xi)} \\ &\cdot\left[P^{\pm}(z,\nu)+P^{\mp}(z,\nu)\right] \mp P^{\pm}(z,\nu)\cdot\sum_{\xi>\nu}\frac{\nu}{\xi}\frac{C_R^0}{2}\cdot\frac{A_0}{A_{eff}(\nu)} \\ &\cdot\left[P^{\pm}(z,\nu)+P^{\mp}(z,\nu)\right] \qquad (1)\end{aligned}$$

where P is the propagating power channels in Watt units, both in forward and backward direction that is indicated by the ± sign in the superscript. z is the length coordinate along the fiber, ν is the frequency of the specific channel that is evaluated. α the background loss of the medium. C_R^0 is the measured Raman gain coefficient efficiency corrected by a scalar multiplication with a value very close to 1 which scalar multiplication can take into consideration the uncertainty of the measurement. We investigate the effect of this multiplication factor later below when we compare the difference between measurements and simulations. A_0 is the effective core area of the fiber at the frequency where the measurement was done. One can see that the Raman gain coefficient efficiency (C_R^0) scales with the ratio of effective core areas at new and original frequencies, enabling calculation of Raman gain at different frequencies. ξ represents the frequency of that channel that influences channel ν.

Other possible method to implement the frequency dependence of the Raman gain along with the measured frequency dependent effective core area is to use the following estimation by Cordina[9)]:

$$C_R(f,\Delta f) = C_R^0(f_0,\Delta f)\cdot\left(\frac{f_0}{f}\right)^{\varepsilon} \qquad (2)$$

Where f_0 is the frequency where the Raman gain coefficient efficiency was measured, f is the frequency that influences other channels depending on the Δf frequency difference. ε is a material dependent coefficient that is for AllWave® fibers, for example, has a fitting value of 2.8.

Boundary values of all signals and pumps are essential for the solution of Eq. (1), forward and backward propagating signals need to have the initial values at the beginning and at the end of the fiber, respectively. Solutions are carried out by a second order Runge-Kutta (RK2) method combined with a matrix formalism that contains all the possible interactions between the propagating channels.

Key part in every Raman amplifier simulation is the handling of backward propagation. We studied several methods[4)-8)] to treat this problem using different estimation techniques to determine the starting values for backward signal channels which was used to integrate the equation in the forward direction. Iteration techniques used to minimize the difference between the boundary conditions and the actual powers at the end of the fiber. Our backward propagation method can be described in five steps which are the followings:

1. Propagation only in the forward direction (all channels, except backward pumps propagate in the forward direction).
2. Use the obtained power values at the end of the fiber for doing now backward propagation including the backward pumps.
3. The result of the backward propagation provides initial values for the backward pumps at z=0 m and use them as starting values for the 1st iteration step.
4. Apply the Nelder-Mead simplex method, to find the exact starting values for the backward pumps after a few iteration steps which provide acceptable error compared to the specified boundary values at z=L.
5. Use the starting values from the previous (4th) step, to make the final propagation with and without amplification to calculate on/off gain.

This method uses the experiences from the above referenced papers combined with our matrix formalism of signal interactions to achieve high accuracy within short computational time.

3. RESULTS

We differentiate two kinds of pumps in these simulations: narrow-linewidth laser diodes, effectively modeled as single-frequency “Dirac delta” functions (c-pumps, or coherent pumps), and broad-spectral pumps modeled by sampling their spectra in several frequency points and their overall spectral distribution is Gaussian (i-pumps, or incoherent pumps). During solver testing, simulated and measured On/Off gains were compared for various pump configurations and signal channels. On/Off gain, the ratio of amplified to unamplified signal powers in decibels, is a common performance metric for Raman amplifiers.

Figure 1 compares simulations and measurements for 2 dBm input signals amplified by a 1423 nm c-pump in an 80 km AllWave fiber with varying pump powers. Excellent agreement is observed. The experiment was repeated using a 1425 nm i-pump (right-hand side of Figure 1). Although the measured spectrum was sampled for the simulation, the correlation between measured and simulated results is good, with discrepancies attributable to inherent uncertainties in Raman gain measurements, as

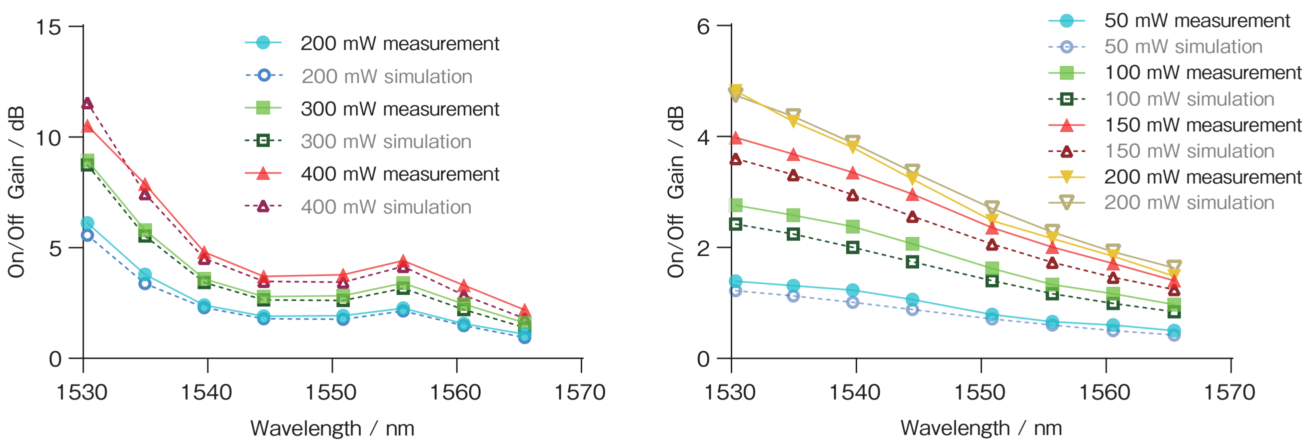

Figure 1　On/Off gain measurement-simulation comparison using c-pump(left) and i-pump(right) with different pumping powers.

discussed later. Still the difference between the measurements and simulations after 80 km of amplification remains well below the 0.4 dB error.

We further explore multi-pump configurations, employing five c-pumps as secondary pumps and four i-pumps as primary pumps to amplify a 47-channel signal across the C and L bands in a 40 km AllWave fiber. Theoretically, secondary Raman pumps amplify the broad-spectrum primary pumps, contributing to a flat gain profile desirable in telecommunication systems. Figure 2 compares measured and simulated On/Off gains for various input signal powers. The results exhibit good agreement, with noticeable discrepancies only at longer wavelengths. The average difference remains always below 0.5 dB. This close match validates the simulation's accuracy, particularly considering inherent uncertainties in Raman gain measurements.

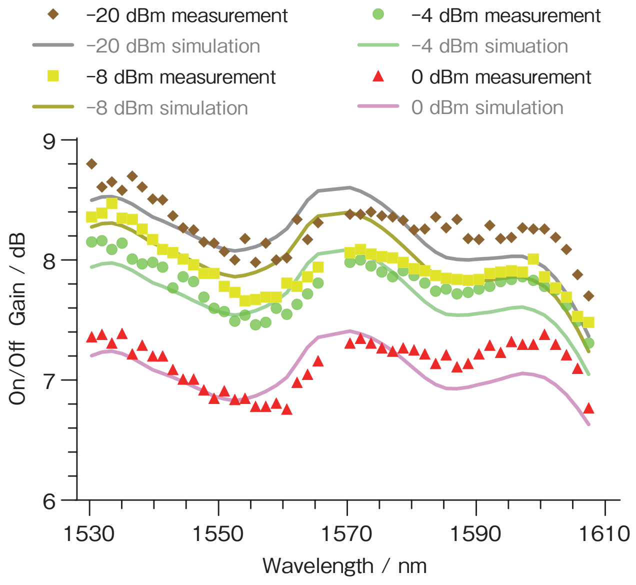

Figure 2　Comparison of measurement and simulation for On/Off gain in multi pump system with different signal input powers.

Accounting for measurement uncertainties in Raman gain coefficients can further enhance accuracy. These uncertainties, typically ranging from 1-3%, can induce deviations in the calculated, stimulated Raman gain values. Interestingly, we observed a tendency for the solver to overestimate gain in certain cases. To address this issue and to obtain better agreement with the measurements, we reduced the Raman gain and recalculated the average difference across various gain efficiencies as shown in Figure 3. As evident in the figure, lowering the gain by 2-3% significantly improves the solver's accuracy, particularly in the low input power regime. At 0.96-0.97 multiplication factor we get average deviations for all input signals that are not exceeding the 0.3 dB average error. This is a promising correction to get even better accuracy, therefore we implemented this correction factor to our code.

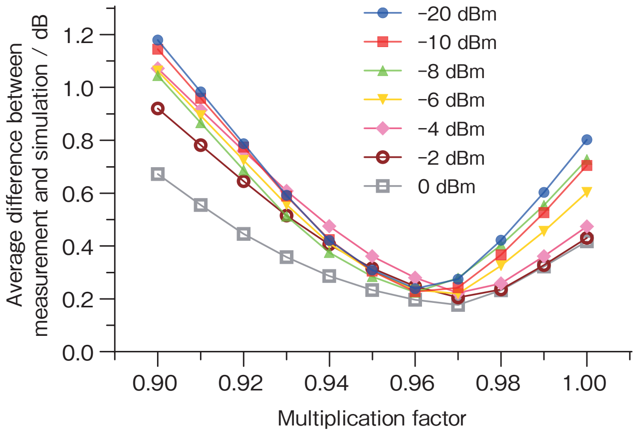

Figure 3　Average difference between the measurements and simulations using a multiplication factor for the measured Raman gain coefficient efficiency data. Calculations are repeated for several input signal values. Minimum deviation from the measurements are at 3% smaller Raman gain values than the original one.

We extensively tested our code's backward pump solving capabilities with diverse configurations and the statistic of the computational time is illustrated in Figure 4. Note, that most of the calculations require 200-1000 steps with the RK2 method for the 40-80 km propagation lengths and the number of the propagating signals including the sampling points of the i-pumps gives more than 200 frequency channels that are propagating simultaneously. Figure 4 encompasses various setups, including 1-6 second-order forward c-pumps, 1-4 first-order forward i-pumps, and fiber lengths ranging from 40 to 80 km. Figure 4 presents the average simulation time for 30-40 different Raman amplifier configurations, along with the 95% confidence interval, indicating the typical range within which most simulations are completed using an average laptop computer Today. This information aids in understanding the code's computational efficiency under different load scenarios.

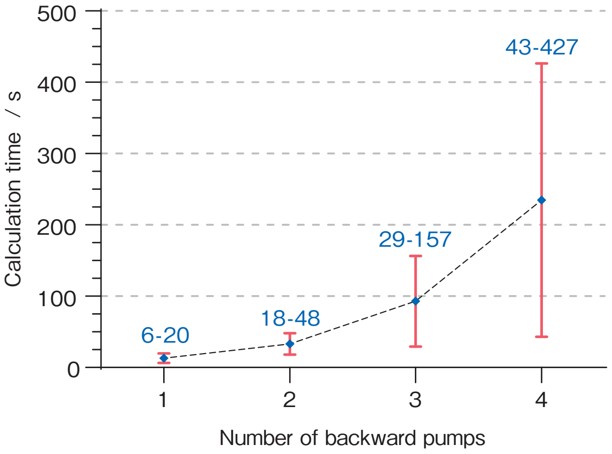

Figure 4 **Average calculation time and 95% confidence interval as functions of the number of backward pumps. Blue numbers are representing the low and upper end values of the confidence interval. Gray dashed line is just for guiding the eyes and emphasizing the exponential growth of the average values.**

4. CONCLUSION

In conclusion, we have presented a modified and efficient numerical scheme for simulating complex Raman amplifiers in optical telecommunication systems. This scheme effectively handles diverse pump configurations, including Raman pumps in both directions and incoherent pumps with broad spectra.

Furthermore, the software incorporates frequency-dependent loss and Raman gain coefficients, along with inter-signal Raman gain, offering a comprehensive simulation environment. By leveraging this scheme, we demonstrated the ability to accurately evaluate signal evolution and achieve flat gain performance for WDM signals using various pump combinations.

The effectiveness of our proposed scheme is underscored by the excellent agreement between our simulations and actual measurements reported in our previous work3). This agreement validates the accuracy and reliability of our tool, establishing it as a valuable resource for researchers and engineers designing and optimizing Raman amplifiers for enhanced performance in practical optical telecommunication systems.

This work opens doors for further exploration of complex pump configurations and optimization algorithms within Raman amplifier design. Our plan to integrate this Raman Amplifier code with FETI's propagation simulator (PropSim)10) will give further opportunities in complex and nonlinear optical design. The ability to achieve high fidelity simulations while maintaining close correlation with experimental results paves the way for significant advancements in optical fiber-based system designs.

* Allwave is a registered trademark or trademark of OFS Fitel, LLC in Japan and other countries.

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