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Invited paper

Integral form expansion of fiber Raman amplifier problem

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Abstract

We propose a novel fiber Raman amplifier (FRA) modeling method based on the expansion of the complicated Raman ordinary differential equation (ODE) into a closed integral/matrix form. By taking the effective length as the interim solution and updating its value along the iteration axis, Raman gain and pump/signal evolution can be calculated with orders of magnitude increase in convergence speed at the equivalent accuracy when compared to the previous approaches based on the direct numerical method for the ODE. Application of this formalism to the problem of (i) gain prediction with a given parameters, (ii) gain spectrum engineering for the search of optimum pump power set under the given constraints, (iii) gain clamping problem for the channel reconfiguration, and (iv) derivation of analytic formula for the faster FRA dynamic control have been addressed.

Keywords: Optical amplifier; Raman; Algorithm; Gain control; Optimization methods; Integral equations

1. Introduction

The fiber Raman amplifier (FRA) has become an indispensable technology with its distinctive advantages—such as flexible gain bandwidth and intrinsically lower noise characteristics [1,2]. For the optimal design of the Raman amplifier/amplified transmission

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systems, various approaches have been proposed for the efficient/accurate modeling of the Raman amplifier [3–6]. Although different in their algorithm details, levels of convergence speed and accuracies, still all these approaches share the common platform of coupled ordinary differential equations (ODE) for the Raman equation set that must be solved along the long length of fiber propagation axis, resulting exhaustive calculation efforts.

In this work, we introduce an alternative, highly efficient modeling method for FRA analysis. By formulating the coupled ODEs for general FRA problem to a closed recursive form based on the integral equation, Raman amplifier is solved along the iteration axis rather than the fiber axis, enabling orders of faster convergence speed at the equivalent accuracy achievable with the previous approaches. With this platform, we show that the traditional FRA problems such as (i) gain prediction with a given parameters, (ii) gain spectrum engineering for the search of optimum pump power set under the given constraints, and (iii) gain clamping under the channel reconfiguration can be treated in a much simpler/faster way.

2. Closed form expansion of Raman equation

To construct such an algorithm/platform stated in the introduction, we treat the Raman gain coefficient as the perturbation factor in the adiabatic process and (1) derive a recursive relation of Raman integral equation, (2) construct a matrix formalism for the efficient calculation of the relations.

2.1. Formulation

Focusing to the conventional, distributed FRA which use long length of transmission fiber as the gain medium, the effect of amplified spontaneous emission (ASE) and Rayleigh scattering can be ignored in good approximation [1,7]. Under these assumptions (which will be justified later), the coupled nonlinear Raman processes between waves in the fiber can be expressed as [7–9]

$$\pm\frac{dP_i}{dz} = -\alpha_i P_i + \sum_{j=1}^{M+N} g_{ji} P_j P_i,$$
$$g_{ji} = \begin{cases} \frac{g_R(\nu_j-\nu_i)}{2A_{\text{eff}}} & \text{when } j \leqslant i, \\ -\left(\frac{\nu_i}{\nu_j}\right)\frac{g_R(\nu_i-\nu_j)}{2A_{\text{eff}}} & \text{when } j > i, \end{cases} \tag{1}$$

where P_i is the power of ith wave, α_i is the attenuation coefficient, $g_R(\Delta\nu)$ is the Raman gain coefficient between waves separated by $\Delta\nu$, A_{eff} is the effective area, M is the number of pumps, and N is the number of signal waves. After dividing Eq. (1) by P_i and integrating over z, we get

$$P_i(z) = P_i(0)\exp\left[\mp\alpha_i z \pm \left(\sum_{j=1}^{M+N} g_{ji}\int_0^z P_j(\zeta)\,d\zeta\right)\right]. \tag{2}$$