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A novel, simple model of cascaded fiber Raman lasers

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ABSTRACT

We present a simple numerical method for modeling an *n*th-order cascaded continuous wave fiber Raman laser. The novelty of this model is the method by which power is transferred between waves, which provides simplicity without the need for any approximations of the equations related to laser dynamics, or simplification of the experimental arrangement. It was found that the results based on the proposed method matches exactly with the results based on established techniques available in the literature.

1. Introduction

Lasers in the mid-IR spectral band are becoming increasingly popular for their applications in trace gas sensing, spectroscopy and medicine [1, 2]. Raman fiber lasers (RFLs), which are based on stimulated Raman scattering (SRS) effects in optical fibers, enable one to produce a laser at any desired wavelength [3–7]. In order to develop a RFL, it is important to know several design parameters, including the length and nonlinear properties of the Raman gain fiber, as well as the reflectivity of the reflectors. In general, a continuous wave (CW) cascaded RFL is described by a system of coupled differential equations [8,9]. There are a number of techniques and software packages available in order to solve the differential equations. It is always challenging to obtain a solution without any simplifying assumptions or a good guess values, and in some cases the computation becomes very cumbersome with increased number of Stokes orders [10–12].

In this article we proposed and demonstrated a simple technique to obtain optimum parameters required in developing a fiber Raman laser using a finite difference method, considering the interaction between forward and backward propagating waves. The proposed technique was able to produce results reported in the literature by AuYeung and Yariv, [13] Thielen et al., [14] and Rini et al. [15]. We also presented theoretical results for a cascaded RFL, where the optimal laser parameters were determined using the proposed technique.

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2. Numerical model

The pump and Stokes waves in an optical fiber evolve according to equations given below [13]

$$\frac{dP_S}{dz} = G\,P_S P_P - \alpha_S P_S$$
$$\frac{dP_P}{dz} = -\frac{\omega_P}{\omega_S} G P_S P_P - \alpha_P P_P \tag{1}$$

where $G = g_R/A_{eff}$ (g_R=Raman gain coefficient and A_{eff} is the effective core area), P_S (P_P), ω_S (ω_P), and α_s (α_p) are power, frequency and linear absorption coefficient for Stokes (pump) wave. Further, the total number of photons (Eq. (2)) remains constant during the SRS process [16]

$$\frac{d}{dz}\left[\frac{P_P}{\omega_P} + \frac{P_S}{\omega_S}\right]_{SRS} = 0 \tag{2}$$

Fig. 1 shows a Raman fiber laser (RFL), which was formed using fiber Bragg gratings. RFLs are described by a first-order system of nonlinear two-point boundary value ordinary differential equations [8]. In the proposed technique, the resonant cavity was divided into N number of sections, as shown in Fig. 2 [14]. The power carried by each wave (forward and backward propagating Stokes and pump) is represented by a one-dimensional array. The individual array elements are denoted as $P_i^{\pm}(k, t)$, where i denotes the Stokes (S) or pump (P) wave, k is the spatial position (ranging from 0 to $N-1$), $\pm$ denotes forwards/backwards propagation directions, and t is the number iteration. The progression in time is

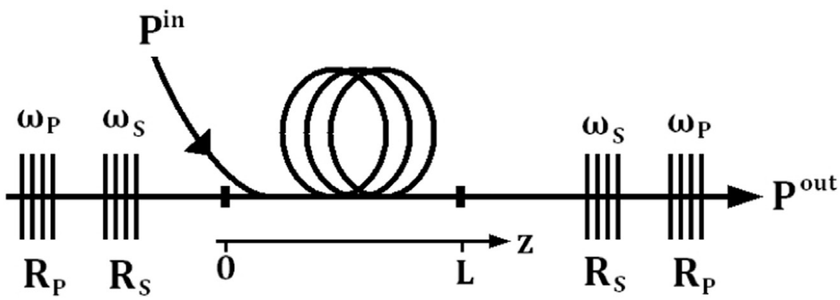

Fig. 1. Setup of a Raman fiber laser.

achieved by allowing the power to flow into neighboring elements, which corresponds to a length given as

$$\Delta z = \frac{L}{N-1} \tag{3}$$

where Δz is considered to be a positive quantity regardless of direction of propagation. The spatial index (k) increases for forward-propagating, and decreases for backward-propagating waves. The solution of the pump wave (Eq. (1)) for a small value of Δz (for which the change in power is also small) is given as

$$P_P^{\pm}(k \pm 1, t+1) = P_P^{\pm}(k, t) \times \exp\left\{\left[-\frac{\omega_P}{\omega_S} G\left[P_S^{+}(k, t) + P_S^{-}(k, t)\right] - \alpha_P\right]\Delta z\right\} \tag{4}$$

Typically, a similar exponential solution is assumed for the progression and growth of the Stokes wave [8]; however, this was found to produce solutions which violated the conservation of photon number (Eq. (2)) if implemented directly in numerical simulations. In general, established methods require complex numerical algorithms [17, 18] and/or dedicated problem solving packages. In order to rectify this, we rearranged Eqs. (1) and (2), and obtain Eqs. (5) and (6), the simplified form for the exchange of power between various waves.

$$\left(\Delta P_S^{+} + \Delta P_S^{-}\right)_{SRS} = -\frac{\omega_S}{\omega_P}\left(\Delta P_P^{+} + \Delta P_P^{-}\right)_{SRS} \tag{5}$$

and

$$\left(\Delta P_S^{+}\right)_{SRS} = \frac{P_S^{+}}{P_S^{+} + P_S^{-}}\left(\Delta P_S^{+} + \Delta P_S^{-}\right)_{SRS} \tag{6}$$

Eq. (5) relates the amount of power gained by the Stokes waves to the depleted pump power, and Eq. (6) shows how this power is distributed between the forward and backward propagating waves. Within a given cell, the power depleted from the pump wave is calculated according to Eq. (4), and is transferred to the Stokes wave according to Eq. (5). A new array is then required which determines how this power from the pump is distributed between the forward and backwards Stokes wave components according to Eq. (6). The new array is called the power coupling index, and is denoted by B_S (k, t). The expression for the power coupling index after the introduction of weighted time averaging, which ensures convergence of the solution, is given as

$$B_S(k, t) = \frac{\left[\Delta P_S^{+}(k, t)\right]_{SRS}}{\left[\Delta P_S^{+}(k, t) + \Delta P_S^{-}(k, t)\right]_{SRS}} = \frac{\sum_{j=0}^{t}(0.97)^j P_S^{+}(k, t-j)}{\sum_{j=0}^{t}(0.97)^j\left[P_S^{+}(k, t-j) + P_S^{-}(k, t-j)\right]} \tag{7}$$

The $(0.97)^j$ term serves to give greater weight to recent iterations in order to dampen self-reinforcing oscillations between forward and backward Stokes waves. The specific value of 0.97 was found using a brute-force search to provide the fastest convergence in a wide variety of simulations, regardless of boundary or initial conditions.

Using Eq. (7), we obtain expressions (Eqs. (8) and (9)) for the growth of the forward and backward propagating Stokes waves.

$$P_S^{+}(k+1, t+1) = P_S^{+}(k, t)\exp(-\alpha_S \Delta z) + \frac{\omega_S}{\omega_P} B_S(k, t)\left[P_P^{+}(k, t) + P_P^{-}(k, t)\right] \left\{1 - \exp\left[-\frac{\omega_P}{\omega_S} G\left[P_S^{+}(k, t) + P_S^{-}(k, t)\right]\Delta z\right]\right\} \tag{8}$$

$$P_S^{-}(k-1, t+1) = P_S^{-}(k, t)\exp(-\alpha_S \Delta z) + \frac{\omega_S}{\omega_P}\left[1 - B_S(k, t)\right]\left[P_P^{+}(k, t) + P_P^{-}(k, t)\right] \left\{1 - \exp\left[-\frac{\omega_P}{\omega_S} G\left[P_S^{+}(k, t) + P_S^{-}(k, t)\right]\Delta z\right]\right\} \tag{9}$$

In order to run the simulation, a minimum value of Stokes power was maintained in each cell, which acts as the seed. In absence of the seed, the pump will propagate without generating any Stokes power, depleted only by linear absorption. Special consideration must be taken in implementing the boundary conditions at the first and last elements, which are related to the reflectivity of the Bragg gratings and the input pump power (Fig. 2). The input and output Bragg gratings can be considered as the

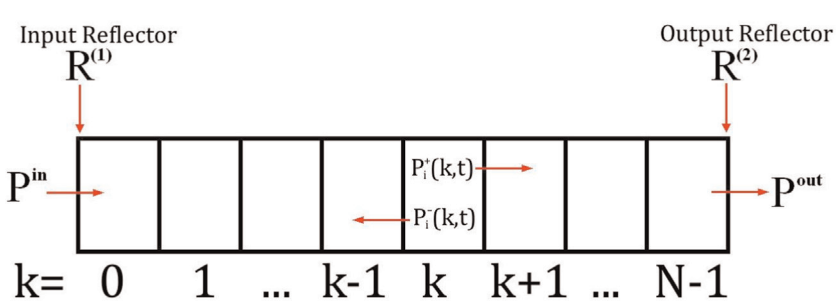

Fig. 2. Laser cavity with N number of sections of length Δz.