Optimal Design of Flat-Gain Wide-Band Fiber Raman Amplifiers
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Abstract—We present a novel method for designing multiwavelength pumped fiber Raman amplifiers with optimal gain flatness and gain-bandwidth performance. We show that by solving the inverse amplifier design problem, relative gain flatness well below 1% can be achieved over bandwidths of up to 12 THz without any gain equalization devices. This constitutes a substantial improvement in gain flatness compared to the existing wide-band optical fiber amplifiers.

Index Terms—Optical crosstalk, optical fiber amplifiers, optical fiber communication, optical fiber losses, optical fiber theory, Raman scattering.

I. INTRODUCTION

Because the gain bandwidth of erbium-doped fiber amplifiers (EDFA) is much narrower than the low loss window of standard optical communication fibers, there is growing interest in wideband flat-gain optical fiber amplifiers (OFAs) to exploit more of the available fiber bandwidth and increase the capacity of wavelength division multiplexing (WDM) systems [1], [2]. Gain bandwidths in excess of 10 THz (approximately 80 nm) have been demonstrated using either hybrid fiber amplifiers [3]–[5] or fiber Raman amplifiers pumped at multiple wavelengths (MW-FRA) [6]–[10]. However, all of these amplifiers, especially those with larger bandwidths, have a serious drawback of poor gain flatness. Among the demonstrated OFAs with bandwidth exceeding 60 nm, the relative flatness lies within the 15%–30% range [4]–[9], which can be reduced to the 4%–10% range by the use of gain equalizers [10], [11].

In the case of Raman amplifiers with multiple pumps, the gain profile can be adjusted by appropriately choosing the relative positions and powers of the pump waves. In principle, this can allow for the design of amplifiers with any required gain spectra, e.g., the ones that would provide flat net gain. However, the corresponding inverse MW-FRA design problem has not been effectively solved (to the best of our knowledge). One of the main difficulties is that pump-to-pump and pump-to-signal stimulated Raman scattering, and wavelength-dependent linear attenuation experienced by both pump and signal waves. In steady state, this system is described by the following set of coupled nonlinear equations:

$$\frac{dP_k(z)}{dz} = -\alpha_k P_k + \sum_{j=1}^{k-1} \frac{g_{kj}(\nu_j - \nu_k)}{K_{\text{eff}} A_{\text{eff}}} P_j P_k - \sum_{j=k+1}^{m+n} \frac{\nu_j g_{kj}(\nu_k - \nu_j)}{K_{\text{eff}} A_{\text{eff}}} P_j P_k, \quad k = 1, 2, \ldots, n+m. \quad (1)$$

Here, the frequencies are numerated in decreasing order ($\nu_i > \nu_j$ for $i < j$). indexes $k = 1, \ldots, n$ correspond to the backward-propagating pump waves (the minus sign on the left hand side) and indexes $k = n+1, \ldots, n+m$ correspond to the forward-propagating signal waves (plus sign on the left hand side). Here, the values $P_k$, $\nu_k$, and $\alpha_k$ describe, respectively, the power, frequency, and attenuation coefficient for the $k$th wave.

In this paper, we propose an efficient automatic method to solve the inverse amplifier design problem, which makes it possible to design multiwavelength pumped Raman amplifiers with gain flatness close to the optimum. Given amplifier specifications such as the signal level, required gain profile, and number of allowed pump channels, this method generates a combination of pump wavelengths and input powers that would result in the gain profile approximating the specified one as closely as possible. Optimizing the input pump spectrum by solving this inverse problem allows for a drastic improvement in the relative gain flatness compared to unoptimized MW-FRA designs [7]–[12].

II. AMPLIFIER MODEL AND DESIGN METHOD

Wave propagation in the backward-pumped multipump Raman amplifier is characterized by a large number of effects [12], the most important of which, for the purposes of the present consideration, are pump-to-pump and pump-to-signal stimulated Raman scattering, and wavelength-dependent linear attenuation experienced by both pump and signal waves. In steady state, this system is described by the following set of coupled nonlinear equations:

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Manuscript received April 18, 2001; revised October 25, 2001.

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Publisher Item Identifier S 0733–8724/02$17.00 © 2002 IEEE
The amplification factor for every signal channel \( k = n + 1, n + 2, \ldots, n + m \) can be expressed in terms of the power integrals \( I_j \equiv \int_0^L P_j(z) \, dz, \, j = 1, 2, \ldots, n + m \) as

\[
G_k = \frac{P_k(L)}{P_k(0)} = \exp \left( -\alpha_k L + \sum_{j=n+1}^{n+m} g_{j,k} I_j \right) \exp \left( \sum_{j=1}^{n} g_{j,k} I_j \right)
\]

\[
=G_{L,k} G_{G,k}
\]

(2)

where \( g_{j,k} = g_{j,k}(\nu_j - \nu_k)/K_{S,eff}A_{eff} \) for \( \nu_j > \nu_k \) and \( g_{j,k} = -g_{j,k}(\nu_k - \nu_j)/K_{S,eff}A_{eff} \) for \( \nu_j < \nu_k \). The first exponential term in (2), \( G_{L,k} \), represents the effects of fiber attenuation and signal-to-signal Raman scattering (Raman tilt), whereas the second term, \( G_{G,k} \), describes the ON–OFF or gross (pump-to-signal) Raman gain experienced by the channel \( k \). Assuming the terms \( G_{L,k} \) are known, the complex inverse problem finding the pump combination that yields the flattest net gain profile breaks into two simpler problems to be solved one after the other. The first problem is to find such a set of frequencies \( \nu_j \) and constants \( I_j^* \), so that the sum \( \sum_{j=1}^{n} g_{j,k} I_j^* \) is close to \( \log G_{L,k}^{-1} \) for all of the frequencies \( \nu_k \) within the specified gain band. The second problem is to find such a set of input pump powers \( P_{j,0} \) for these frequencies, so that the solutions \( P_j(z) \) of (1) with the initial conditions \( P_{j,0} \) have the integrals \( I_j \) exactly equal to the optimal values \( I_j^* \). We refer to the set of \( I_j^* \) as the integral pump spectrum.

The proposed design algorithm takes the Raman gain spectrum \( g_{R}(\Delta \nu) \) and the attenuation spectrum \( \alpha(\nu) \) of the fiber as the given \( a \, p \, i \, o \, r \) characteristics (see Fig. 1). Also, one should specify the amplifier length \( L \), the input signal level \( P_{0,s} \), the wavelength range for signal and for pump waves, and the number of signal and pump channels \( m \) and \( n \), respectively.

In the first stage of the method, one out of all possible sets of \( n \) pairs \( \{\nu_j, I_j^*\} \) is chosen to minimize the relative gain flatness parameter, defined as the difference (in decibels) between the maximal and the minimal gains \( \log G_{G,k}^{-1} \) normalized by their target values \( \log G_{L,k}^{-1} \) as

\[
F_{rel} = \left[ \frac{\log G_{G,k}^{-1}}{\log G_{L,k}^{-1}} \right]_{\max} - \left[ \frac{\log G_{G,k}^{-1}}{\log G_{L,k}^{-1}} \right]_{\min} \cdot 100\%.
\]

In order to find the best integral pumping spectrum \( \{\nu_j, I_j^*\}_{j=1}^{n} \), we apply a genetic algorithm in a \( 2n \)-dimensional object space [13]. Starting with a randomly chosen large set (population) of \( n \)-component pump spectra \( \{\nu_j, I_j^*\}_{j=1}^{n} \), we iteratively apply the three evolution procedures (crossover, mutation, and natural selection) until the population fitness level stops improving, and the best (fittest) individual is chosen as the final pump spectrum. The fitness parameter (i.e., the parameter to be evolutionarily optimized) of an individual (spectrum \( \{\nu_j, I_j^*\}_{j=1}^{n} \)) is the corresponding relative gain flatness (3). On each iteration step (generation), a fixed number of the fittest individuals is chosen (natural selection); among them, couples are formed with their parameters mixed (crossover with discrete recombination) to create the next generation. Mutation is implemented by small random changes in one or more of \( 2n \) parameters of each individual. Note that because the integral pump spectrum \( \{\nu_j, I_j^*\}_{j=1}^{n} \) is being sought, the flatness computation does not require the time-consuming solution of (1), which enables the use of large enough population sizes. Consistency in the results shows that, for a reasonable number of pumps (\( n < 20 \)), the optimal or nearly optimal integral pump spectrum can always be found.

At the second stage of the design procedure, we fix the optimal frequencies obtained in the first stage and search for the optimal input pump powers \( P_{j,0} \). To do this, we apply an iterative algorithm. Starting with some reasonable initial guess, which allocates relatively more power to the higher-frequency pump channels to compensate for pump-to-pump Raman interactions, we solve (1), compare the resulting pump power integrals \( I_j \) to the optimal values \( I_j^* \), and adjust the input powers \( P_{j,0} \) appropriately. The difficulty here is that, because of the highly nonlinear nature of the system (1), the increase in the input power for some pump channel \( j \) may not lead to an increase in the corresponding integral \( I_j \). Nevertheless, we found it quite straightforward to adjust the iteration procedure so that it converges to the desired distribution. For any reasonable integral spectrum target \( \{\nu_j, I_j^*\}_{j=1}^{n} \), we were able to obtain the input spectrum \( \{\nu_j, P_{j,0}\}_{j=1}^{n} \) so that the resulting integral spectrum \( \{\nu_j, I_j\}_{j=1}^{n} \) matches the target with any given precision.

To conclude the description of this design algorithm, we have to resolve one remaining subtlety. Each iteration of the second stage requires the solution of (1), which could be efficiently implemented numerically by any marching method (e.g., Runge–Kutta), if the boundary conditions were all assigned at one point. However, in the case of backward pumping, the input pump powers are assigned at \( z = L \) while the input signal powers are given at \( z = 0 \), which seriously complicates the numerical problem. We surmount this difficulty by assigning the boundary conditions for the signal powers at \( z = L \) using...
Fig. 2. Optimization results for 10 THz (83 nm) system with pump channels (left, central, and right columns, respectively). (a)–(c) optimal integral pump spectra. (d)–(f) optimal input pump spectra. (g)–(i) the corresponding gross gain (dashed lines), fiber attenuation (dash-dotted lines), and net gain profiles (solid lines). Vertical dotted lines indicate the band occupied by the signal channels.

(2) with the integral pump spectrum selected at the first stage of the method, \( P(L) = P(0)G_{L,k} \exp(\sum_{j=1}^{n} \delta_{jk}) \). This approach, which makes the proposed method fast and efficient, is valid only if the iterations converge to the target with high precision. Fortunately, this is always the case for the algorithm in question. In fact, this approach makes the numerical solution of the difficult inverse problem for backward-pumped MW-FRA (finding the input pump spectrum which would provide the specified gain profile) almost as fast as the numerical solution of the simpler direct problem (finding the gain, given the input pump spectrum).

It is important to notice that although the choice of pumps \( \{\nu_j, P_{j0}\}_{j=1}^{m} \) depends on the terms \( G_{L,k} \) in (2), these terms contain the signal power integrals \( I_j \) and, thus, depend on the pumping spectrum. Therefore, the MW-FRA design problem must be solved self-consistently. This difficulty can be overcome by iterating the procedure described here, starting with the signal power integrals computed in the absence of any pumping and updating them after each (outer) iteration step using the new values \( \{\nu_j, P_{j0}\}_{j=1}^{m} \). Normally, these outer iterations converge very quickly (after three or four steps), because the effect of Raman tilt is negligible, and the terms \( G_{L,k} \) are simply the linear attenuation factors. The pump frequencies are chosen from the grid with 100-GHz spacing, which provides sufficient spectral resolution because the features of the Raman gain spectrum are substantially broader than 100 GHz.

The optimal pumping spectra and the corresponding Raman gain profiles are shown in Fig. 2. The ON–OFF (gross) Raman gain profile approaches the fiber attenuation profile resulting in flat net gain profile around 0 dB. The gain flatness improves dramatically with increase in the allowed number of pump channels and reaches the value of 0.83% for 16 pump channels. This corresponds to a signal power deviation of less than 0.05 dB from its initial value after propagation through a 50-km-long fiber span (for all of the channels). As an example, we consider a 10-THz WDM system pumped at \( n = 4, 8, \) or 16 wavelengths. There are \( m = 100 \) signal channels with 100-GHz spacing. We take the input signal level at \(-3\) dBm/ch, and assume that the effect of Raman tilt is negligible, and the terms \( G_{L,k} \) are simply the linear attenuation factors. The pump frequencies are chosen from the grid with 100-GHz spacing, which provides sufficient spectral resolution because the features of the Raman gain spectrum are substantially broader than 100 GHz.

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III. NUMERICAL EXAMPLE

We have applied the proposed method to design optimal flat-gain wide-bandwidth multiwavelength pumped Raman amplifiers operating in the 1500-nm region in standard single-mode silica fibers (\( A_{\text{eff}} = 50 \) \( \mu \text{m}^2 \)) with the Raman gain and attenuation spectra shown in Fig. 1. We fix the amplifier (or fiber span) length at a practical value of \( L = 50 \) km and the required net gain at \( G = 0 \) dB (the corresponding gross gain is \( \sim 10–13 \) dB for different channels). As an example, we consider a 10-THz WDM system pumped at \( n = 4, 8, \) or 16 wavelengths. There are \( m = 100 \) signal channels with 100-GHz spacing. We take the input signal level at \(-3\) dBm/ch, and assume that the effect of Raman tilt is negligible, and the terms \( G_{L,k} \) are simply the linear attenuation factors. The pump frequencies are chosen from the grid with 100-GHz spacing, which provides sufficient spectral resolution because the features of the Raman gain spectrum are substantially broader than 100 GHz.

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The total required pump power does not depend on the number of pump waves and is approximately 530 mW in this example.
Fig. 3. Evolution of (a) pump and (b) signal powers upon propagation through the amplifier for $n = 16$. Data from the simulation of Fig. 2(c), (f), and (i).

IV. DISCUSSION

The proposed method makes it possible to design multiwavelength pumped Raman amplifiers with the best possible (or very close to that) gain flatness within the specified constraints, such as the number of pump waves and the gain bandwidth. The capabilities of method in terms of achieving flat-gain wideband amplifiers are summarized in Fig. 4, which shows the best possible relative flatness [defined in (3)] as a function of the number of pump channels $n$ for three different values of required gain bandwidth. Quite understandably, the achievable flatness degrades with the increase in the bandwidth and improves (faster than $1/n$) with the increase in the number of pump channels $n$. Also shown in Fig. 4 (open dots) are the flatness results for wideband Raman amplifiers without gain equalization, as reported in the literature (from [3]–[12]). Clearly, the relative flatness achievable by the proposed method is much better (with the other parameters kept equal) than that in the previously published results. In fact, optimal design with a sufficiently large number of pump waves provides better flatness than that reported even for amplifiers with gain-equalizing filters, which can make the latter completely unnecessary. Obviously, this is a promising approach to gain-flattening, since no signal power is wasted for filtering, and, ultimately, the efficiency and noise performance of the optically amplified system are improved.

As the example in Section III shows, the proposed method makes it possible to design MW-FRAs not only with flat gain but with any reasonably smooth gain profile to compensate for propagation effects such as wavelength-dependent fiber loss and signal-to-signal Raman scattering. The latter is particularly important for the long-haul transmission of a wideband signal [14]. It is important to notice that the achievable gain flatness depends on this profile; it improves for the concave and degrades for the convex on/off gain profiles (such as in Fig. 2). This is because the single-pump Raman gain spectrum (Fig. 1) is concave (except for a few small peaks), making it easier to generate concave composite profiles. The flatness results of Fig. 4 assume an intermediate case—flat gain profile—in order to be consistent with other publications.

In conclusion, we have proposed an efficient method of designing flat-net-gain wideband multiwavelength pumped fiber Raman amplifiers. The main feature of this method is that the inverse amplifier design problem is broken into two simpler inverse problems that are solved separately and, hence, efficiently. Compared to the previously published results, this method allows for substantial improvement, approaching the theoretical limits for gain flatness-bandwidth performance of fiber Raman amplifiers.

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