Theoretical Optimum Designation of Distributed

Raman Amplifiers in Different Media

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Abstract: - Raman Amplifiers (RAs) are a group of amplifiers which have various applications in optical communications. Data transmission media utilized for RAs are optical fibers operating in nonlinear regime. We present the performances and characteristics of RAs by utilizing a set of coupled differential equations and numerical simulations. Two types of fibers with different gain characteristics, germanium-doped and silica fibers are used in our numerical simulations. So, the optimum initial values of the pump powers for a system with 10 pumps are recalculated and optimized again. We did our simulation to have a flat gain and low noise characteristics. Another aspect of the fiber media is their effective areas and we studied the effects of this parameter on the net gain of the RAs. Finally, the noise figure computations are discussed for our 10 pumps bidirectional amplifier which is optimized.

Key-Words: - Raman amplifiers, Noise figure, Nonlinear gain, Numerical simulation, Optimization

1 Introduction

Multi-wavelength pumped Raman amplifiers (RAs) have attracted more and more attention in recent years [1]. In this type of amplification a widely used concept, for high capacity long distance wavelength division multiplexing (WDM) transmission systems was used. They have been already used in many ultra long-haul dense WDM (DWDM) transmission systems [2]. It supports high bit rate data transmission over long fiber spans, due to its benefits such as proper gain and optical signal-to-noise ratio (OSNR) [3]. In addition, it can be used for increasing the bandwidth of Erbiumdoped fiber amplifiers (EDFAs) in hybrid systems [4]. Another important feature of RAs is its gain bandwidth, which is determined by pump wavelength. Multi-wavelength pumping scheme is usually used to increase the gain flattening and bandwidth for high capacity WDM transmission systems. In backward-pumped fiber Raman amplifiers, other noise sources, such as the relativeintensity noise (RIN) transfer are minimized [5], because this scheme can suppress the related signal power fluctuation. Of course, the reported results in the literatures show the OSNR of this excitation is tilted, and channels with longer wavelength have longer OSNR respect to the shorter wavelength channels [6].

These amplifiers also have the unique characteristic of being tuneable at any wavelength, simply by changing the pump frequency, since gain depends only on the signal-pump frequency shift [7]. The saturation power of fiber Raman amplifiers is by far larger than that of the equivalent EDFAs, thus, limit the effects of cross-gain modulation in reconfigurable DWDM systems. Due to these reasons, Raman amplifiers are widely used in the fiber optical communication systems. Indeed, attention has been focused on RAs because of the availability of high-power compact pump lasers [8], their superior performance, such as ultra-wide bandwidth, low noise and suppressed nonlinearity performances in transmission systems, and lower noise figure. The performance of a RA depends on the characteristics of fiber gain. So, to design appropriate fibers, it is useful to predict the fiber properties. In silica-optical fibers, Ramanamplification band extends over a few terahertzes, and it can be further broadened by multiple pumping schemes [5] and [7]. There are many methods to design a multistage gain flattened fiber RAs using multi-wavelength pumping scheme (for example in [9]). Using equally spaced pumps with a fixed central pump wavelength we can analyze the amount of the gain flatness of multi-wavelength pumped fiber RA [10]. The gain spectrum of such systems has a lower ripple and good OSNR. In another scheme, W-type fibers are used for gain flattening with a simple system which has good noise performances [11]. In this technique a fiber is used so its leakage loss spectral variations are optimized similar to the variations of Raman gain spectrum. Other methods for optimizing the noise and having a flatten gain spectrum use multi-pump techniques [12]-[14], which used a few pumps to increase the bandwidth.

In this paper, we present the mathematical formulation of RAs at first. After that, two different types of fibers such as germanium-doped and silica fibers, to have Raman gain, are discussed. In the third section a designed structure are simulated and corrected when a 10 pump Raman amplifier with optimum noise figure and optimum gain spectrum is used. A brief summery is given in last Section.

2 Mathematical Formulations

Theoretically the response of optical fibers to light becomes nonlinear when an intense electromagnetic field excites the fiber. Propagation of these electromagnetic fields in an optical fiber contains a scattering mechanism [15]-[16]. If the frequency (or energy) of scattered light remains unchanged, the type of scattering called elastic scattering, such as Rayleigh scattering. On the other hand, when the frequency of the scattered light is shifted, an *inelastic* scattering mechanism is occurred. Raman scattering is an example of this phenomenon. In an optical fiber, the pump wave photons are scattered by the silica molecules and this means a scattering of a photon to a lower energy photon, such that the energy difference appears in the form of a phonon. We entitled these phonons 'Optical Phonons'. The result of this process is a loss of power at incident frequency. The scattering cross section at low power levels is negligible, but at high power levels the nonlinear occurrence of stimulated Raman scattering becomes important. If the incident power exceeds a threshold value the scattered light intensity grows exponentially. In fact, similar to the laser process, the Raman scattering mechanism becomes stimulated if the pump power exceeds this threshold value. During the scattering, some pump photons give up their energy to create other photons of reduced energy at a lower frequency. The energy difference is absorbed by the fiber molecules, which end up in an excited vibrational state. This energy transfer from pump to excited signal is signal amplification.

The basic structure of a RA is shown in Fig. 1(a) and its energy level diagram is plotted in Fig. 1(b). The gain medium is a single mode fiber and the pump powers are injected to the fiber using the couplers with forward and backward wave propagations. In this (usually silica) fiber, stimulated Raman scattering is occurred and a strong pump laser provides excess gain for signals which are at shorter and longer wavelengths, respectively.

Physically, there is a beating between the pump and the forward and backward scattered light which creates a component at the beat frequency.



Fig. 1 (a) Schematic of a Raman amplifier system, (b) Energy band diagram of process

The analysis and simulation of fiber Raman will be emit amplifiers are based on a set of coupled differential numerical ap

equations. These equations include the physical effects such as the spontaneous Raman emission, its temperature dependence, Rayleigh scattering, amplified spontaneous emission (ASE), spontaneous Raman scattering, higher-order Stokes generation, and arbitrary interaction between an arbitrary number of pumps and signals.

Pump sources of these amplifiers are usually semiconductor or Raman fiber lasers. In the steady state, the coupled differential equations in fiber Raman amplifiers can be described as the following equations [17]-[21]:

$$\pm \frac{dP_{k}}{dz} = -\alpha_{k}P_{k} + \sum_{j=1}^{n_{k}+n_{p}} g_{i,j}P_{j}P_{k}$$
(1a)

$$\pm \frac{dP_{ASE,k}}{dz} = -\alpha_k P_{ASE,k} +$$

$$\sum_{j=l}^{n_s+n_p} g_{jk} P_j \left(P_{ASE,k} + h v_k \varDelta v F_{jk} \right)$$
(1b)

$$-\frac{dP_{SRB,k}}{dz} = -\alpha_k P_{SRB,k} + \sum_{j=1}^{n_s+n_p} g_{jk} P_j P_{SRB,k} + KP_k$$
(1c)

$$\frac{dP_{DRB,k}}{dz} = -\alpha_k P_{DRB,k} + \sum_{j=1}^{n_s+n_p} g_{jk} P_j P_{DRB,k} + K P_{SRB,k}$$
(1d)

In these relations, n_p are the number of pump waves and n_s is the number of signal channels.

The values P_l , v_l and α_l (l=j or k) describe the power, the frequency, and the total attenuation coefficient for the *j*-th and *k*-th wave respectively, where the subscripts $j=1, 2, \ldots, n_p+n_s$ and $k=1, 2, \ldots, n_s$.

The quantities $P_{ASE,k}$ and $P_{SRB,k}$ are the powers corresponding to amplified spontaneous emission (ASE) noise, single Rayleigh backscattering (SRB), and double Rayleigh backscattering (DRB), respectively and *K* is the Rayleigh backscattering coefficient.

ASE is the principle noise source in these amplifiers. Generated photons are emitted spontaneously in all directions and some of them will be emitted in the direction that fall within the numerical aperture of the fiber, and hence captured and guided by fiber. The captured photons are amplified and ASE is formed. It is emitted in both forward and backward directions, but only the forward term is in a direct concern to system and can degrade its performance. The backward term can reduce the medium gain too.

Rayleigh scattering is a fundamental loss mechanism in optical fibers. During the fiber fabrication, there are density fluctuations which can lead to a disturbance in the refractive index of the fiber. Such fluctuations are on a scale smaller than the optical wavelength and can cause light scattering called Rayleigh scattering [22].

The gain coefficient, g_{jk} , describes the power transferred by the stimulated Raman backscattering between *jth* and *kth* waves and is given by [23]-[24]:

$$g_{jk} = \left(1 / 2A_{eff}\right)g_{j}\left(v_{j} - v_{k}\right) \quad \text{for} \quad v_{j} > v_{k}$$
(2)

and

$$g_{jk} = -\left(1/2A_{eff}\left(v_k - v_j\right)g_j\left(v_j - v_k\right) \text{ for } v_j < v_k$$
(3)

where $g_i(\Delta v)$ is the Raman gain spectrum measured (with an unpolarized source) respect to the pump frequency v_i , shown typically in Fig. (corresponding to the core of the fiber) for four types of fibers [24]. It can be measured for a given fiber index profile and pump wavelength. All of them have a peak at a determined frequency. For silica fiber and germanium-doped fiber this factor is plotted in Fig. 3 [20]. In fact inside the silica fibers there are other nonlinear mechanisms that can provide gain such as parametric gain resulting from four-wave mixing (FWM) [16]. In these fiber amplifiers (parametric amplifiers) it is possible to have gain bandwidth more than 100nm. The relationship between the pumping power and the amount of the fiber nonlinearity may be in the reverse direction.

Another factor in the above equations, A_{eff} is the fiber effective area defined as:

$$A_{eff} = 2\pi \frac{\int \psi_p^2 r dr \int \psi_s^2 r dr}{\int \psi_p^2 \psi_s^2 r dr}$$
(4)

0.5

0.4

0.3

0.2

0.1

0.8

0.6





Fig. 2 Typical predicted (solid) and measured (dashed) Raman gain coefficient for four types of fibers, (a) silica fibers, (b) true wave reduced slop transmission fibers, (c) dispersion compensated fibers (DCFs) and (d) Raman gain fibers [24]



Fig. 3 Gain spectrum of different types of fiber versus wavelength [20]

In the previous equation, ψ_p^2 and ψ_s^2 are the distribution of modal fields, in the radius direction, at pump and signal wavelengths, respectively [23]. This factor determines how tightly an optical mode is confined to the core and the smaller values of A_{eff} , means the stronger nonlinear effects through the fiber [15]-[16].

This parameter can be described by a simple relation in the form of [15]:

$$A_{eff} \approx \pi w^2 \tag{5}$$

where w is the *spot size* [15] of beam. w is called *field radius* too. In fact the field distribution can be described by a set of Bessel's functions (n-th order first and second kind) and since its calculations are cumbersome in practice, it is approximated by a Gaussian distribution.

The temperature dependent term contributing to ASE noise is given by:

$$F_{jk} = N_{phot} + 1 \qquad \text{for} \qquad v_j > v_k \tag{6}$$

$$F_{jk} = N_{phot}$$
 for $v_j < v_k$ (7)

where

$$N_{phot} = \left[\exp(h | v_j - v_k | / k_B T) - 1 \right]^{-1}$$
(8)

Here, the parameter *T*, k_{B} , and *h* are the temperature of the system, the Boltzmann's constant and the Plank's constant, respectively.

For a fiber with length L, the boundary conditions

(to solve the equations) are defined at z=0 for a signal waves $P_k(0)=P_{k0}(k=1,2,...,n_s)$, and at z=L for the backward-propagating pump waves $P_k(L)=P_{k0}(k=n_s+1, n_s+2,..., n_s+n_p)$. In equations (1), the \pm sign denote the forward and backward waves.

3 Simulation Results

For solving Raman amplifier equations, the numerical method is used and then the results are discussed for two types of fibers such as silica fibers and germanium-doped fibers. As mentioned, it is possible to improve the output OSNR of a feedback pumped RA using forward or bidirectionally pumping scheme. Because of the Raman gain behaviors; this has a higher signal power distribution level; as shown in Fig. 4 [21].



Fig. 4 Distribution of signal powers along the fiber length in forward, bi-directionally and backward pumped RAs (undepleted pump approximation), with Raman net gain fixed at 0.0 dB [21]

In a fiber medium, we can optimize the pump powers and their wavelengths to have low noise and flatted gain. The optical characteristics of a fiber with single mode designation, such as the refractive index and the Raman gain behaviors; depend on the materials which make up the fiber. Most common fibers are silica (SiO₂) based. To increase the refractive index and forming a proper guide medium, some germania (GeO₂) is added to the fiber core. Usually these fibers have wellcharacterized refractive index profiles with corecladding index differences ranging from 0.015 to

0.049 [24].

The radial distribution of the germania and silica composition in the mixed structure can be calculated using Sellmeier data with the aid of a linear combinations of these materials [25]. It is clear that the magnitude and the spectral shape of the Raman gain depend on the germania concentration.

In a typical optical fiber the germania concentration is low and we can assume that the Raman gain coefficient increases with the peak germania concentrations linearly [24]. The reported results are shown in Fig. 5 [24]. As seen, with increasing the peak germania concentration, the gain coefficient increases too. Indeed, there is a core diameter with a related maximum gain for a determined germania concentration. This core diameter corresponds to the refractive index profile (it has the largest value of the overlapping between pump and signal intensities).

These results have important role in calculation of an optimized structure considering the pump powers and wavelengths, which is used in our computations too.



Fig. 5 Raman peak gain for the various fiber core diameters and germania concentration (λ_p =1455nm). The peak gain is considered in units of (W.km)⁻¹ [24]

Figures 6, 7 show the Raman gain coefficients for these two types of fibers. It is clear from this figure that the peak Raman gain coefficient for germanium-doped fibers is grater than that from the silica fibers, but silica fibers has a larger bandwidth [20]. This system has two forward pumps and eight backward-pumps.



Fig. 6 The on-off gain for silica fiber versus wavelength and $A_{\rm eff}$



Fig. 7 The on-off gain for germanium-doped fiber versus wavelength and A_{eff}

In this analysis, the signal-signal, the pump-signal and the pump-pump effects are considered and the Rayleigh effect is neglected. The forward-pump wavelengths are calculated and optimized to tune in 1423 nm and 1450 nm with powers 155 mw and 140 mw respectively (more steps respect to [21], [26] and [27]). The backward-pump wavelengths are also computed to tune in 1434, 1436, 1450, 1465, 1483, 1494 and 1512.2 nm. From the data reported in [21] and after more optimization considering noise and gain bandwidth specifications, the backward-pump powers are designed in: 254, 28, 160, 112, 93, 67, 77, and 136 mw. The length of the silica fiber is 75 km and for

germanium-doped fiber is 100 km. The number of channels is equal to 100 with 0.2 mw for each signal from 186.33THz to 192.95THz and the frequency guard of 95THz from the each other. It is clear that by decreasing the value of effective area (A_{eff}) , the on-off gain and its variation will increase. On the other hand, for longer values of wavelengths, the growth of gain is grater with respect to the shorter wavelengths. In fact RAs can work at any wavelength with suitable wavelength for pumps. This property with wide band effects of them can cause the efficient usage for WDM systems. Of course one drawback of RAs is polarization dependency of the Raman gain [28]-[29]. Generally, when the signal and pump have the same polarization the gain is in its maximum value and for orthogonal polarization of signal and pump, there is a reduction for this maximum. But when the pumping excitation is done by two orthogonally polarized lasers, this problem is removed. Also, this gain behavior should be uniform over the entire signal bandwidth for WDM systems. All channels must experience the same gain (gain flatness) for Raman amplification. Gain spectrum flatness is done by utilizing several pumps at different wavelengths. The superposition of several pumps can create a relatively flat gain over a wide range of frequency. Using the multi-pump laser scheme, bandwidths of more than 100nm are realizable [15], [30] (see Fig. 8). This is a typical example of the measured Raman gain spectrum for a RA made by a 25-kilometers long dispersion-shifted fiber, pumped by twelve laser diodes. To have a relative flattened gain profile [17], [31]-[32], the frequencies and pump powers are designed as the table shown in Fig. 8 [30]. Note also that all the power levels are less or equal to 98mW. The gain ripple is about 0.1dB with an average of 10.5dB over 80nm wavelength bandwidth. It is very suitable for L and C band, used in DWDM systems.

The most important factor which must be considered is the inclusion of pump-pump interaction. As mentioned, it is studied in our simulation. Raman gain interacts with multipump beams and some power from the shorterwavelength pumps is transferred to the longerwavelength pumps [16].

Another factor is the effective area seen in the gain coefficient, equations 2 and 3. As shown in figures 6 and 7, by increasing A_{eff} , the on-off gain decreases and longer wavelengths are affected much more than shorter wavelengths. For A_{eff} equal to $85 \mu m^2$,

the on-off gain will be flat with minimum ripples. The value of on-off gain is between 16.8-17.6 dB and it is almost flat with 80nm bandwidth. As shown in Fig. 6, the longer wavelengths have more variations than a shorter wavelength which is tightly depends on the effective area of the fiber, A_{eff} .



Freqency (THz)	Power (mW)
212.2	91
211.1	98
210.2	95
209.2	52
208.2	52
207.3	39
206.2	38
205.3	29
204.2	35
203.3	33
200.1	51
199.3	32
(b)	

Fig. 8 (a) Measured gain profile (typical) of Raman gain using a multi-pump scheme, (b) Used pump frequencies and powers; the structure is made by a 25-kilometers long dispersion-shifted fiber, pumped by twelve laser diodes [15]

In addition, for $A_{eff}=100 \ \mu m^2$, amplifier with germanium-doped fiber has an on-off gain between 20.2-22dB which is higher in comparison with silica fiber, as may be expected.

The noise figure (*NF*) is calculated and shown in Fig. 9, for different wavelengths and different effective areas, A_{eff} in silica fiber.



Fig. 9 The NF for silica fiber versus wavelength and A_{eff}

From the figure, the *NF* is between 0.3-1.8dB and its value increases as the A_{eff} decreases (for a fixed wavelength). To obtain an appropriate value for *NF*, we must consider large A_{eff} or equivalently the spot size, but with large value of A_{eff} the optimum gain can't be obtained. So the value of A_{eff} is designed so that we have both flattened gain spectrum and the proper *NF* amounts. This is an important criterion for optimum designation.

The different values of NF for germanium-doped fibers are also shown in Fig. 10. From this figure, and comparing it with Fig. 9, it is clear that the NF value in germanium-doped fibers is more than that in silica fibers. It is true that the Raman gain coefficient increases linearly with the germania concentration, but the reason for a larger NF is the more amplification of ASE in the germanium-doped fibers with respect to silica fibers. In conclusion, the values plotted in figures 6, 7, 9 and 10 are designed for minimum noise figure and maximum gain flattening simultaneously.

Fig. 11 shows net-gain for silica and Fig. 12 shows this parameter for germanium-doped fibers. As shown in the figures, when A_{eff} changes, the net gain variation of silica fibers are more than that the variations of the germanium-doped fibers (note that the maximum of gain increases). Also, for optimum

value of A_{eff} to have a flat on-off gain, the net gain curve is flat relatively.



Fig. 10 The NF for germanium-doped fiber versus wavelength and A_{eff}



Fig. 11 The net gain for Silica fiber versus to wavelength and $A_{e\!f\!f}$

For example in this simulation, for a silica fiber A_{eff} is typically $100\mu m^2$ and for a germanium-doped fiber A_{eff} is $85\mu m^2$. In addition, it can be shown that for shorter length fibers the ASE noise is less than that the fibers with longer length. The ASE parameter becomes important especially for the low power signals.

4 Conclusion

In this paper we discussed the different values of effective areas for a bidirectional optimized Raman amplifier with 10 pumps by using the numerical simulation. In this amplifier, we used two types of fibers; germanium-doped and silica fibers. We found that the peak gain coefficient for germaniumdoped fibers is grater than that from the silica fibers.

It is shown that the ASE noise and NF vary with different values of effective areas in silica and germanium-doped fibers and usually the first has lower NF than that the second. In addition the sensitivity of two different types of fibers with variations of the effective area is shown. Finally, the optimum value for effective area (or at least an accepted range) is obtained to have a flat gain spectrum and low noise figure for both types of the fibers.



Fig. 12 The net gain for germanium-doped fiber versus wavelength and $A_{\rm eff}$

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