Simulation of Distributed Multi-Pump Raman Amplifiers in Different Transmission Media

Mohsen Katebi Jahromi and Farzin Emami

***Abstract*—**Three types of distributed Raman amplifiers; forward, backward and bidirectional pumping configurations are simulated and compared in this paper. Since the nonlinear effect of the fiber type is an important parameter in determining the simulation process, two types of fibers are used in our simulation; Z-fiber and dispersion shifted fiber (DSF). In each case the optimum parameters such as pump and signal powers, amplified spontaneous emission and noise figure are derived. We found that there is minimum total input power for backward case and there is minimum fluctuation in signal power along the fiber which leads to having the lowest ripple in signal to noise ratio. Indeed, DSFs have proper noise figure level and more uniform signal gain relative to the Z-fibers. Generally speaking, the fiber parameters have strong effects on the operation of multi-pump distributed Raman amplifiers, because of their nonlinearities.

***Keywords*—**Raman amplifiers, Z-fibers, dispersion shifted fibers, numerical simulation.

I. Introduction

Rapid growth of optical amplifiers in optical communication systems enhance the channel capacities and transmission lengths and in this relation Raman amplifiers (RAs) play an important role [1]-[3]. These amplifiers are used in wavelength division multiplexed (WDM) systems. Raman amplification is based on stimulated Raman scattering (SRS) phenomena, which is a nonlinear effect in optical fibers and its result is optical signal amplification [4]. They used a fiber medium to generate the necessary Raman gain [2] and this is very important in these systems which need simultaneously multi-channel amplification [3].

The RA operation is the energy transfer of the pump to the signal due to Raman interaction between the optical modes and the vibrational modes of the medium molecules [5]. Another important feature of RAs is its gain bandwidth, which is determined by pump wavelength [6]. Multi-wavelength pumping scheme is usually used to increase the gain flattening and bandwidth for high capacity WDM transmission systems [7]. Due to needs for improved fiber RAs, there are numerous works in the literature on high power semiconductor lasers to handling the amplification process too. One scheme to increase the bandwidth and the gain uniformity along the passband of RAs is utilization of the multipump RAs. To do this, it is necessary to design the configuration of RA for low noise and wide band operation; in a proper configuration [8]. In backward-pumped fiber Raman amplifiers, other noise sources, transfer are minimized, because this scheme can suppress the related signal power fluctuation.

These amplifiers also have the unique characteristic of being tunable at any wavelength, simply by changing the pump frequency, since gain depends only on the signal-pump frequency shift [5]. Due to these reasons, Raman amplifiers are widely used in the fiber optical communication systems.

This paper is arranged as follows. In section II, we present the coupled differential equations governing the RAs. We discuss the designation subject in Section III, considering the gain spectrum and noise behavior of these amplifiers. Our simulation procedure is based on analyzing a WDM system with 45 channels in three different configurations and two separate transmission media. The results and a brief discussion are found in Section IV and Section IV respectively. This paper concentrates on the overall approach and the key results.

II. Mathematical Formulation

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. 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 [9]. If the frequency, or equivalently the 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 scattering of 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

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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 [9].

In silica-optical fibers, Raman-amplification band extends over a few terahertzes, and it can be further broadened by multiple pumping schemes [10]. Shown in Fig. 1 there is a simple schematic structure of a distributed RA, used in optical fiber communication:

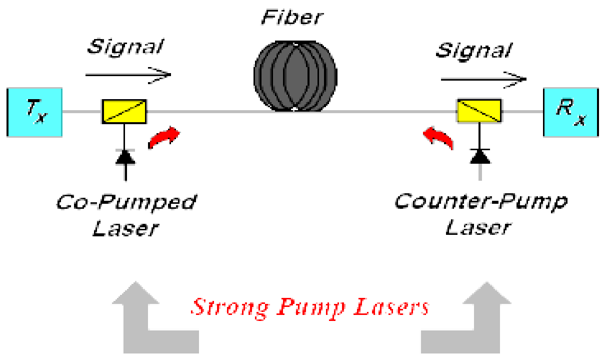


Fig. 1 Schematic of a DRA used in optical communication system

As shown, the gain medium is a single mode fiber (SMF) with equivalent length '*L*' and the pump powers, with forward and backward wave propagations, are injected to the fiber using the couplers. In this fiber, stimulated Raman scattering is occurred and a strong pump laser provides excess gain for signals which are at shorter and longer wavelengths, respectively. The analysis and simulation of RAs are based on a set of coupled differential equations, including 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. Laser pump sources of these amplifiers are usually semiconductor or Raman fiber lasers.

The coupled differential equations describing the average signal power amplification in a typical WDM system are [9], [11]-[14]:

$$\frac{dP_\nu^\pm}{dz} = \mp\alpha_\nu P_\nu^\pm \pm \varepsilon_\nu P_\nu^\mp \pm P_\nu^\pm \sum_{\mu\rangle\nu} \frac{C_{R\mu\nu}}{\Gamma}\left(P_\mu^+ + P_\mu^-\right)$$

$$\pm 2N_{E_\nu} \sum_{\mu\rangle\nu} \frac{C_{R\mu\nu}}{\Gamma}\left(P_\mu^+ + P_\mu^-\right)\left[1+\frac{1}{\exp\left[\frac{h(\mu-\nu)}{KT}\right]-1}\right]$$

$$\mp P_\nu^\pm \sum_{\mu\langle\nu} \frac{\omega_\nu}{\omega_\mu}\frac{C_{R\mu\nu}}{\Gamma}\left(P_\mu^+ + P_\mu^-\right)$$

$$\mp P_\nu^\pm \sum_{\mu\langle\nu} \frac{\omega_\nu}{\omega_\mu}\frac{C_{R\mu\nu}}{\Gamma} 4N_{E\mu}\left[1+\frac{1}{\exp\left[\frac{h(\nu-\mu)}{KT}-1\right]}\right] \qquad (1)$$

This equation contains the signal-signal, signal-pump and pump-pump interactions, amplified spontaneous emission (ASE) and thermal effects, as previously mentioned.

In (1) ν and μ indices denote the optical frequencies, + or – sign indices are for forward and backward propagating waves, P_ν is the optical power, α_ν is the attenuation coefficient and ε_ν is the Rayleigh backscattering factor. $C_{R\mu\nu} = \frac{g_{\mu\nu}}{A_{eff\,\mu}}$ is the Raman gain efficiency between the ν and μ frequencies. The factor $g_{\mu\nu}$ is the Raman gain at frequency ν due to pump at frequency μ, A_{eff} is the effective cross section of the optical fiber at frequency μ, $N_{E\nu} = h\nu\Delta\nu$ is the ASE power in the bandwidth of $\Delta\nu$ with a central frequency of ν, and finally Γ is the polarization factor which is considered to 2. The effective area 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.

III. DESIGNING PROCEDURE

Designing problem is equivalent to find a proper gain spectrum and then found the related noise specifications. Usually the first factor has a drastic effect on the amount of signal and pump powers. They are interrelated to the signal and pump wavelengths too. Also, the second factor determines the value of the signal to noise ratio (SNR). So, to design a proper RA it is needed to know the gain and the noise behaviors.

A. The gain spectrum

To have a multicolor pump spectrum it is possible to generate the gain spectrum using a combination of the multipump wavelength structure. If ν_p, ν_{Ph} and ν_s are the optical pump frequency, the optical phonon and the optical signal, it is possible to have a SRS [5], when:

$$\nu_s = \nu_p - \nu_{ph}$$

If we apply multipump frequencies to the Raman medium simultaneously the SRS effect is occurred for each of the pump frequency at the same time and their relation between them will be:

$$\nu_{s,i} = \nu_{p,i} - \nu_{ph}$$

In fact, the different frequency components of the input signal can achieve the different gains from the various frequency components of the pump power in a single medium at the same time. It is an important specification which is used in the wide band amplification in the WDM systems [12]. So, with this idea, there is a wide and uniform Raman gain in the optical fiber using the different pump frequencies (WDM pumping). In the WDM pumping the generated Raman gain of a single pump frequency lies on the Raman gain of the other pump frequency and they have an overlap. Any signal frequency achieves an additive effect of overlapping gains from pump frequencies.

To have WDM telecommunication we have to design the RAs such that there is a wide and uniform spectrum with an appropriate noise operation considering the number of pumps, signal bandwidth and the fiber types. Bandwidths of more than 100nm are realizable in 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; the results are shown in Fig. 2. [12].

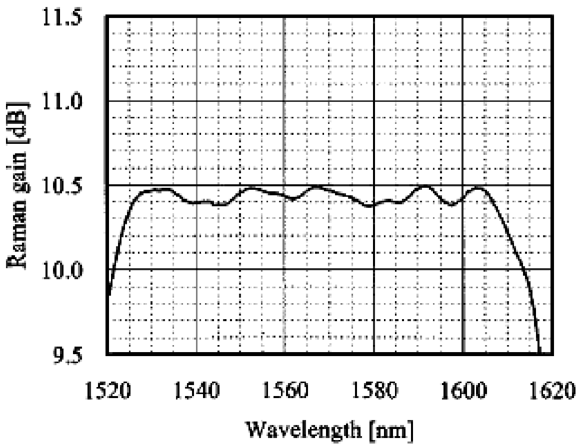


Fig. 2 Measured gain profile (typical) of Raman gain using a multi-pump scheme [12]

B. Noise operation

An important parameter of RA noise is its noise figure (or noise factor, *NF*), which defines as the input to output signal to noise ratios and denotes the signal degradation [16]. In RAs the equivalent noise figure is used and defined as the following equation [2]:

$$NF_{eq}^{dB} = NF_R^{dB} - (\alpha_\nu L)^{dB} \tag{2}$$

An expression for NF_R^{dB}, containing the shot noise, ASE and signal beating is [6]:

$$NF_R = \frac{1}{G_N} + \frac{P_{ASE}}{G_N h\nu\nu\Delta} \tag{3}$$

where G_N is the net gain and P_{ASE} is the (unpolarized) ASE power. From (2) it is found that a negative noise figure is possible; which is not physically feasible but it shows the very interesting aspect of RAs. If in power analysis, the signal-signal, signal-ASE and Rayleigh scattering are not considered the amount of noise figure is more affected in different types of RAs [18].

IV. NUMERICAL SIMULATIONS

At first we study a brief review of ASE. The ASE spectrum of a typical DRA is a function of the wavelength and usually it has a minimum over a limited band [18]. In Fig. 3, the ASEs of a structure with three different types of pumping scheme are plotted. These types are deriving by a set of five pump diode configurations classified as follows:

1) *Five backward pumping diodes (Co-Pumped case, shown by Type-1 hereafter),*

2) *Two backward (P_1 and P_2) and three forward (P_3, P_4 and P_5) diodes (Bidirectional-pumped, Type-2),*

3) *Five forward pumping diodes (counter-pumped, Type-3).*

For smaller difference between pump and signal frequencies the generated ASE will be larger, as shown. So, there is more generated ASE for the signals with lower wavelengths. This effect introduces *noise figure tilt*. As a comparison, it is found that ASE is better for co-pump case with respect to bidirectional and counter-pumped cases [18].

The Rayleigh backscattering coefficient, existed in (1), is a function of the fiber length [18]. Due to Rayleigh reflections, a fraction of the signal is scattered and after this, half of the recaptured Rayleigh scattered signal-light propagate in the same direction as the signal and the other half in the opposite direction. The part that propagates in the opposite direction may again undergo a reflection and after two reflections it propagates in the same direction as the signal. It appears like as an echo of the signal which interferes to the original signal. This double Rayleigh backscattering (DBR) light is amplified in three structures. In other words, we have multiple reflections along the fiber; rather than two (multi-path interference [MPI], which is more severe in long length fibers) [9], [12].

A typical shape of this parameter is drawn in Fig.4. As shown DRB light power for type-2 is less than that type-3 and in these results we used the data reported for an optimum structure [18]. From the results it is found that the total required pump power (to achieve an optimum case) for bidirectional-pump DRA is more than the other cases, considering the gain profile and the noise restrictions.

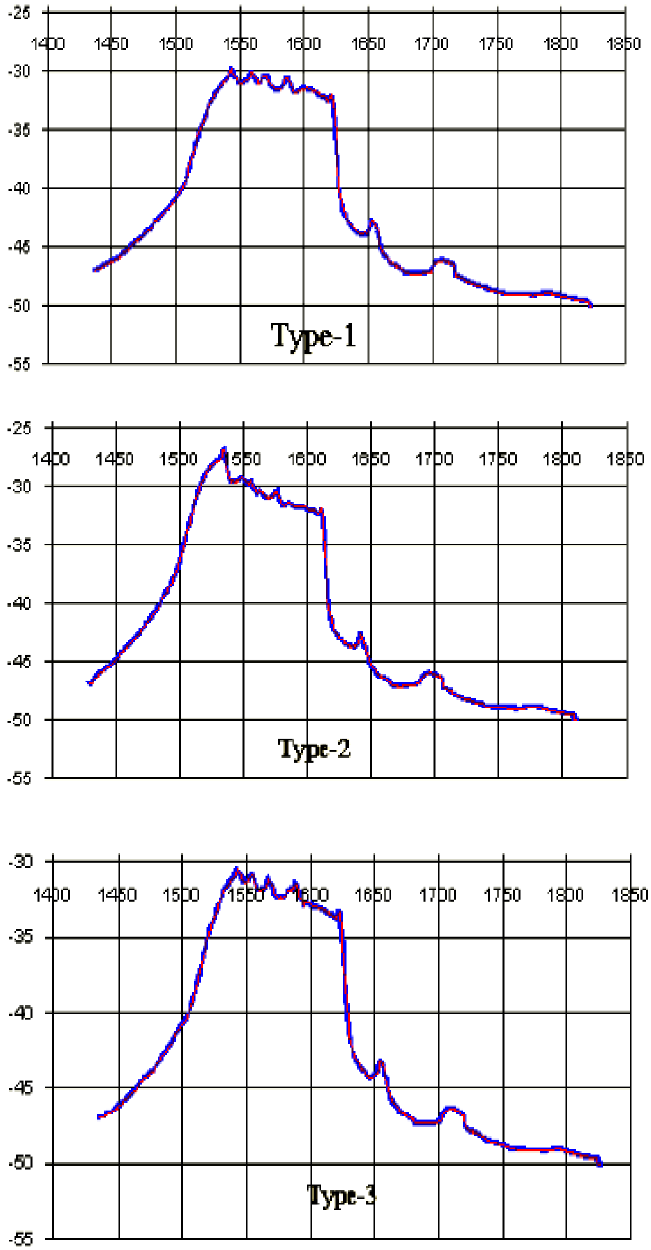


Fig. 3 The ASE spectrum for a typical five-pumped DRA

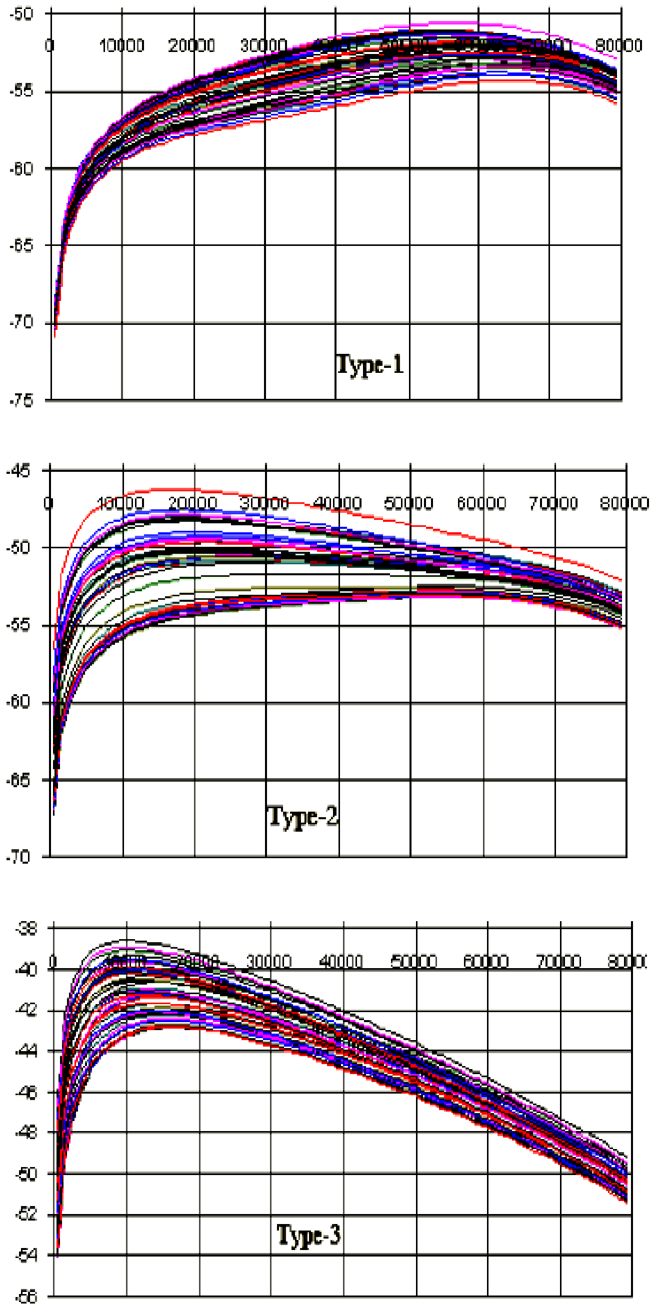


Fig. 4 DRB light power for a typical fibe-pumped DRA

The noise figure (*NF*) of the three cases is shown in Fig. 5. As shown, this parameter for counter-pump case is more than two another cases. In fact:

$$NF_{\text{Co-pump}} < NF_{\text{Bidirectional}} < NF_{\text{Counter-pump}} \tag{4}$$

As mentioned, another factor which must be considered in noise figure is noise figure tilt (i.e. its variations). For example, due to shifting from 1539.5 to 1600*nm* there is about 1.97dB variation or tilt in NF_{eq}^{dB} for bidirectional case. Noise figure tilt in this case is more uniform and less than that the other cases.

If in power analysis, the signal-signal, signal-ASE and Rayleigh scattering are not considered the amount of noise figure is more affected in type-3. The typical NF_{eq}^{dB} spectrum is plotted in Fig. 6. As shown in the figure, the value of NF_{eq}^{dB} degrade about 0.5dB with respect to the previous case.

Between the effective factors in NF_{eq}^{dB} spectrum, the signal-signal is more dominated. If the signals power changed, the NF_{eq}^{dB} and hence, some other parameters will be varied. The results are shown in Fig. 7.

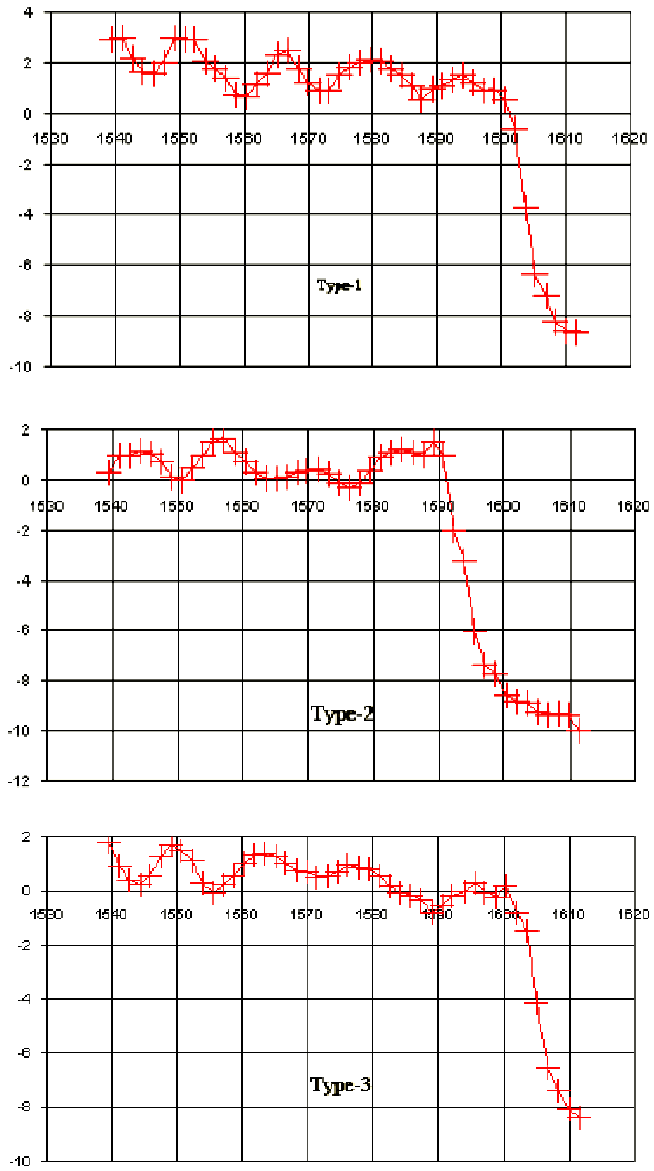


Fig. 5 The noise figure at the different signal wavelength

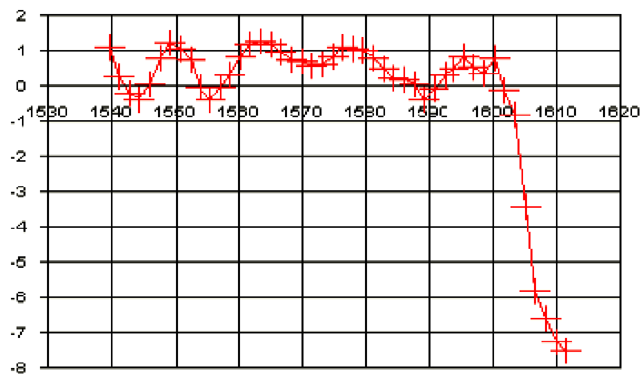


Fig. 6 Typical spectrum of NF_{eq}^{dB} in forward-pumped case (signal to signal and signal-ASE interactions are not considered)

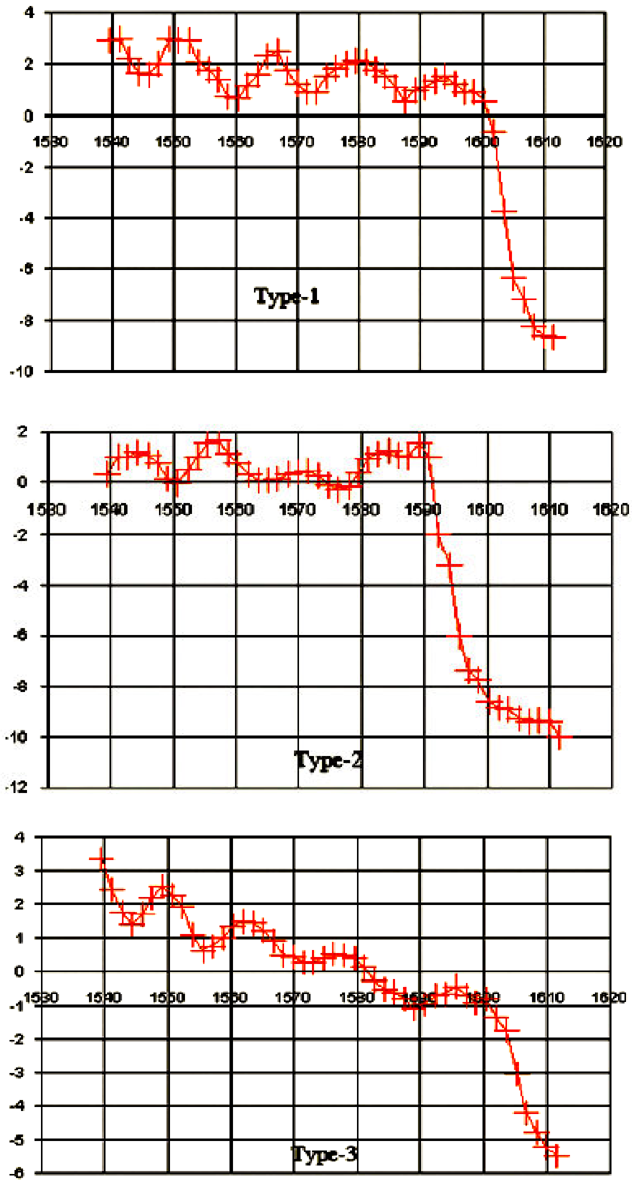


Fig. 7 Spectrum of NF_{eq}^{dB} for 0dBm input signal power for three types of DRA

In this figure NF_{eq}^{dB} spectrum are plotted for a signal with 0dBm power. As shown, NF_{eq}^{dB} variations for co-pumped case is grater than that the other cases; bidirectional and counter-pumped cases.

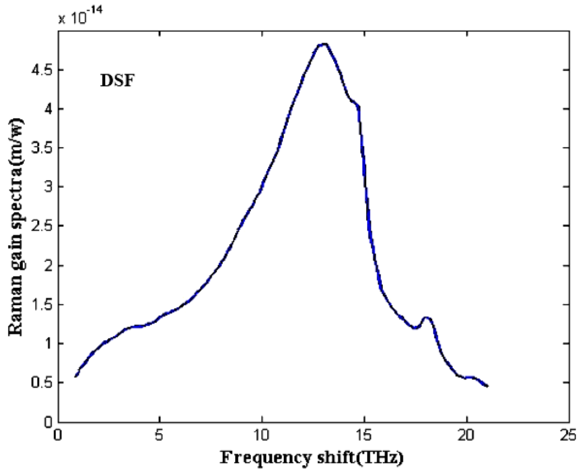
To survey the effect of the fiber media in RAs, we chose 45 channels WDM system in the range of 1539nm to 1611nm with a guard of 200GHz and Δλ=72nm; and for data transmission two types of fibers are used, DSF [15] and Z-fiber (ZF). The Fiber characteristics are shown in Table I.

Each signal channel power is -10dBm through the 80Km distance. Their specifications are written in Table I and The Raman gain spectrums for two types of fibers are shown in Fig. 8. [17].

In two cases the power and wavelengths of the pumps are calculated to have an optimized signal power, considering its uniformity and noise specifications [18]-[22]. Our procedure is similar to the method proposed by [11].

Table I Characteristics of the Used Fibers [18]-[20]

	DSF	ZF
A_{eff} $(*10^{-12}cm^2)$	46.7	85.5
GeO_2 *Concentration %*	8.3	0.0
Attenuation Coefficient (dB/km)	0.21	0.17



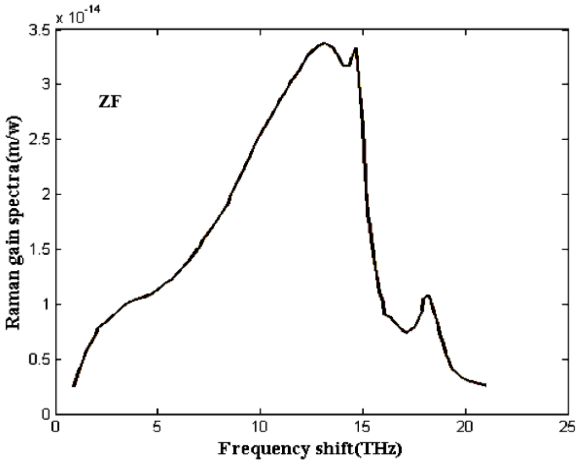


Fig.8 The Raman gain spectrum for dispersion-shifted Fiber (DSF) and Z-fiber

The output signal spectrum is shown in Fig. 9, based on the optimized data used in Table II. From the figure, there are different uniformities for signal powers in two types of fibers so the transmission medium has important role in the signal power.

The signal power variation is almost 1.62dB for DSF whereas we have the value of 2.86dB for ZF.

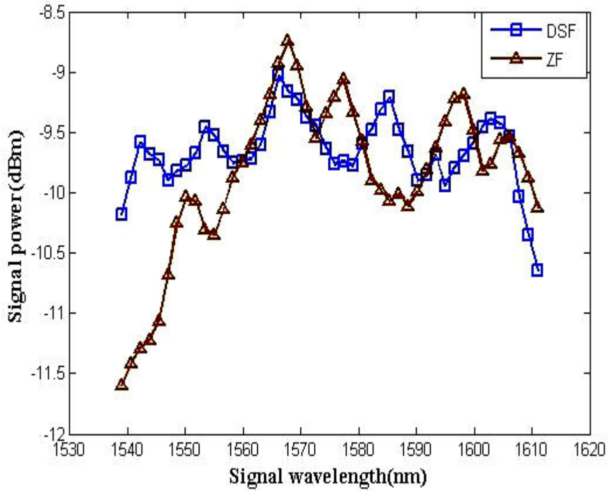


Fig.9 Signal powers for DSF and ZF

Table II Optimized parameter set (the pump powers are in milliwatt and wavelengths in nanometer)

	DSF	*ZF*
P_1	196	265
λ_1	1434.2	1440.5
P_2	130	270.2
λ_2	1443.9	1456
P_3	138.5	250.3
λ_3	1454.5	1464.5
P_4	118	115
λ_4	1471.5	1485
P_5	124.2	290
λ_5	1501	1506
Total Power of Input Pumps	706.7	1190.5

The equivalent noise figures for two types of channels are calculated and drawn in Fig. 10. This factor is a figure of merit for a distributed RA. As shown, the DSF has an appropriate operation respect to ZF relating the noise considerations.

There is a maximum noise factor of 2.69dB for DSF whereas the value of 3.97dB is the maximum for ZF. So, in some signal wavelengths the noise effects in ZF improved relative to DSF.

Finally, based on the power considerations in Table II, to achieve an optimum case, the total exciting pump powers for DSF is 706.7mW and for ZF is 1190.5mW and this is another advantage of DSF to choose for a transmission medium.

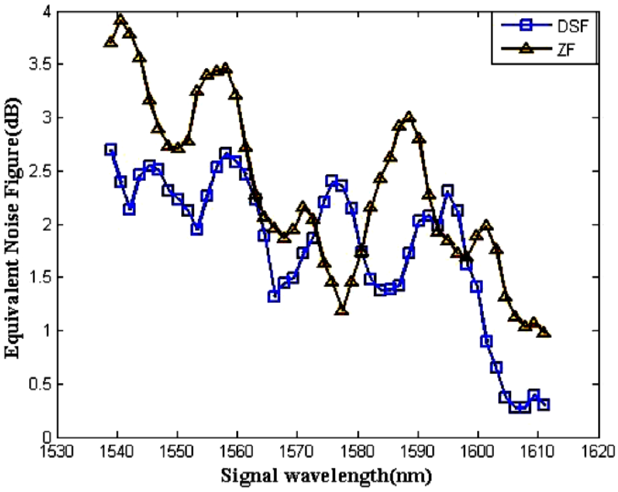


Fig.10 The NF^{Eq} for DSF and ZF

V. CONCLUSIONS

Designing the distributed multipump RAs depend on some ingredients such as pump configuration and the fiber medium. In this paper the pump configuration was in backward excitation and was so prepared to have an optimized operation of a RA. From the simulation results, the fiber substance affects the multipump RA operation. One of the effective factors is GeO_2 concentration. By changing this concentration from 0.0% in ZF to 8.3% in DSF, the amplifier operation was improved. In conclusion we can compare the advantages and drawbacks of these fibers as follow:

-DSF has a proper gain uniformity respect to ZF and the signal power variations are less than the ZF whereas the attenuation coefficient of DSF is higher than the ZF;
-The RAs, which use the DSF as a transmission medium, have better equivalent noise figure;
-The optimized pump power of RA which uses DSF is very less than the ZF.

Therefore, selecting a fiber for transmission medium of a distributed RA considering the noise effects and optimized pump power in a special wavelength is an important design parameter for these amplifiers.

REFERENCES

[1] Q. Hen, J. Ning, H. Zhang, and Z. Chen, "Novel Shooting Algorithm for Highly Efficient Analysis of Fiber Raman Amplifiers," *IEEE J. Lightwave Technol.*, vol. 24, no. 4, pp. 1946-1952, Apr. 2006.
[2] C. Headley and G. P. Agrawal, *Raman Amplification in Fiber Optical Communication Systems,* San Diego, CA: Academic, 2005.
[3] C. Martinelli, D. Mongardien, J. C. Antona, C. Simonneau and D. Bayart" Analysis of Bi-directional and second-order pumping in long-haul systems with distributed Raman amplification," *ECOC* 2003, Paper P3. 30.
[4] M. N. Islam, "Raman amplifiers for telecommunications," *IEEE J. of Select. Topics in Quantum Electron.,* vol. 8, no. 3, pp. 548–559, May 2002.
[5] M. N. Islam, Ed., *Raman Amplifiers for Telecommunications.* N.Y.: Spring.-Verlag, 2003.
[6] J. Bromage, *"Raman amplification for fiber communication systems",* in *Proc. Optical Fiber Communications Conf.,* 2003.
[7] J. Bromage, "Raman amplification for fiber communication systems, " *IEEE J. of Lightwave Technol.*, vol. 22, no. 1, pp. 79-93, January 2004.
[8] S. Kado, Y. Emori, S. Namiki, N. Tsukiji, J. Yoshida, and T. Kimura, "Broadband flat-noise Raman amplifier using low-noise Bi-directionally pumping sources," in *Proc. Europ. Conf Optical Communications,* 2001.
[9] G. P. Agrawal, *Nonlinear Fiber Optics,* San Diego, Academic, 1989.
[10] A. Galtarossa, L. Palmieri, M. Santagiustina, and L. Ursini, "Polarized backward Raman amplification in randomly birefringent fibers," *J. Lightwave Technol.*, vol. 24, pp. 4055–4063, Nov. 2006.
[11] X. Liu, J. Chen, C. Lu, and X. Zhou, "Optimizing gain profile and noise performance for distributed fiber Raman amplifiers," *Opt. Express,* vol. 12, no. 24, pp. 6053–6066, Nov. 2004.
[12] G. P. Agrawal, *Fiber optical communication systems,* New York, John Wiley and Sons, 2002.
[13] I. Mandelbaum, M. Bolshtyansky, "Raman amplifier model in single-mode optical fiber," *IEEE Photon. Technol. Lett.,* vol. 15, no. 12, pp. 1704– 1706, Dec. 2003.
[14] S. Hu, H. Zhang and Y. Guo, "Stiffness analysis in the numerical solution of Raman amplifier propagation equations*", Opt. Exp.* vol. 12, pp. 1656-1664, 2004.
[15] Shirley P.N. Cani, Márcio Freitas, Renato T.R. Almeida and Luiz C. Calmon, "Raman Performance of Dispersion Compensating Fibers*", SBMO/IEEE MTT-S IMOC 2003Proceedings,* pp. 553-558, Sept. 2003.
[16] L. T. Jordanova, and V. I. Topchiev, "Improvement of the Optical Channel Noise Characteristics Using Distributed Raman Amplifiers, " *ICEST Conference,pp. 20-23*, June 2008.
[17] Y. Kang, "Calculation and Measurements of Raman Gain coefficientticient of Different Fiber Types," M.S.thesis,Dept Electrical Engineering .Virgina Polytechnic Inst. Blacksburg VA. [Online]., Available: http:// scholar.lib .vt.edu/ theses/available/etd- 01102003-020757/,2002.
[18] F.Emami , M.katebi, *"Analaysis and comparison of optimized multi-pump Raman amplifier," In Proc. of ICEEE-2007 Conf., Mexico city,* Mexico 2007.
[19] M.Katebi Jahromi and F.emami , "Analysis and Comparison of Optimized Multipump Distributed RamanAmplifiers in Different Fiber Medias*", Proc. Of 8th WSEAS Int. Conf. on Electronics, Hardware, Wireless and Optical Communications (EHAC'09),* Cambridge, UK, Feb. 21-23, 2009, pp. 112-115.
[20] Farzin Emami, Amir H. Jafari, " Analysis of Low Noise and Gain Flattened Distributed Raman Amplifiers Using Different Fibers*", Proc. Of 8th WSEAS Int. Conf. on Electronics, Hardware, Wireless and Optical Communications (EHAC'09),* Cambridge, UK, Feb. 21-23, 2009, pp. 119-123.
[21] F. Emami, "An approach to solve the Raman amplifiers equations by an optimized method," *In Optoelectronic Research of Shiraz University of Technology,* Shiraz, Iran, unpublished.
[22] F. Emami, and A. H. Jafari, "Theoretical optimum designation of distributed Raman amplifiers in different media," *WSEAS Trans. On Electron.*, submitted for publication.

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