Gain and Noise Performance of Fiber Raman Amplifiers

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Abstract— **This work presents a study to obtain the gain and noise figure of fiber Raman amplifiers (FRAs) by the two coupled equations of Raman-amplification process. The effects of pump power and length are investigated as well as the noise transferred between pump and signal. Relative intensity noise (RIN) is also studied showing the effect of Raman on-off gain and dispersion. Three different amplifier configurations are considered using three different fiber types.**

Index Terms—**Fiber Raman Amplifiers, Stimulated Raman Scattering, Noise figure, Relative intensity noise, SMF, Freelight, Truewave.**

I. INTRODUCTION

One of the advanced technologies achieved in recent years is the advent of Fiber Raman Amplifiers (FRAs) that has enabled the optical signals in an optical fiber to be amplified directly in high bit rate systems beyond Terabits.

Distributed fiber Raman amplifiers (DFRAs) are well known to reduce the noise generation and to smooth the signal level variation along the link, reducing system vulnerability to nonlinear effects. DRFA based on the stimulated Raman scattering (SRS) are well-known to offer the advantage of flat gain and wideband amplification in conventional low-loss silica fibers itself, at any wavelength for which a pump, with frequency higher than that of signal by the Stokes shift, is available. They also allow a distributed amplification over a length of several tens of kilometers which is significantly larger than the distribution length of erbium doped fiber amplifiers (EDFAs), just acting as nearly lump amplifiers when they are used in long span transmission.

Therefore, the DRFA allows smaller magnitude excursion of the signal level and therefore low nonlinearity impairments and lower noise than EDFA [1].

A FRA is usually designed employing the averaged power analysis considering forward and backward propagation directions for the pump and the signal through the optical fiber.

SRS is a nonlinear effect due to interactions between light waves with molecular vibrations in silica fiber as shown in Fig 1.

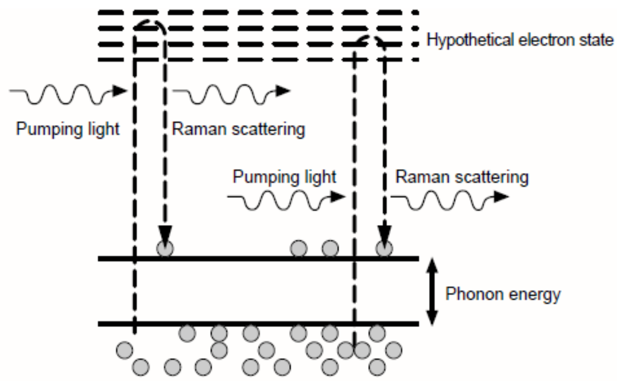

Fig. 1 Stimulated Raman Scattering.

The noise is a fundamental limitation in realising long haul point-to-point fiber optical communication links and optical networks. Also, accompanying an optically amplified signal plays an important role in understanding the basic properties of the gain medium while, at the same time, it is of practical significance as it determines the signal detectability. This noise includes pump noise transfer and noise figure.

The paper is organized as follows: Section II introduces the mathematical and theoretical information about solving Raman amplifier propagation equation. Noise figure derivation and characteristics are presented in Sec III. RIN is explained in sec. IV. Simulation and discussion are found in Sec. V followed by the conclusion in Sec. VI.

II. THEORETICAL AND MATHEMATICAL BACKGROUND

A. *Propagation Equation*

The signal power, P_S, and the pump power, P_P, propagation equations in a nondepleted FRA are expressed as [2]

$$\frac{dP_s}{dz} = -\alpha_S P_S + C_R P_p P_S, \quad (1)$$

$$\pm\frac{dP_p}{dz} = -\alpha_P P_P, \quad (2)$$

Where α_S and α_P represent the fiber attenuation coefficients for the signal and the pump, respectively. The sign ± refers to the forward or backward propagation of the pump, C_R is the fiber Raman gain efficiency. G is the Raman net gain and G_R is the Raman on–off gain.

Solving Eq. (2), one obtains the total pump power, $P_p(z)$, at a distance z in the form

$$P_P(z) = P_0 e^{-\alpha_P Z}. \quad (3)$$

Substituting Eq. (3) in Eq. (1), one can get

$$\frac{dP_s}{dz} = C_R P_0 e^{-\alpha_P Z} P_S - \alpha_S P_S. \quad (4)$$

Because of pump absorption, the effective amplification length is reduced from L to L_{eff}, where

$$L_{eff} = \frac{1 - e^{-\alpha_P L}}{\alpha_P}. \quad (5)$$

B. *Gain and Output Signal Power*

Solving Eqs. (4) and (5) the signal power, P_S, at a distance (z=L) is obtained in the form

$$P_S(L) = P_S(0) e^{(C_R P_{Po} L_{eff} - \alpha_S L)} \equiv G(L) P_S(0), \quad (6)$$

where G(L) is the net signal gain and P_{Po} is the launched pump power.

The net signal gain are derived from Eq. (6) as

$$G(L) = e^{(C_R P_{Po} L_{eff} - \alpha_S L)}. \quad (7)$$

It can simply expressed in decibels as

$$G(L) = 4.343[C_R P_{Po} L_{eff} - \alpha_S L]. \quad (8)$$

By this simple equation, it is clear that high Raman gain can be achieved with high pump power, long effective lengths, high gain coefficient as well as low signal and pump attenuations.

If the Raman gain is not sufficient to overcome fiber losses. It is useful to introduce the concept of the on–off Raman gain using the definition [1]

$$G_R(L) = \frac{P_S(L) \text{with pump on}}{P_S(L) \text{with pump off}} = e^{C_R P_{Po} L_{eff}}. \quad (9)$$

Clearly, $G_R(L)$ represents the total amplifier gain distributed over a length L_{eff}.

Substituting Eq. (7) in Eq. (8), the Raman net gain as a function of Raman on-off gain is obtained as

$$G(L) = G_R(L) e^{-\alpha_S L}. \quad (10)$$

III. NOISE FIGURE

The noise figure, NF, of an amplifier is the ratio of the SNR of the input signal to SNR of the output signal. It is a measure of how much the amplifier degrades the signal. In a Raman amplified system, the equivalent noise figure, NF_{eq}, represents the NF of an amplifier placed at the receiver end of the transmission span. It is needed in the absence of Raman amplification to provide the same SNR as that obtained using DRA [3].

For a FRA, the evolution of the spectral density, N_S, of the optical noise at the signal wavelength is expressed as [4]

$$\frac{dN_S}{dz} = -\alpha_S \left[N_S - \frac{h\nu_S}{2}\right] + C_R P_P \left[N_S + \frac{h\nu_S}{2}\right], \quad (11)$$

When the input signal is limited to the vacuum fluctuation, meaning shot-noise limitation of a hypothetical power detection, the spectral density of the output optical noise is

$$N_S = G\frac{h\nu_S}{2} + (G-1)\frac{h\nu_S}{2} + 2\alpha_S G D_{inv} \frac{h\nu_S}{2}, \quad (12)$$

where

$$D_{inv} = \int_0^L \left[\frac{1}{G(Z)}\right] dz, \quad (13)$$

The vacuum fluctuation, D_{inv}, is an input noise reference which amplification contributes to the output noise, in addition to intrinsic amplification noise generation.

The original formulation of NF in the optical domain defines it as the degradation of the optical signal-to-noise ratio [5].The input noise is defined as the vacuum fluctuation. If we consider the noise as white Gaussian in the limited optical measurement bandwidth, the NF is defined as

$$NF = \frac{N_S}{G\frac{h\nu_S}{2}}, \quad (14)$$

$$NF = 1 + \frac{G-1}{G} + 2\alpha_S D_{inv}. \quad (15)$$

IV. PUMP NOISE TRANSFER

The Raman gain process is extremely fast, <1 ps. Therefore, any fluctuations in the pump at frequencies <1 THz can cause fluctuations in the Raman gain and consequently in the signal power [7]. This phenomenon is generally referred to as pump to signal relative intensity-to-noise transfer, RIN. The RIN is a standard measure of the noise in a laser.

The RIN results from the amplification of the signal by the pump noise. Thus, it is necessary to know the evolution of the pump noise. The transfer of the pump noise in the evolution of the spectral density at the signal wavelength is defined as [6]

$$\frac{dN_P}{dz} = \mp\alpha_P\left[N_P - \frac{h\upsilon_P}{2}\right], \tag{16}$$

$$\frac{dN_S}{dz} = -\alpha_S\left[N_S - \frac{h\upsilon_S}{2}\right] + C_R P_P\left[N_S + \frac{h\upsilon_S}{2}\right] + C_R N_P P_S. \tag{17}$$

In the optical domain, the RIN is usually expressed as the ratio of the spectral density of the optical noise over the averaged power. Taking into account attenuation plus amplification noise sources and the pump noise transfer, the optical RIN of the signal is expressed as [4]

$$RIN_S^{Out} = RIN_S^{in} + \left[\frac{G-1}{G} + 2\alpha_S D_{inv}\right]\frac{h\upsilon_S}{2P_{SO}} + ln(G_R)\left[RIN_P^{in} + \frac{h\upsilon_P}{2P_{PO}}\alpha_P\left(L - L_{eff}\right)\right]. \tag{18}$$

RIN_S^{in} and RIN_P^{in} correspond to the input RINs for the signal and the pump, respectively.

The maximum RIN treated before does not represent a real case of propagation. The pump and the signal do not propagate necessarily in the same direction and with the same group velocities. Thus, fiber chromatic dispersion must be included in the pump noise transfer analysis as in [6] and [7].

The pump RIN causes nonnegligible temporal power fluctuations. Thus, one can represent the spectral densities of the RIN as $N_S^{rin}(z,t) = N_S^{rin}(z)\, e^{i\omega t}$ and $N_P^{rin}(z,t) = N_P^{rin}(z)\, e^{i\omega t}$ for the signal and the pump, respectively. ω is the RIN modulation pulsation. The signal is forward propagating and the pump is either forward (upper signs) or backward propagating (lower signs). The propagation equations of N_S^{rin} and N_P^{rin} in time and space can be described as

$$\frac{d}{dz}N_S^{rin} = (-\alpha_S + C_R P_P)N_S^{rin} + C_R N_P^{rin} P_S, \tag{19}$$

$$\frac{d}{dz}N_P^{rin} + i\omega\beta^{\pm}N_P^{rin} = \mp\alpha_P\left(N_P^{rin} - \frac{h\upsilon_P}{2}\right), \tag{20}$$

$$\beta^{\pm} = \frac{1}{v_S} \pm \frac{1}{v_P}, \tag{21}$$

where V_S, and V_P are the group velocities of the signal and the pump, respectively. The propagation constants are

where $\beta^- \approx \frac{2}{v_S}$ for a backward pumping and $\beta^+ = D(\lambda_S - \lambda_P)$ for a forward pumping. D is the chromatic dispersion at the signal wavelength and P_{S0} is the input signal power.

The RIN transferred from the pump to the signal in the optical domain, is expressed as [4]

$$RIN_S^{Out} = T^{\pm}(\omega)\left[RIN_P^{in} + \frac{hv_P}{2P_{PO}}\alpha_P\left(L - F(\omega)\right)\right], \tag{22}$$

where, F(ω) is defined as

$$F^{\pm}(\omega) = \frac{1 - e^{-\alpha_P L}}{\alpha_P + i\omega\beta^{\pm}}. \tag{23}$$

Assuming a long-haul distributed FRA, the electrical RIN transfer functions are defined as [4]

$$|T^{\pm}(\omega)|^2 \approx \frac{\ln^2(G_R)|F^{\pm}(\omega)|^2}{{L_{eff}}^2}. \tag{24}$$

V. SIMULATION RESULTRS AND DISCUSSION

Based on the described model, MATLAB ver. 7.5 is used to perform calculations. Table 1 presents the values of the parameters which will be used to numerically solve Raman amplification.

Table 1 Measured Fiber Parameters [4].

Fiber type	Freelight	SMF	Truewave-RS
α_S(dB/Km)	0.2	0.2	0.2
α_P (dB/Km)	0.260	0.263	0.256
C_R (1/W.Km)	0.54	0.42	0.69

V.1 Raman Gain Characteristics

Dependence of Raman gain on Pump Power

Figure 2 shows the variation of gain with pump power for different fiber lengths at a constant signal input power. In this simulation, a span of 100 km for three different fiber types is used and the pump power supplied was increased from 0 to 1500 mW. It is clear that, the gain of the FRA linearly increases with pump power, after that the increase in gain becomes smaller when the population inversion is provided for all ions in the fiber and therefore, amplifier goes to saturation. As a result, the gain efficiency in dB/W reduces for high pump powers. In addition, a higher gain can be obtained at a longer Raman fiber with sufficient pumping. The Truewave fiber has a higher gain than the two other fiber types.

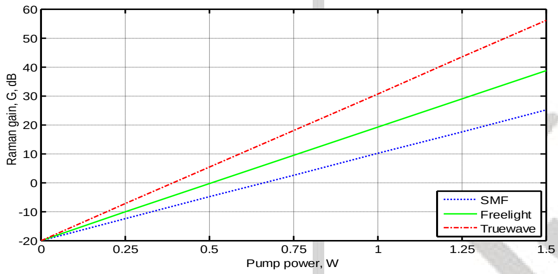

Fig. 2 The Raman gain as a function of pump power for 100 km fiber span of different fiber types.

Dependence of Raman Gain on Fiber Length

The variation of gain with fiber length is displayed in Fig.3 for the same studied fibers having different Raman gain efficiencies and constant signal input power at 800 mW pump power.

As shown, the gain increases up to a certain fiber length, and then begins to decrease. This occurs because of insufficient population inversion due to excessive pump depletion and getting higher losses than the provided gain at the signal wavelength due to high total signal loss.

The comparison between three different fiber types, Fig.3, ensures that the Truewave fiber has the maximum gain than the others due to its high Raman gain efficiency.

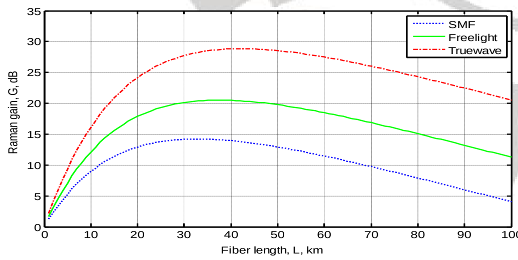

Fig. 3 The Raman net gain as a function of fiber length for different types of fiber at 800 mW pump power.

V.2 Noise Figure

Based on Eq. (16), one has obtained the noise figure as a function of Raman on-off gain, as shown in Fig. 4. It shows how the Raman on-off gain controls the noise figure, NF. The NF increases with the Raman on-off gain (depending on fiber span, pump power and fiber type).

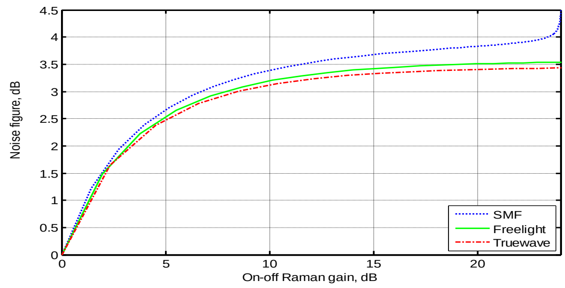

Fig. 4 Noise figure as a function of on-off Raman gain with 800 mw pump power.

These results of noise figure are in a good agreement with that obtained by B. Bristiel et al. [4] and K.Rottwitt et al.[8].

Dependence of Noise Figure on Fiber Length

Using Eqs. (8) and (15), one can obtain the noise figure as a function of fiber length for different pumping powers at a constant signal input power and different fiber types, as shown in Figs. 5 and 6.

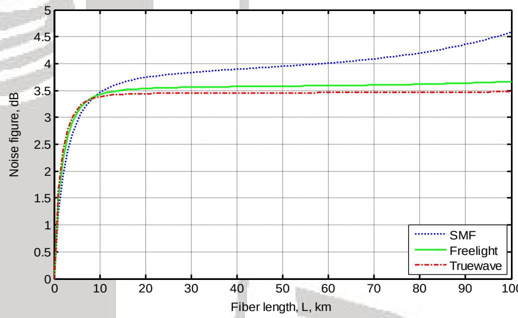

Fig. 5 Noise Figure as a function of fiber length at 800 mW pump power.

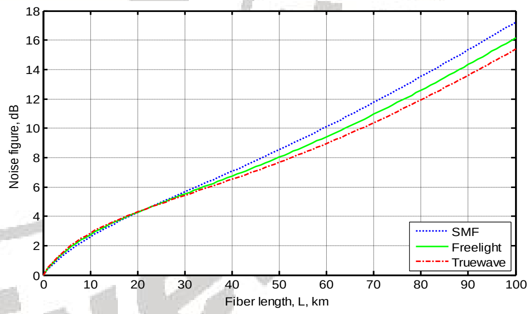

Fig. 6 Noise Figure as a function of fiber length at 100 mW pump power.

From both figures, it is clear that, when the length approaches zero there is no noise figure. In case of 800 mW pump power, the increase in NF from 0 to 3.5 dB can be clearly noticed in case of freelight and truewave fiber, but in case of SMF the NF increases over 3.5 dB at 10 km fiber. The reason for this increase is the decreasing gain with sharp pump depletion. Again, the obtained NF results versus fiber length are in a fair agreement with that obtained by A. Cem Çokrak et al. [9].

In case of low pump power 100 mW, Fig. 5, NF increases nearly linear with fiber length. For small fiber length less than 20 km, the Truewave has NF larger than SMF, but for fiber lengths greater than 20 km, the SMF has NF larger than Truewave. It reaches approximately 17 dB at 100 km fiber length.

Dependence of Raman Gain on Pump Power

Figure 7 shows the NF variations as a function of pump power for a span of 100 km fiber at a constant signal input power. The simulation is performed for three different fiber types and the pump power are increased from 0 to 1000 mW.

Clearly, it can be seen that NF decreases with the pump power. This is because the high gain in an active fiber with the total population inversion provided causes the spontaneous emission to stay in low levels. The NF of the FRA varies linearly with amplified spontaneous emission, ASE, power and inversely with the amplifier gain. Therefore, the NF of an FRA can be reduced to a minimum level by increasing the gain. The same behavior of NF versus pump power is obtained by D. Dimitropoulos et al. [10].

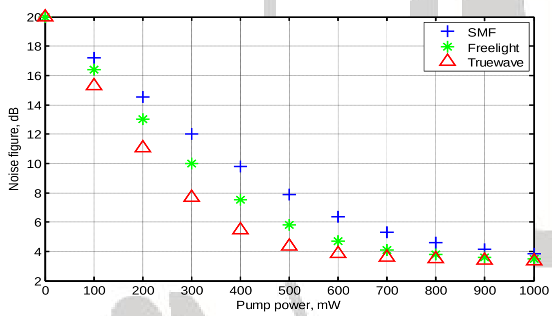

Fig. 7 Noise Figure as a function of pump power for 100 km different fiber types.

For a passive fiber with no DRA (on-off gain = 0) over 100 km, the NF degrades by 20 dB. By pumping with an on-off gain of 25 dB, the NF is reduced to ≈ 3.5 dB. Though, there is a high NF; it does not mean that distributed amplifiers are noisier than that of the lumped type as shown in Fig 8.

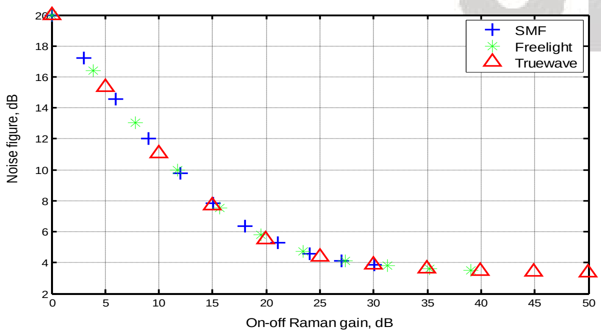

Fig. 8 Noise figure versus on-off Raman Gain for a 100km fiber varying input pump power using different fiber types.

V.3 Pump Noise Transfer

Based on Eqs. (23) and (24), a plot of the RIN transfer function as a function of the noise frequency is obtained. It measures how much of the pump modulation is transferred to the signal,

Table 2 Parameters used in RIN Simulation.

Fiber Type	Freelight	SMF	Truewave-RS
α_P (dB/Km)	0.260	0.263	0.256
Chromatic dispersion @1555nm (ps/nm/Km)	10	15	5
Pumping wavelength nm)	1455		
Signal wavelength (nm)	1555		

As shown in Fig. 9, for low RIN modulation frequencies, the RIN transfer is a maximum. This is because the different direction of propagation, the resulting electrical RIN transfer functions are second-order low-pass filters with cutoff frequencies $\alpha_P/2\pi\beta^{\pm}$ of the order of kHz and MHz for backward and forward pumping.

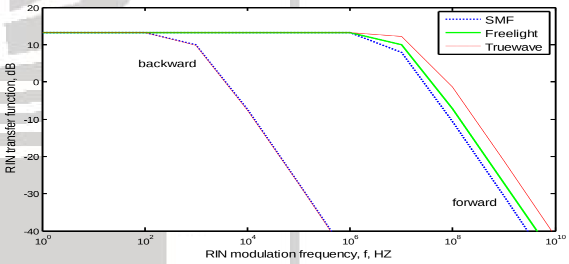

Fig. 9 RIN transfer function T^2, in the electrical domain, as a function of the RIN modulation frequency. Both forward and backward pumping schemes are considered for a transmission span of 100 km and GR =20 dB.

For very low frequencies, the noise on the pump is amplified (RIN transfer >0 dB) as it is impressed on the signal, but it is attenuated at higher frequencies. Less transfer occurs at higher frequencies since the averaging effect due to walk-off between the pump and the signal is more significant. The RIN transfer between the pump and the signal is reduced in a backward configuration, since any pump noise will be averaged over the length of the fiber. For the case of a forward pump and signal, the only averaging effect is from the walk-off due to chromatic dispersion as expressed in Eqs. (23) and (24) and shown in Fig.9.

In case of 10 dB Raman on-off gain, in forward pumping, RIN is enhanced by a factor of ≈ 6 in the frequency range of 0 – 2 MHz for the SMF. The frequency range increases to 9 MHz for the Truewave, when backward pumping is used, RIN is actually reduced at all frequencies except for frequencies below a few kHz as shown in Fig. 10. The results are compared to that obtained by B. Bristiel [4] showing a fair agreement.

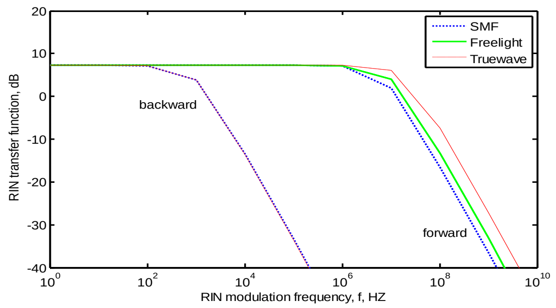

Fig.10 RIN transfer function T^2, in the electrical domain, as a function of the RIN modulation frequency. Both forward and backward pumping schemes are considered for a transmission span of 100 km and GR =10 dB.

In case of 20 dB Raman on-off gain, in forward pumping, RIN is enhanced by a factor of nearly 15 in the frequency range of 0 – 2 MHz for the SMF. The frequency range increases to 9 MHz for the Truewave because of its relatively low value of dispersion and the curve becomes more smoothed than in case of 10 dB Raman on-off gain as shown in Fig. 10.

In general, the noise enhancement is relatively small in the backward pumping configuration and for large values of *D*. This behavior can be understood physically as follows: the distributed Raman gain builds up as the signal propagates inside the fiber. In the case of forward pumping and low dispersion, pump and signal travel at nearly the same speed. As a result, any fluctuation in the pump power stays in the same temporal window of the signal. In contrast, when dispersion is large, the signal moves out of the temporal window associated with the fluctuation and sees a somewhat averaged gain. The averaging is much stronger in the case of backward pumping because the relative speed is extremely large (twice that of the signal group velocity).

In this configuration, the effects of pump-power fluctuations are smoothed out so much that almost no RIN enhancement occurs. For this reason, backward pumping is often used in practice even though, the NF is larger for this configuration. Forward pumping can only be used if fiber dispersion is relatively large and pump lasers with low RIN are employed.

VI. CONCLUSION

In this study, the rate and propagation equations characterizing FRAs are numerically solved. The results are graphically displayed. Gain, noise figure are obtained as functions of fiber length, pump power. In this way, the gain and NF performance could be simulated for the given FRA parameters or the required fiber parameters and signal/pump power values could be optimized for a desired FRAs gain-NF performance.

According to the obtained results, it is seen that the 800 mW pump power applied to FRA gives the minimum NF (≈ 3.5 dB). In addition, gain and NF are strongly dependent on the fiber length and pumping power. When the FRA is supplied with sufficient pump power, it is shown that FRA could be operated in saturation regimes leading to maximum gain and minimum NF. The differences between three different fiber types are satisfied.

Finally, the RIN as a function of noise frequency shows that the change in chromatic dispersion appreciably affects the forward pumping and has no effect in backward pumping.

RIN depends on Raman on-off gain. In case of 10 dB Raman on-off gain, in forward pumping, RIN is enhanced by a factor of nearly 6 in the frequency range of 0–2 MHz for the SMF and the frequency range increases to 9 MHz for the Truewave, while in case of 20 dB, RIN is enhanced by a factor of nearly 15 dB in the same frequency range for the same fiber type.

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