A simplified model and gain analysis of Raman-EDFA hybrid amplifier for DWDM system

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Abstract
Present communication provides a hybrid amplifier that can find suitable applications in DWDM optical network. The proposed hybrid amplifier includes EDFA and Raman amplifiers to envisage high gain characteristics for 64 channels in both the S + C band and S + C + L wavelength band (1545–1570 nm). Various parameters of the hybrid amplifier, such as doping concentration, pump power, pump wavelength, and fiber length, is chosen to optimize the gain profile. Aside from this, simulation upshots for individual amplifiers infer that EDFA shows a high gain of 22.1 dB for co-directional pumping, and the Raman amplifier deduces a gain of 12.2 dB for counter-directional pumping, whereas the EDFA-Raman hybrid amplifier bestows a substantial-high gain of 23.03 dB for co-directional pumping configuration. Additionally, it has been inferred that the hybrid amplifier offers a very minimal gain ripple of 0.8 dB, which indicates the gain is almost flat. The pump power, length, and doping parameters of EDFA and Raman amplifiers are optimized to get the flat gain of the Hybrid amplifier. It has been demonstrated that a maximum gain of 23.03 dB for a 64 × 10 Gbps, 25 GHz system is attainable up to 100 km of transmission distance. Hence, considering the aforementioned high gain and flat gain characteristics, the suggested EDFA-Raman hybrid amplifier opens up an avenue for future optical dense wavelength division multiplexing systems.

Keywords Hybrid amplifier · Raman amplifier · Erbium-doped fiber amplifier · Dense wavelength division multiplexing system

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1 Introduction

With the rapid increase in demand for enhancing the total capacity of the optical transmitting medium, scientists have headed towards the dense wavelength division multiplexing technique. Further, in the age of high-speed internet, the requirement for higher system capacity has become indispensable, which can be achieved by employing a hetero amplifier to envisage excellent amplification in an optical DWDM system. The aforesaid hybrid amplifier must be capable of boosting the gain characteristics with a feeble noise margin without any mode conversion. At the initial stage, researchers incline to use discrete conventional optical amplifiers such as Raman amplifiers, EDFA, SOA etc., in DWDM optical networks. But later, it is explored that the Raman amplifier suffers from many nonlinear effects like stimulated scattering, four-wave mixing and self-phase modulation effects, which ultimately worsen the signal. Similarly, EDFA also shows optical surge difficulties and higher consumption of power which leads to a decrease in the overall SNR of the system to an undesirable value. Hence to mitigate the aforementioned drawbacks of the individual amplifier, scientists and researchers have carefully chosen the amplifier parameters in order to design hybrid amplifiers which can deliver more gain, less noise margin and less gain ripple with excellent channel capacity in the order of terabits per second at reduces channel spacing. Besides this, the high-capacity hybrid amplifier caters to negligible losses during signal transmission. As far as a literature survey on hybrid amplifiers is concerned, a healthy number of research (Disurevire 1994; Headley and Agrawal 2005; Lee et al. 2005; Parekhan et al. 2008; Dipika D. Pradhan and Abhilash Mandloi 2018; Elbers and Glinkener 2001) have already been carried out pertaining to the same. In reference (Parekhan et al. 2008), authors have investigated EDFA characteristics for different pump configurations and optimized the gain parameters. Similarly, Simranjit Singh et al. (2014) implemented a genetic algorithm to enhance the gain profile of the Raman amplifier. Further, (Sing and Kelar 2012) proposed hybrid amplifier with a smaller number of channel spacing for various data rates which can find suitable application in DWDM optical networking systems. Furthermore, authors in Castellani et al. (2009); Martini et al. 2009; Cani et al. 2009), stated that Raman amplifier can be efficiently combined with EDFA to result from hybrid amplifier, which shows flexibility in spectral spacing and find major application in broadband communications. Again Singh (2016) have reported a hetero amplifier to reduce nonlinearities having nearly 21 dB gain and less than 7 dB noise figure. Considering the above issues, the present research deals with the Raman-EDFA hybrid amplifier to optimize the gain profile for numerous types of pumping. Andis Supe et al. investigated hybrid amplifier cascaded with Raman and fiber optical parametric amplification in a 16 channel at a high data rate for a multichannel WDM system. It was achieved a 0.2THZ wider bandwidth and 1.9 dB gain variation ratio (Supe et al. 2021). In reference (Dipika 2019) fluoride-based hybrid configuration comprising of Raman and TDFA amplifier is lucidly presented to accomplish maximum gain, low gain variation ratio (GVR) and minimum noise figure by solving the rate equations.

This paper proceeds as follows: the proposed model for hybrid amplifier has been explained in Sect. 2, whereas numerical analysis is deduced in Sect. 3. Result discussions are presented in Sect. 4, and finally, conclusions are described in Sect. 5.
2 Proposed hybrid amplifier

In the current communication, the DWDM system has been lucidly analysed by considering a hybrid amplifier that includes both Raman amplifier and EDFA as shown in Fig. 1, where the employed DWDM system is capable of multiplexing 64 signals through an optical multiplexer. The DWDM transmitter is designed to generate different signals having a wavelength in the range of 1530–1581 nm. Here, a pump source of 50 mW and 980 nm is used to excite EDFA, whereas another laser source having 400 mW power and 1413 nm is used to pump the Raman amplifier. Aside from this, 64 channel DWDM receiver has been deployed to receive the demultiplexed signal from the hetero amplifier. Further, simulation is performed towards improving the gain characteristics of both Raman amplifier and EDFA individually by suitably manipulating various parameters of amplifiers such as ion density, length of the fiber, core radius, and numerical aperture of the fiber etc. Finally, the two amplifiers are cascaded to study the gain characteristics of hybrid amplifiers to get optimum outcomes.

3 Mathematical analysis

Mathematical analysis for a hybrid amplifier is based upon rate equations of both Raman amplifier and EDFA. The rate equations of EDFA are modelled with three levels. Let the total erbium in the core of EDFA is denoted as $N_t$. Further, $N_1$ and $N_2$ represent the population density in the ground state and metastable state, respectively. Hence, for the ground state, the rate of change in the population (Emori et al. 1999) can be expressed as:

$$N_1 + N_2 = N_t$$

(1)
where \( \nu_s \) is the signal frequency, \( P_{PE} \) and \( P_{SE} \) are the pump power and signal power of EDFA.

\( \Sigma P_a \) is the absorption cross-section, \( \sigma_a \) absorption cross-section at signal frequency, whereas \( \nu_s \) be the emission cross-section at the signal frequency. Similarly, \( a_p \) represents the fiber cross-sectional area for \( \lambda_p \) and denotes the fiber cross-sectional area for \( \lambda_s \), and \( \tau_{sp} \) is the spontaneous emission lifetime during the transition from \( E_2 \) to \( E_1 \). Similarly, the rate of change in population (\( N_2 \)) at the upper amplifier level can be mathematically expressed as below (Mahran 2015)

\[
\frac{dN_2}{dt} = \frac{\sigma_{pa} P_{PE} N_1}{a_p h \nu_p} - \frac{\sigma_{sa} P_{SE} N_1}{a_s h \nu_s} - \frac{\sigma_{se} P_{SE} N_2}{a_s h \nu_s} - \frac{N_2}{\tau_{sp}}
\]  

(3)

Under steady-state condition

\[
\frac{dN_2}{dt} = 0
\]

Putting this in Eq. (3) and on rearranging, we can write

\[
\frac{N_2}{\tau_{sp}} = \frac{\sigma_{pa} P_{PE} N_1}{a_p h \nu_p} + \frac{P_{SE}}{a_s h \nu_s} \left[ \sigma_{sa} N_1 - \sigma_{se} N_2 \right]
\]

(4)

Then by ignoring the effect of spontaneous emission, variation of pump power (\( P_p \)) and signal power (\( P_S \)) along the length of the amplifier is calculated as below:

\[
\frac{dP_{SE}}{dz} = \Gamma_S \left( \sigma_{se} N_2 - \sigma_{sa} N_1 \right) P_{SE} - a P_{SE}
\]

(5)

\[
\text{Gain} = \frac{P_{SO} - R}{P_{SI} - R} = \exp \left[ \frac{L_R \exp \left\{ -\Gamma_S \sigma_{sa} N_1 L_E + \Gamma_S \left( \sigma_{sa} + \sigma_{se} \right) N_{2av} \right\} g_R}{-\alpha_s \exp \left\{ -\Gamma_S \sigma_{sa} N_1 L_E + \Gamma_S \left( \sigma_{sa} + \sigma_{se} \right) N_{2av} \right\} L_R} \right]
\]

(6)

4 Results analysis

A high gain hybrid amplifier is illustrated in this communication for the optical DWDM network, where the hybrid amplifier includes both Raman amplifier and EDFA. Here, we have optimised both the Raman amplifier and EDFA individually, and further, we formed a hybrid amplifier, which shows excellent gain enhancement. We analysed gain characteristics of the Raman amplifier for different pumping configurations such as co-directional, counter directional, and bidirectional pumping. We found that Raman amplifier bestows maximum gain in counter directional pumping configuration. Figure 2 depicts the gain characteristics of the Raman amplifier for counter directional pumping, where gain in dB scale is plotted in the vertical axis, and frequency in THz is shown in the horizontal axis. Again, here gain of the hetero amplifier profile is scrutinised for frequency ranges from
189.4\text{THz} \text{ to } 196 \text{ THz}. From this figure, it is explored that the highest gain of 8.8 dB is achieved at 193.7\text{THz}, which can be regarded as an encouraging outcome.

Similarly, simulation is performed to investigate the gain profile of EDFA for different pumping configurations, and it is revealed that optimised value of gain is obtained for co-directional pumping. Figure 3 shows the gain characteristics of EDFA for co-directional pumping configuration where the gain profile is analysed for frequency ranges from 189.4\text{THz} to 196 \text{ THz} and from this figure it can be clearly stated that optimised gain of 13 dB is attained at 189.5\text{THz}. Also, the gain profile is almost flat, which leads to negligible gain variation ratio and stability in gain characteristics.

Further, we cascaded both Raman amplifier and EDFA to design a hybrid amplifier, which shows outstanding gain characteristics and can play an essential role as an amplifier in an optical DWDM network. On cascading, it is shown that gain is substantially increased to 40 dB at frequency 193.1\text{THz}, which is depicted in Fig. 4. Also, from this figure, it is revealed that this excellent gain is obtained at directional pumping, where the gain variation ratio is in an acceptable range (Figs. 5, 6).

The system BER and Quality factors are directly affected by crosstalk. Due to nonlinearities in the optical amplifier, the crosstalk effect arises. Figures 7 and 8 show the Quality factor and BER characteristics of the proposed amplifier. The variations in BER and quality factors are due to nonlinearities and cross talk in the system. We could observe how the BER and Q–factor change in relation to the bit rate. The BER worsens in its receiving side with the increasing bit speed and the length of the optical fibre. The BER and Q–factor dependent on the length of the optical fibre and bit speed. The acceptance BER is less than $10^{-9}$, and the quality factor is less than 8 dB.

Hence, if we compare the individual amplifier with a hybrid amplifier, then it can clearly state that gain for hybrid amplifier is nearly four times high as compared to the
Fig. 3  Gain characteristics of EDFA for co-directional pumping configuration

Fig. 4  Gain characteristics of Raman-EDFA hybrid amplifier for co-directional pumping configuration
Fig. 5  Gain characteristics of EDFA, Raman and Raman-EDFA hybrid amplifier for DWDM system

Fig. 6  Noise figure (NF) characteristics of EDFA, Raman and Raman-EDFA hybrid amplifier for DWDM system
Fig. 7 Q-factor as a function of signal wavelengths of EDFA, Raman and Raman-EDFA hybrid amplifier for DWDM system.

Fig. 8 BER as a function of signal wavelengths for Raman-EDFA hybrid amplifier for DWDM system.
individual optical amplifier. So, by incorporating hybrid amplifiers in optical networks, the need of the number of required amplifiers reduces over a long-distance transmission.

5 Conclusion

Detail studies on the gain characteristics of the hybrid amplifier are meticulously addressed in this present research, where the proposed hybrid amplifier consists of a cascade connection of Raman and EDFA. Further gain profile of both individual and hybrid amplifiers is optimised by suitably selecting different amplifier parameters such as fiber length, pump power, doping concentration etc. Apart from this, simulation outcomes revealed that EDFA shows a high gain of 13 dB for co-directional pumping, and the Raman amplifier infers a gain of 8.8 dB for counter-directional pumping, whereas the EDFA-Raman hybrid amplifier bestows a substantial-high gain of 23.03 dB for co-directional pumping configuration. So, the proposed high gain hybrid amplifier surely can find priority in the optical DWDM system for fruitful amplification.

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