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Hybrid Raman/Erbium-Doped Fiber Amplifiers for WDM Transmission Systems

Sunil P. Singh*

Department of Physics, Kamla Nehru Institute of Physical and Social Sciences, Sultanpur (UP)-228118, India
*Corresponding author: s_psingh74@rediffmail.com

Abstract As light pulses propagate along the optical fiber, their energy dissipates. Beyond a certain distance the number of photons in pulses becomes too small to be detected. The optical pulses in fibers are energized by utilizing optical fiber amplifiers. The rapid growth of the internet and data traffic in optical fiber communication networks has stimulated the study of wideband optical amplifiers. Widening the bandwidth of fiber amplifiers is the primary issue in enlarging the capacity of wavelength-division multiplexed (WDM) transmission systems. This may be achieved by hybrid Raman/Erbium-doped fiber amplifiers. In this paper hybrid Raman/Erbium-doped fiber amplifier is simulated and almost flat gain of 21 dB is obtained for 1530-1565 nm wavelength range.

Keywords: *hybrid fiber amplifier, raman fiber amplifier, erbium-doped fiber amplifier, WDM*

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1. Introduction

The increase in demand for higher transmission capacity in wavelength division multiplexing systems; the channel speed, channel number, and spectral efficiency need to be upgraded. Wide-band and flat gain optical fiber amplifiers are indispensable for wide-band and long distance WDM optical network systems around 1550 nm. To this end, Raman amplifiers have become essential in overcoming the limitations of gain tilt and noise figure (NF) of conventional doped fiber amplifiers [1,2,3,4,5].

The spectral variation of the amplifier gain may result in significant transmission impairments due to gain tilt and ripple in wavelength division multiplexed transmission systems. Passive devices may be used to attenuate selected channels to reduce gain tilt and ripple. However, this approach increases system components hence power loss and therefore overall cost of the system. Another approach is to use Raman amplifiers in conjunction with erbium-doped fiber amplifiers (EDFA) to get flattened and ripple free gain over the bandwidth [6,7].

Hybrid Raman/semiconductor optical amplifier and hybrid Raman/erbium-doped fiber amplifier are discussed in this paper. Simulation study of hybrid Raman/erbium-doped fiber amplifier is carried out by using optisystem and optiamplifier software. A distributed Raman amplifier is combined with erbium gain medium to eliminate gain tilt and ripple. Optisystem software is capable of simulating and analyzing broad spectrum of optical networks. It tests and optimizes virtually any type of optical fiber network and easier to handle as compared to other software dealing with optical communication systems.

2. Hybrid Raman/Semiconductor Optical Amplifier

The improvement in the cost and performance of semiconductor optical amplifier led it to metro and access optical networking applications. Unlike ultralong-haul and long-haul applications, which put limit on total capacity and reach, metro and access systems must balance performance with flexibility and cost. The metro and access systems often require widely spaced wavelength plans which can take full advantage of inexpensive standardized technology such as the un-cooled laser transmitters used in passive optical networks (PON) or un-cooled lasers adhering to the coarse wavelength division multiplexing (CWDM) grid [8,9].

Initially hybrid Raman/semiconductor optical amplifiers employed distributed designs, for which pump light is launched into the transmission fiber, forming a distributed Raman amplifier. The distributed Raman stage is then combined with a semiconductor optical amplifier (SOA) stage to form the hybrid amplifier as shown in Figure 1. This arrangement improves the gain and noise performance of semiconductor optical amplifiers for dense wavelength-division multiplexing (DWDM) applications [8,9]. The Raman stage increases significantly the total gain bandwidth of hybrid amplifier, approaching to the 13.2 THz frequency shift of the Raman process [10,11,12].

The gain spectra of the semiconductor optical amplifier and Raman stages are arranged such that the monotonically increasing gain of the distributed Raman stage compensates the monotonically decreasing gain of the semiconductor optical amplifier stage. This results in broad and flat gain over any wavelength band supported by single-mode fiber. The peak gain of the hybrid amplifier is determined by the peak gain of the semiconductor optical amplifier, with the Raman stage only providing gain-tilt compensation. Thus, this arrangement requires moderate Raman gain (< 8 dB) and therefore a single moderate Raman pump. This arrangement not only produces the widest possible gain spectrum from the semiconductor optical amplifier-Raman combination, while minimizing the cost and power required for the Raman pump, but also minimizes saturation-induced wavelength-division multiplexing (WDM) crosstalk in the semiconductor optical amplifier. As input powers increase into the saturation regime, the carriers at the top of the conduction band (shortest-wavelengths) are the first to be depleted, resulting in lower saturated input powers (i.e. increased crosstalk) with decreasing wavelength [12]. So the best arrangement to minimize wavelength-division multiplexing crosstalk is to place the entire WDM spectrum to the long-wavelength side of the semiconductor optical amplifier gain peak.

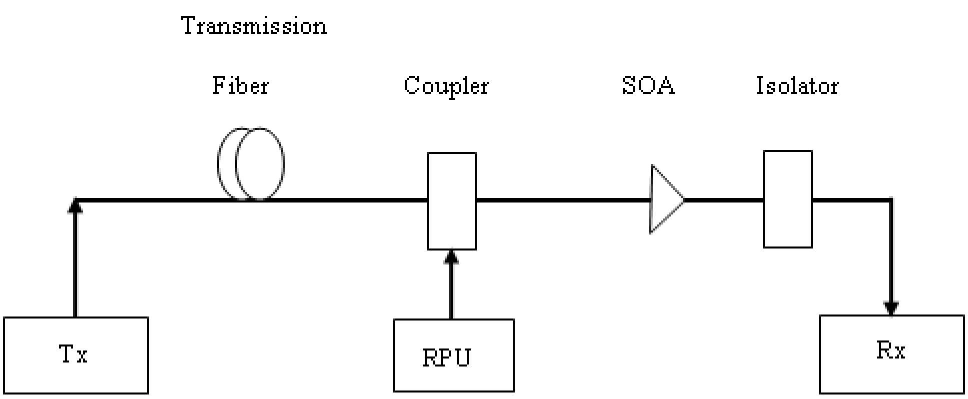

Figure 1. A schematic diagram of hybrid Raman/Semiconductor optical amplifier. RPU stands for Raman pumping unit

3. Hybrid Raman/Erbium-Doped Fiber Amplifier

It has been shown that wavelength-division multiplexing (WDM) technology offers a cost effective way to increase the transmission capacity by transmitting closely spaced number of channels over a single fiber. However, the number of different wavelength channels that can be launched into a single fiber is severely restricted by the fiber-attenuation and transmission bandwidth of fiber [13,14]. This problem can be resolved by widening the bandwidth of the transmission link. Hybrid Raman/Er-doped fiber amplifier (HFA) is one of the promising technologies to provide a widened and flattened gain-bandwidth over the C-band (1530-1565 nm) and L-band (1565-1625 nm). A typical hybrid Raman/Er-doped fiber amplifier is shown in Figure 2. Kawai et al. experimentally demonstrated a WDM system over the C+L band via HFAs enabling 900 km transmission of 14 × 2.5 Gbit/s with 60 km repeater spacing [2] and Neilsen et al. demonstrated 3.28 Tb/s (82 × 40 Gb/s) transmission in a 3 × 100 km system [5].

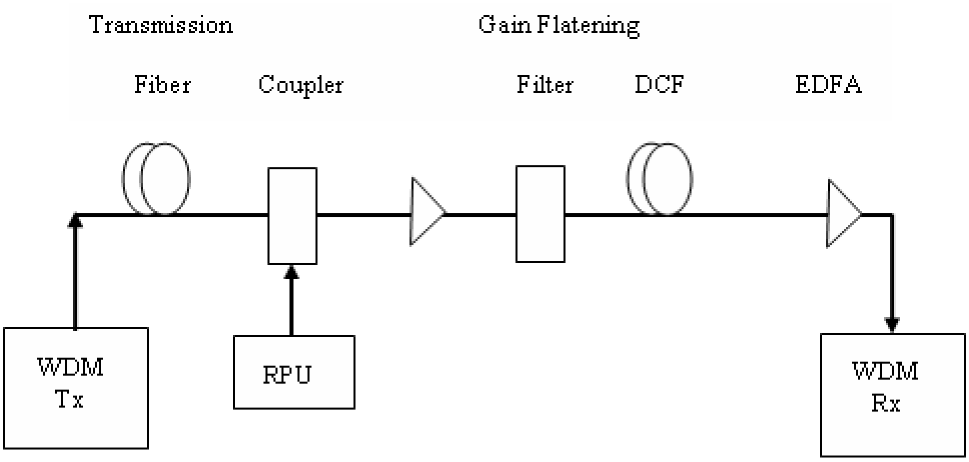

Figure 2. A typical hybrid Raman/Erbium-doped fiber amplifier. RPU stands for Raman pumping unit

The use of hybrid Raman/Er-doped fiber amplifier provides an overall reduction of the amplified spontaneous emission (ASE) noise at the receiver end. The hybrid fiber amplifiers can be designed to minimize nonlinear impairments along transmission fiber due to high path averaged signal power. Such nonlinear impairments are not desired because they will degrade the optical signal-to-noise ratio (OSNR) at the receiver. An optimal configuration of hybrid Raman/Er-doped fiber amplifier was reported with successful exploitation of fiber nonlinear impairment and ASE noise to maximize the output optical signal-to-noise ratio [15,16,17]. Low-noise Raman amplification can be applied to enhance the system margin in WDM transmission systems. The enhanced margin can be utilized in several ways, such as to increase the separation between amplifiers, to increase the overall reach of the transmission system, and to increase the spectral efficiency of transmission.

4. System Design and Results

The finest amplification span length is one that facilitates the best trade-off between the low-cost requirements and stringent system performance. Long amplifier spans result in high input powers to maintain a good optical signal-to-noise ratio (OSNR), leading to increased effects of nonlinearities. In such situation a best balance between the high optical signal-to-noise ratio and nonlinear impairments is necessary. The solution of this problem is use of distributed Raman amplification (DRA). As compared to Erbium-doped fiber amplification scheme, DRA improves significantly the link's OSNR. Distributed Raman amplifier in combination with Erbium-doped fiber amplifier termed as, hybrid fiber amplifier, can be used for better control of nonlinear effects. In our system reverse dispersion fiber (RDF) is used instead of dispersion compensating fiber (DCF). In DCF based Raman amplification systems pump power efficiency is very low and a significant amount of pump power is unused and wasted. This can be attributed to strong nonlinear effects in dispersion compensating fibers.

A distributed hybrid Raman/Erbium-doped fiber amplifier is simulated and optimized in 1530 nm to 1565 nm wavelength range. The schematic design of the system under consideration is shown in Figure 3. A 60 km (30 km SMF+30 km RDF) transmission fiber is pumped by a backward Raman pumping unit (BRPU). This unit consists of pumps at wavelengths 1440 nm and 1450 nm with pump powers 120 mW and 60 mW respectively. An Erbium-doped fiber of length 8 m is forward pumped by 980 nm laser diode of pump power 12 mW. Forward pumping in Erbium gain medium and backward pumping in Raman amplifiers give better conversion efficiency and noise figure. The fiber parameters used in simulation are given in Table 1. Almost flat gain of 21 dB with gain tilt ±0.4 dB is obtained over entire wavelength range. The noise figure is well below 7 dB. Gain and noise figure spectra of the hybrid amplifier is given in Figure 4. The Noise figure is slightly high in lower signal wavelength region because of allocation of higher pump energy in this range. Thermal instabilities, pump-to-pump Raman interactions and power fluctuation in pumps result in more noise figure in lower signal wavelength region.

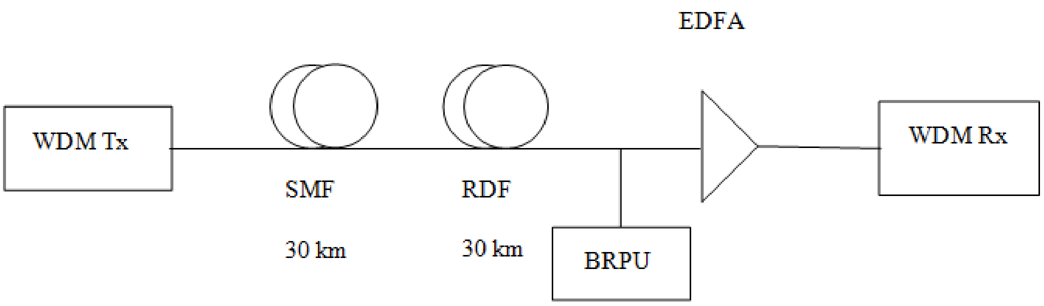

Figure 3. Schematic design of hybrid Raman/Erbium-doped fiber amplifier (HFA)

Table 1. Fiber parameters used in simulation at 1550 nm

Fiber Type	Group Velocity Dispersion (ps/nm/km)	Dispersion Slope (ps/nm^2/km)	Loss (dB/km)	Effective Area(μm^2)
SMF	16	0.07	0.21	78
DCF	-90	-0.35	0.50	20
RDF	-16	-0.07	0.23	30

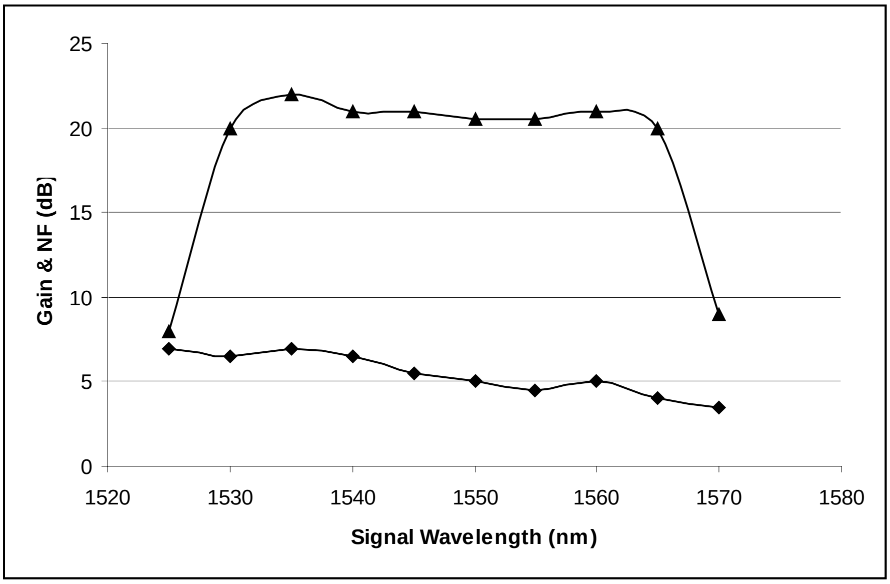

Figure 4. Gain and noise figure of hybrid Raman/Erbium-doped fiber amplifier (HFA) for different signal wavelengths

5. Conclusion

Hybrid Raman/erbium-doped fiber amplifiers are promising technology for future dense wavelength division multiplexed (DWDM) multiterabit systems. Hybrid Raman/erbium-doped fiber amplifiers are designed to maximize span length and/or to minimize nonlinear impairments and to enhance bandwidth of EDFAs. A flat gain of about 21 dB is obtained over entire wavelength range. The noise figure is well below 7 dB.

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