Optical Engineering

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Optical Engineering 54(10), 100901 (October 2015)

REVIEW

Review on recent developments in hybrid optical amplifier for dense wavelength division multiplexed system

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Abstract. Hybrid optical amplifiers (HOAs) are crucially important for broadband band amplification, and are widely deployed in high-capacity dense wavelength division multiplexed systems. We summarize the present state-of-the-art in this rapidly growing field. In addition, theoretical background and various inline configurations of optical amplifiers have been presented. Various issues such as gain flatness, gain bandwidth, transient effect, and crosstalk were presented in HOAs. Results show that the HOAs provide better gain flatness without using any expensive gain flattening techniques, and an acceptable range of gain, noise figure, bit error rate, and transience. [DOI: 10.1117/1.OE.54.10.100901]

Keyword: hybrid optical amplifier; dense wavelength division multiplexed system; gain flatness; crosstalk.

Paper 150953V received Jul. 14, 2015; accepted for publication Sep. 1, 2015; published online Oct. 6, 2015.

1 Introduction

The most recent information indicates that multimedia and high-capacity wavelength division multiplexed (WDM) networks need high bandwidths. The optical fiber is the only medium that offers such a huge bandwidth by means of a better performance.[1] Since 1980s, optical fiber communication was one of the better alternatives for the rapidly growing industries. It can also be used to fulfill the demands of broadband applications. In the early days, optical fiber could not be used for commercial applications because it had a very high attenuation of up to 1000 dB/km. But currently, various optical fibers are available with low losses (0.2 dB/km) which can be efficiently utilized in various multiterabit and bandwidth efficient applications.[2]

For efficient utilization of bandwidth, dense wavelength division multiplexing is a technique which allows parallel transmission of various optical channels at different frequencies on a single fiber.[3] Early WDM systems were initiated in the late 1980s using two broadly spaced channels which belong to two different bands i.e., 1310 and 1550 nm.[4] In the early 1990s, the second generation of WDM was presented, in which more than six optical channels were processed. This is called a narrow-band WDM system since the channels are located over the wavelength grid with compact spacing (i.e., 400 GHz). In those days, the optical communication system with reduced channel spacing was the hot research topic as the way to efficiently utilize the bandwidth for cost effective solutions. In the beginning of 1990s, dense wavelength division multiplexed (DWDM) systems were developed with 20 to 50 channels with a 100 to 200 GHz interval. By the late 1990s, the great evolution of DWDM systems had been observed with the transmission capability of 60 to 160 parallel channels, densely packed at 50 GHz.[5,6]

In the optical fiber communication, the degradation in signal along with the transmission distance is present due to the various nonlinearites and other dominating errors.[7] The number of users can be improved by increasing the power budget, or reducing the losses in the network by using optoelectronic regenerators. But such regenerators become quite complex, time consuming, and costly for DWDM systems because of the various processing levels, i.e., demultiplexing, optical-electrical-optical (O-E-O) conversion, and multiplexing. This reduces the reliability of the system or network as a regenerator is an active device. Therefore, upgradation of the multichannel WDM network will require optical amplifiers which directly amplify the transmitter optical signals without going through O-E-O conversions.[8] The optical amplifiers are mostly used in WDM applications as all the channels with different wavelengths can be simultaneously amplified. An optical amplifier increases the light signal power as a preamplifier (by placing it just after the transmitter) and as a postamplifier (by placing it just before the receiver). As the need of higher capacity and long haul nonrepeated transmission distance increases, the advent transmission methods have to be investigated to fulfill the demand of current technology. There are so many nonlinear effects [such as self-phase modulation (SPM), cross phase modulation (XPM), gain saturation, four wave mixing (FWM), and so on] and phase noises present in the optical amplifiers which restrict its used for various applications in optical communication systems. Therefore, there is a demand for optical amplifiers which provide a better performance (in term of nonlinearities, transient performance, power crosstalk, gain flatness, larger gain bandwidth, and so on) for DWDM systems. In our previous work (reported in Ref. 5), we have presented the various concepts of optical amplifiers, but little introduction of hybrid optical amplifier (HOA) was provided. In this review paper, in an extension of our previous work, we have included the various advanced concepts/ issues of the HOAs including gain flatness, transience, crosstalk, and so on.

At present, the HOAs are promising and widely used technology for today's high-speed broadband applications to enhance the system performance without using costly techniques.[9] Like most technologies, HOAs also come with some drawbacks that should be taken into account. These

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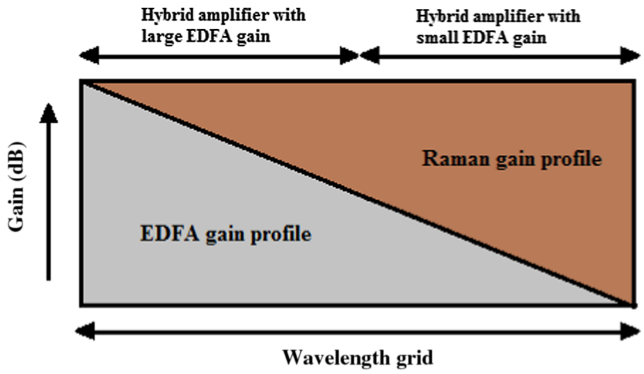

Fig. 1 General presentation of gain partitioning in hybrid Raman-erbium doped fiber amplifier (EDFA).

include transient response, induced crosstalk, as well as other sources of noise that are particular to fiber Raman amplifiers (FRAs), such as double Rayleigh backscattering, pump-mediated relative intensity noise transfer, and problems with nonlinearities, due to high-path average power in the fibers. The aim behind proposing the HOA is to: (1) increase the gain bandwidth of a WDM system with the least gain variation over the effective bandwidth, (2) reduce the losses due to induced nonlinearities, and (3) avoid the constraint of high-cost gain flattening filters and multipumps for large gain flatness.

In general, the combination of more than one optical amplifier in any configuration is called an HOA. Islam[10] described the net gain of the hybrid Raman-erbium doped fiber amplifier (EDFA) HOA, G_{Hybrid}, as the sum of the two individual gains (in dB) of Raman and EDFA, respectively. Gain partitioning in a hybrid amplifier is as shown in Fig. 1. Therefore, in the case of Raman-EDFA HOA the net gain is

$$G_{\mathrm{Hybrid}} = G_{\mathrm{EDFA}} + G_{\mathrm{Raman}}.$$

The HOAs are the enabling and capable technology for high-capacity DWDM systems, as also described in Refs. 9, 11, and 12.

From Fig. 1, it can be seen that some part of the wavelength band is efficiently amplified by EDFA with a high gain and the other is amplified by Raman, which means that over the whole wavelength grid, a single amplifier shows a large variation. But if the Raman amplifier is combined with EDFA in any configuration (cascaded or parallel), then the large gain flatness can be achieved even with the highest possible gain.

1.1 *Comparison between Optical Amplifiers*

The basic principle of all the optical amplifiers is almost same, but its existence in a particular application depends on the features and constraints, as described in Table 1. As onchip switches, wavelength converters or logic gates the semiconductor optical amplifiers (SOAs) are the best alternatives because of their compact size and less power compensation requirement as compared with Raman and EDFA. In addition, the single Raman and SOA, the HOAs and EDFAs are the best alternatives for the high-gain application. The EDFA, Raman, and HOAs make the system costly as it will require a high-pump power to operate, while the SOAs need only an electrical bias supply at levels of around 50 mA. In addition, the nonlinear crosstalk and intermodulation distortion in DWDM systems are negligibly small in fiber amplifiers as compared with SOAs. According to the various features of an optical amplifier, described in Table 1, the HOA can be recommended for a high-capacity DWDM system where the high gain and/ or gain bandwidth with less variation is required. In addition, for limited users and a short haul DWDM communication system, the single EDFA or Raman can be used with an appropriate pump wavelength and pump power, respectively.

1.2 *Basic Arrangements of Inline Optical and Hybrid Optical Amplifiers*

Masuda[13] proposed the four types of hybrid configurations and it was extended by Lee et al.,[9] who presented various configurations of low-cost HOAs using a single pump. Further, we have extended the previous work by addressing the various relative issues (such as gain-flatness, gain

Table 1 Comparison between optical amplifiers.

Feature	EDFA	SOA	Raman	HOA
Wavelength of operation	1525 to 1565 nm	Any (but limited to <50 nm bandwidth)	Any, depend on pump wavelength and power	Any with high gain[a]
Gain bandwidth	10 to 40 nm	20 to 50 nm	20 to 50 nm	>80 nm with the large gain flatness[a]
Noise	Low	Low	Very low	Low
Directions	Unidirectional and bidirectional	Unidirectional and bidirectional	Unidirectional and bidirectional	Unidirectional and bidirectional
Polarization sensitivity	0 dB	> few mW	0 dB	Vary[a]
Optical pump wavelength	980, 1400 to 1500 nm	NA	Stoke shift below signal	Same as COAs, but residual pump wavelength can be from
Optical pump power	20 to 50 mW	NA	100 to 500 mW	Same as COAs, but residual pump it can be from 100 to 600 mW

[a]Depends on which amplifiers are used in hybrid configuration.

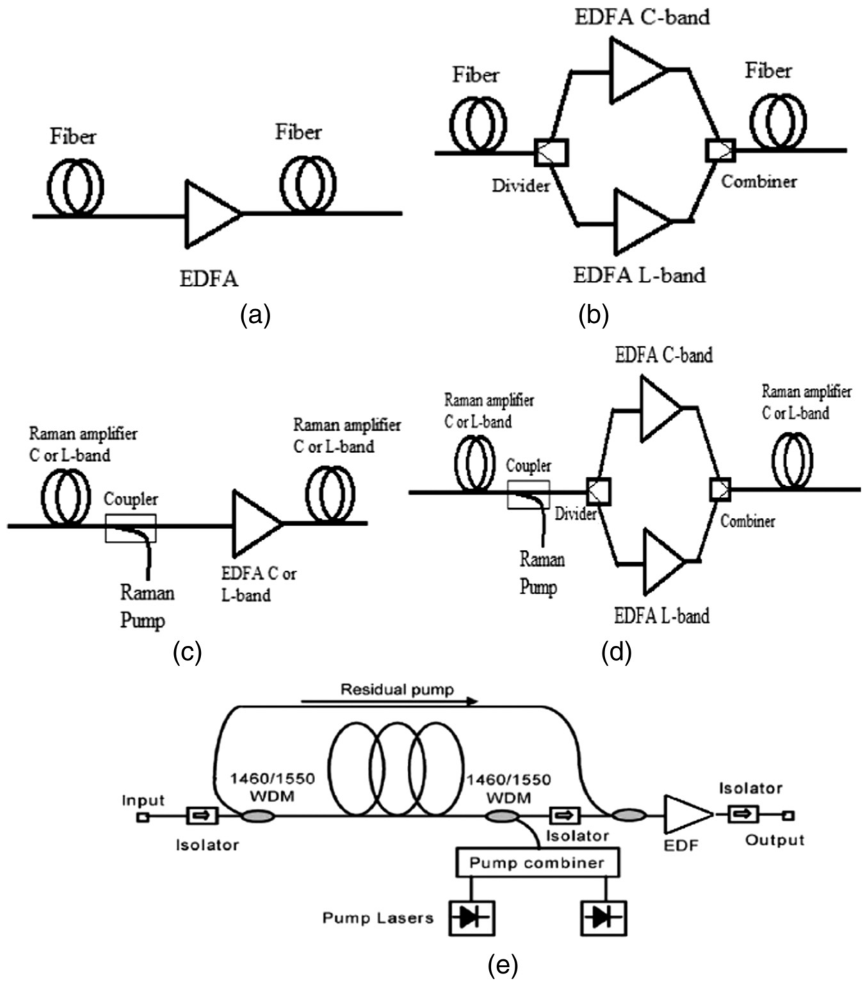

Fig. 2 Architectures of inline optical and hybrid optical amplifiers: (a) a EDFA; (b) dual C-or L-band EDFAs in parallel configuration; (c) C + L band Raman-EDFA Hybrid optical amplifiers (HOA) in cascaded configuration; and (d) Raman-EDFA HOA, where the EDFAs are used in parallel configuration (CMB: combiner, DIV: divider); (e) cost effective Raman-EDFA HOA with residual pump.[9]

bandwidth, transience, crosstalk, optimum placement, and so on) present in HOAs.[14–19] Figure 2 shows some basic architectures of an inline amplifier.

Different configurations of optical amplifiers are shown in Fig. 2. Figures 2(a) and 2(b) show the configurations using a single EDFA (amplify limited bandwidth) and multiple/parallel EDFAs (amplify multiple bands), respectively. In addition, for amplifying a large gain bandwidth, Figs. 2(c) and 2(d) show the configurations of hybrid Raman and EDFAs. Figure 2(e) shows a cost effective configuration of HOA using residual pumping. In this configuration, a single pump is used to amplify both the Raman and EDFA which directly reduces the cost.

2 Historical Development of Hybrid Optical Amplifiers

Optical amplifiers are the essential elements in advanced fiber-based telecommunications networks. They provide the means to counteract the losses caused by the fiber, inline optical components, and power division at optical splitters.[20] Hence, amplifiers facilitate the high-global capacities, long transmission spans, and multipoint-to-multipoint connectivity required for operation with growing data volumes. In their absence, fiber networks would need many more O-E-O converters for the electronic repeating, retiming, and reshaping of attenuated and noisy bit streams. The consequences would be transmission at significantly lower data rates, requiring numerous fibers in each cable; more node buildings, often in an expensive city center locations; larger equipment cabinets, occupying valuable floor space; increased total power consumption, with its associated environmental impact and, very importantly, higher operating costs to be passed on to the customer.[21] For these reasons, optical amplifier technologies have been the key route to ubiquitous information availability.

Fiber amplifiers offer numerous advantages over electronic regenerators including: (1) the system data rate can be changed as per the requirement, (2) it can be possible to transmit multiple channel rates, and (3) there is no need to modify the inline transmission links or components to achieve the above said advantages. This latter feature contributed to the realization of DWDM systems, in which terabit/sec data rates have been demonstrated.[22] Aside from rare-earth-doped glass fibers, which provide gain through stimulated emission, there has been renewed interest in FRA, in which gain at the signal wavelength occurs as a result of glass-mediated coupling to a shorter-wavelength optical pump. As the load on the network is increasing continuously, hybrid amplifiers are a promising and widely used technology to amplify those closely spaced large numbers of channels with a better performance. The intent behind proposing the HOA is to further enhance the gain bandwidth of the WDM system, to diminish the losses due to induced nonlinearities, and to avoid high-cost gain flattening filters or multipumps for better gain flatness.

Improving the gain-bandwidth product of optical amplifiers is the most effective way to efficiently utilize the fiber bandwidth which leads to the enhancement of the number of WDM channels. The gain-bandwidth can be improved by: (1) using novel fiber host materials for EDFA, (2) using gain-equalizing optical filters,[23] (3) employing parallel architecture of two gain-bands EDFAs,[13] (4) using Raman amplifier with multipump wavelengths,[10] and (5) combining Raman with EDFA.[16]

Delavaux et al.[23] demonstrated the two efficient hybrid EDFA structures as a power booster. The two simulation pumps (tuned at 980 and 1480 nm) are used to pump the proposed amplifier. The offered amplifier provides large gain over a broad spectrum (>35 nm) with a better gain flatness (i.e., 1 dB) and output power (17 dBm). They carried out a new hybrid pumping scheme to avoid an interchannel crosstalk effect for pumps of the same wavelength with different pumping powers.

Masuda et al.[24] proposed the broadband HOA which provides a large gain over 65 nm (1549 to 1614 nm) of bandwidth. To obtain that much of a large gain bandwidth, various external schemes and optical components are used, i.e., a new pumping scheme, gain equalizer, and backward pumped Raman amplification. After optimizing the two stage EDFAs, they achieved a broad gain bandwidth of 49 nm ranging from 1556 to 1605 nm. The proposed system becomes unstable due to low-Raman gain compression and high-pump power. Thus, if a Raman amplifier is combined with EDFA, then the bit error rate (BER) and optical signal-to-noise ratio (OSNR) performance can be improved while still keeping the gain and output power at its highest value.

Kawai et al.[25] successfully transmitted the 14×2.5 Gbps WDM signals over 900 km using a highly gain flattened hybrid amplifier. In this investigation, the proposed hybrid amplifier provides better results as compared with a single or discrete EDFA.

Thomas et al.[26] proposed a hybrid thulium dope fluoride amplifier (TDFA) and distributed Raman amplifier (DRA) for short wavelength amplification. Using the offered hybrid amplifier, a gain of greater than 20 dB over a broad bandwidth (that is 75 nm ranging from 1445 to 1520 nm) was achieved with noise figures (NFs) of between 7 and 8 dB. Also, due to the similar gain profile of these amplifiers, the expensive gain flattening techniques are exempt from achieving a large gain flatness.

In a Raman amplifier, it is better to use a single pump wavelength instead of multiple pumps because: (1) it is easy to design with minimum cost and (2) the profile of the Raman gain spectrum is independent of channel loading. Among these two, the second point is very important because the gain shape of the saturated Raman amplifier with multiple pumps can be a complex function of the present channels. Bolshtyansky et al.[27] demonstrated the hybrid flat or tilt free amplifier in a new wavelength range (i.e., L+ band ranging from 1610 to 1640 nm) using a single pump tuned at 1536 nm. It was suggested that to reduce the microbend losses, the Raman gain media should be improved by optimizing the parameters.

Zimmerman and Spiekman[28] studied several gain flattening approaches through numerical simulation. These methods included the hybrid Al-codoped with Al/P-codoped EDFAs, Raman-EDFA HOA, and gain equalizer optical filters. After comparison, it was reported that the gain equalizer filter was the most appropriate method to increase the gain bandwidth product of the EDFAs with a large gain flatness. On the other hand, Raman-EDFA HOA provided the maximum reachable bandwidth without using any high cost or power inefficient optical filters.

Guimarles et al.[29] built the setup in which EDFAs are used as a booster and as an inline amplifier. The hybrid EDFA and fiber optic parametric amplifier (FOPA) was used as a preamplifier. It was reported that for inline amplification, the FOPAs show better results as good as EDFAs. It was observed that the hybrid EDFA and FOPA deliver improved performance as compared with EDFAs. The performance has been improved in the terms of gain, gain bandwidth, NF, and so on. As compared with back to back values, the proposed hybrid optical preamplifier also improved the system power penalty by 3.2 dB.

Seo et al.[11] demonstrated the novel broad band HOA covering 105 nm of gain bandwidth. For this investigation, silica fiber was used as the transmission channel. By numerical calculations and simulations, it was observed that the S, C, and L bands could be amplified simultaneously with the proposed media. The first medium was an inline HOA constructed by an Er-doped cladding and a Ge-doped core. The second medium was a combination of EDFA and dispersion compensating fiber (DCF). In case of the first medium, it was simple to construct the amplifier since the splicer was not used between the media. Additionally, the complete optical signals in the entire band are amplified at the same time along the fiber. The NF can be easily controlled if the inline isolator is used between media. The hybrid Raman-EDFA using the second medium was reported as a more realistic approach.

In recent years, Raman amplifiers based on DCF have generated enormous research attention for their potential applications in future long-haul communication systems. The pumped DCF as a Raman amplifier has two main advantages, i.e., the amplification band can be extended within the transparency window of the optical fiber by simply changing the pump wavelengths. Also, both the losses and the dispersion compensation in the transmission fiber can be obtained at the same time. Lee et al.[9] demonstrated the new HOA, in which the pumped DCF as a Raman amplifier was used with the EDFA cascaded and further characterized in terms of the gain and NF.

Tiwari et al.[30] characterized the hybrid Raman and EDFA in terms of the gain variation and NF measurement. In this work, three types of HOAs are proposed for a multichannel WDM system and it was observed that the multichannel gain spectrum of the HOAs is quite different from the case of a single channel. It was concluded that the hybrid Raman-EDFA configuration using a residual pumping scheme provided the best results in terms of the gain and pump efficiency. But the better BER performance was shown by hybrid I configuration, which is a combination of Raman and EDFA pumped by a residual Raman pump in a copropagating geometry.

Martini et al.[31] demonstrated the Raman-EDFA HOA in the scenario of cost effective recycling residual pumps by choosing an optimized pump wavelength and power. This allows the structure of amplifiers to have a large gain bandwidth product, gain flatness, and high-power conversion efficiency. It was observed that the proposed Raman-EDFA HOA provides the best results when it was pumped with two pump lasers (which were tuned at 1425 and 1468.4 nm, respectively) with the pump powers of 296.3 and 61.3 mW, respectively.

Rocha and Nogueria[32] proposed a cost effective optical amplification over the S + C bands using a hybrid fiber amplifier (HFA). The cost factor has also been reduced by using a single pump wavelength to pump the proposed HFA. The HFA configuration based on an EDFA provides a gain over the C-band with a distributed RFA to attain the gain over the S-band. The HFA was numerically characterized and its optimal configuration was calculated using the optimization procedures based on genetic algorithms. They found an optimum EDFA length, which allows the HFA configuration to operate for several transmission distances. This configuration can operate up to 100 km, achieving a higher gain with an average NF of 5 dB over the analyzed wideband.

Hsu et al.[33] proposed and demonstrated a 100-km dual band HFA in the bridge-type scheme. The proposed HFA consists of a C-band EDFA and an L-band RFA using double-pass dispersion compensators in a loop-back scheme. Power equalization was realized by adjusting the pump ratio and optimizing the fiber Bragg grating (FBG) reflectivity for the corresponding channels. On the other hand, the chromatic dispersion for all C + L band channels was optimally compensated to achieve a flat power spectrum. After comparing simulation and experimental results, it was recommended that the proposed hybrid EDFA and RFA may find vast applications in WDM long-haul systems and in optical networks where power equalization, power budget, and dispersion management are the crucial issues.

Yuan et al.[34] introduced a configuration of the hybrid Raman-EDFA. They also produced some restriction conditions to yield the optimum design. The influence of various Raman amplifier noises [such as amplified spontaneous emission (ASE) and Rayleigh] on the OSNR of the receiver had also been determined in the depth. In this work, various important conclusions have been made such as, with the same span length and with a different large nonlinear weight the value of the Q-factor is larger. On the other hand, the quality degrades if the same nonlinear weight has been chosen with a different span distance. The quality factor degrades with respect to the increment in the span length, which produces the ASE and Rayleigh noise.

For better clarity on the progress of HOAs in the terms of gain flatness, gain bandwidth, and transmission distance, these results have been briefly described in Table 2.

Table 2 Progress of hybrid optical amplifiers.

Author/Year	Types	Gain BW	Channels	Gain flatness	Length
Delavauz et al.[23]	Hybrid EDFAs	35 nm	14	1 dB	300 km
Masuda et al.[24]	Raman + EDFA + equalizer	65 nm	17	6 dB	
Kawai et al.[25]	Raman + EDFFA + equalizer	67 nm	14	1.5 dB	900 km
Carena et al.[35]	Raman + two EDFAs + DCF				>200 km
Yeh et al.[36]	EDFA + SOA + EDFA	60 nm	30	>3 dB	
Sakamoto et al.[37]	TDFA + EDFA	80 nm	9	2 dB	
Ummy et al.[38]	Tendom and unison	60 nm		5 dB	550 m of HNFL
Huri et al.[39]	EDFA + isolator + SOA	30 nm	10	<4 dB	3 m of each EDFA
Singh et al.[40]	Various combinations of EDFA, Raman, and SOA	#19.4 THz for 25 GHz of channel spacing #38.8 THz for 50 GHz of channel spacing #78.2 THz for 100 GHz of channel spacing	100		12 km
Hasan et al.[41]	Raman + EDFA	17 nm	40	<1.5 dB	80 km
Singh and Kaler [42]	Raman + EDFA + DCF	33.37 nm	160	<4.5 dB	100 km
Rocha and Nogueria[32]	Raman + EDFA	60 nm	40	>5 dB	100 km
Singh and Kaler[43]	EDWA + SOA with Raman + EDFA	20 nm	100	1.15 dB	100 km
Hsu et al.[33]	Raman + EDFA + FBGs	70 nm	15	±0.2 dB	100 km
Singh and Kaler[44]	Optimized EDFA + Raman	2.5 THz	100	1.35 dB	100 km

3 Theoretical Background: Physics of Amplification in Hybrid Raman-Erbium Doped Fiber Amplifier

According to Refs. 35 and 42, the total gain of cascaded amplifiers was considered to be the sum or product of their individual gains, but the gain of the second cascaded amplifier (net gain) depends on the first amplifier's gain.[45] Thus, in this section, a net-gain model of a cascaded Raman-EDFA is derived by considering those actual conditions. The mathematical model is divided into two subsections: in Sec. 3.1, an expression for the variation of pump power and signal power along the EDFA length is determined, while in Sec. 3.2, after considering the effect of Raman output power on the EDFA power, an expression for the net signal gain is established.

3.1 *Analytical Computation of the Evolution of Pump Power and Pump Signal along the Length of Erbium Doped Fiber Amplifier*

In this investigation, the EDFA is assumed or modeled as a two-level system, so

$$N_1 + N_2 = N_t, \tag{1}$$

where N_1 is the population density in the ground state, N_2 is the population density in the meta stable state, and N_t is the total erbium ion density in the core of the EDFA. Then the rate of change of population N_1 at ground-level energy E_1 is given as[46]

$$\frac{dN_1}{dt} = \frac{-\sigma_{pa} P_{PE} N_1}{a_p h v_p} - \frac{\sigma_{sa} P_{SE} N_1}{a_s h v_s} + \frac{\sigma_{se} P_{SE} N_2}{a_s h v_s} + \frac{N_2}{\tau_{sp}}, \tag{2}$$

where P_{PE} is the pump power, P_{SE} is the signal power, σ_{pa} is the absorption cross section at pump frequency v_p, σ_{sa} is the absorption cross section at signal frequency v_s, σ_{se} is the emission cross section at signal frequency v_s, h is Planck's constant a_p is the cross-sectional area for the fiber modes for λ_p, a_s is the cross-sectional area for the fiber modes for λ_s, and τ_{sp} is the spontaneous emission lifetime for transition from E_2 to E_1.

On the right-hand side of Eq. (2), the first term $\sigma_{pa} P_{PE} N_1 / a_p h v_p$ is the rate of absorption per unit volume from E_1 to E_3 due to pumping, the second term $\sigma_{sa} P_{SE} N_1 / a_s h v_s$ is the rate of absorption per unit volume from E_1 to E_2 due to the signal, the third term $\sigma_{se} P_{SE} N_2 / a_s h v_s$ is the rate of stimulated emission per unit volume from E_2 to E_1 due to the signal, and the fourth term N_2/τ_{sp} is the rate of spontaneous emission per unit volume from E_2 to E_1 due to the signal.

Similarly, the rate of change of population N_2 at the upper amplifier level is[46]

$$\frac{dN_2}{dt} = \frac{\sigma_{pa} P_{PE} N_1}{a_p h v_p} + \frac{\sigma_{sa} P_{SE} N_1}{a_s h v_s} - \frac{\sigma_{se} P_{SE} N_2}{a_s h v_s} - \frac{N_2}{\tau_{sp}}. \tag{3}$$

Under the steady-state condition, $dN_2/dt = 0$. Then Eq. (3) becomes

$$\frac{N_2}{\tau_{sp}} = \frac{\sigma_P P_{PE} N_1}{a_p h v_p} + \frac{P_{SE}}{a_s h v_s}[\sigma_{sa} N_1 - \sigma_{se} N_2]. \tag{4}$$

By neglecting the contribution of spontaneous emission, the variations of the pump power P_p and the signal power P_s along the length of amplifier are calculated as

$$\frac{dP_{SE}}{dz} = \Gamma_s(\sigma_{se} N_2 - \sigma_{sa} N_1) P_{se}, \tag{5}$$

$$\pm \frac{dP_{PE}}{dz} = \Gamma_p(-\sigma_{pa} N_1) P_{PE}. \tag{6}$$

In Eqs. (5) and (6), the fiber losses (α and α') are also neglected for a small erbium-fiber length.

3.2 *Analytical Computation of Net Gain*

To determine the net gain, first we have to calculate the Raman output power, and then the final gain is calculated by substituting this power into Eqs. (5) and (6). The Raman-amplification process is governed by the following set of two coupled equations by considering a single continuous wave pump beam to amplify an optical signal.[47]

$$\frac{dP_{SR}}{dz} = \frac{g_R P_{PR} P_{SR}}{a_P} - \alpha_S P_{SR}, \tag{7}$$

$$\pm \frac{dP_{PR}}{dz} = \frac{\omega_P}{\omega_S} g_R \frac{P_{PR} P_{SR}}{a_P} - \alpha_P P_{PR}, \tag{8}$$

where P_{SR} is the signal power for the Raman amplifier, g_R is the Raman gain coefficient, P_{PR} is the pump power for the Raman amplifier, a_P is the cross-sectional area of the pump beam inside the fiber, α_s and α_P are the fiber losses at signal and pump frequencies ω_s and ω_P, respectively, with "+" and "−" signs for forward and backward, and the "−" sign for backward pumping.

For practical situations, the pump power is very large compared to the signal power and in this case the pump depletion can be neglected by setting $g_R = 0$ in Eq. (8) and considering forward pumping only,[48]

$$\frac{dP_{PR}}{P_{PR}} = -\alpha_P dz. \tag{9}$$

Integrating both sides,

$$\int_{P_{Pin-R}}^{P_{Pout-R}} \frac{dP_{PR}}{P_{PR}} = -\alpha_P \int_0^z dz.$$

After solving we have

$$\frac{P_{Pout-R}}{P_{Pin-R}} = e^{-\alpha_p z}.$$

From this equation, the Raman output power can be calculated as

$$P_{PR} = P_{Pout-R} = P_{Pin-R} \exp(-\alpha_p z). \tag{10}$$

Substituting the value of $P_{PR} = P_{Pout-R}$ in Eq. (7)

$$\frac{dP_{SR}}{P_{SR}} = -\alpha_s dz + \frac{g_R}{a_P} P_{Pin-R} \exp(-\alpha_p z) dz.$$

Integrating both sides

$$\int_{P_{\text{sin}-R}}^{P_{\text{sout}-R}} \frac{\mathrm{d}P_{\text{SR}}}{P_{\text{SR}}} = \int_0^{L_R} -\alpha_s \mathrm{d}z + \int_0^{L_R} \frac{g_R}{a_P} P_{P\text{in}-R} \exp(-\alpha_p z)\mathrm{d}z,$$

$$\frac{P_{\text{sout}-R}}{P_{\text{sin}-R}} = \exp\left[-\alpha_s L_R + \frac{g_R}{a_p \alpha_p}[1 - \exp(-\alpha_p L_R) P_{P\text{in}-R}]\right].$$

Then the net gain (G_{net}) can be calculated as

$$G_{\text{net}} = P_{\text{sout}-R} = P_{\text{sin}-R} \exp\left[\frac{g_R P_{P\text{in}-R} L_{\text{eff}}}{a_P} - \alpha_s L_R\right], \tag{11}$$

where $L_{\text{eff}} = [1 - \exp(-\alpha_p L_R)]/\alpha_P$.

Then dividing and multiplying the second term of Eq. (11) by L_R

$$P_{\text{sout}-R} = P_{\text{sin}-R} \exp\left[\frac{g_R P_{P\text{in}-R} L_{\text{eff}} L_R}{a_P L_R} - \alpha_s L_R\right],$$

$$P_{\text{sout}-R} = P_{\text{sin}-R} \exp[g_0 L_R - \alpha_s L_R],$$

where $g_0 = g_R P_{P\text{in}-R} L_{\text{eff}}/a_P L_R$.

Also, $P_{\text{sout}-R} = P_{\text{SE}}$ is the input signal to the EDFA.

Substituting the value of P_{SE} into Eq. (5) and rearranging

$$\frac{\mathrm{d}P_{\text{SE}}}{P_{\text{sin}-R}} = \Gamma_s(\sigma_{\text{se}} N_2 - \sigma_{\text{sa}} N_1) \exp[g_0 L_R - \alpha_s L_R].$$

For convenience in solving this equation, let us denote signal power by P_s only

$$\frac{\mathrm{d}P_s}{P_s} = \Gamma_s(\sigma_{\text{se}} N_2 - \sigma_{\text{sa}} N_1) \exp[g_0 L_R - \alpha_s L_R]\mathrm{d}z.$$

Integrating both sides for L_E as the length of the EDFA

$$\int_{P_{\text{sin}-E}}^{P_{\text{sout}-E}} \frac{\mathrm{d}P_s}{P_s} = \int_0^{L_E} (\sigma_{\text{se}} N_2 - \sigma_{\text{sa}} N_1) \exp[g_0 L_R - \alpha_s L_R]\mathrm{d}z.$$

From Eq. (1), we see that $N_1 = N_t - N_2$.

Using the expression for N_1 in the above equation we get

$$\int_{P_{\text{sin}-E}}^{P_{\text{sout}-E}} \frac{dP_s}{P_s} = \int_0^{L_E} \Gamma_s[\sigma_{se} N_2 - \sigma_{sa}(N_t - N_2)] \exp[g_0 L_R - \alpha_s L_R]\mathrm{d}z.$$

After a long calculation and taking the exponential of both sides we have

$$G_{\text{Total}} = \exp\{-\Gamma_s \sigma_{\text{sa}}[\exp(g_0 L_R - \alpha_s L_R)] N_t L_E + \Gamma_s(\sigma_{\text{sa}} + \sigma_{\text{se}}) \exp[g_0 L_R - \alpha_s L_R] N_{2\text{avg}}\}, \tag{12}$$

where $N_{2\text{avg}} = N_t(\omega_P + \omega_{\text{sa}}) L_E / [(1/\tau_{\text{sp}}) + \omega_P + \omega_{\text{sa}} + \omega_{\text{se}}]$, pump rate, $\omega_p = \sigma_{\text{pa}} P_{\text{PE}}/a_p h v_p$, ω_{sa} is the stimulated absorption rate, and ω_{se} is the stimulated emission rate.

4 Hybrid Optical Amplifiers in High-Capacity Dense Wavelength Division Multiplexed System

The SOAs and EDFAs emerged as attractive amplifiers for WDM systems because of their capabilities of offering an extremely high gain and also a longer transmission distance.[49,50,51] The broad-band EDFA can amplify multibands as it distinctly amplifies the optical signals of each band, which yields an increase in the system cost. In recent years, Raman amplifiers have also drawn great attention as a promising technology for high capacity and long-haul optical communication systems. Raman amplifiers can amplify any wavelength within the bandwidth of the fiber by a simple adjustment of the pump wavelength. However, as the gain spectrum for a Raman amplifier is not uniform over the bandwidth, high-cost multiple pumps with gain equalizers and various expensive optoelectronics devices are normally used.[52] On the other hand, according to the current requirements of a multiterabit DWDM system, the hybrid amplifiers are the most capable and widely used technology.[9] The HOAs are designed in order to minimize impairments resulting from the nonlinearities present in the fiber, to enhance the transmission distance, and to increase the ability of the optical communication system in the terms of the channels and/or bandwidth. However, there are various other issues in HOAs that have to be addressed. The issues are listed below.

4.1 *Gain Bandwidth and Gain Flatness*

The gain bandwidth product of the optical amplifiers must be large for an optical communication system in order to transmit multimedia information signals from a large number of users. In literature, various conventional optical amplifiers (SOA, EDFA, Raman, waveguide amplifier, and so on) are reported, but the gain shape is not flattened over the wavelength grid. The gain depends upon the wavelength of the input signal and is restricted by the width of the radiating energy bands. Therefore, HOAs are the best alternative; they not only provide the largest gain bandwidth, but also produce a flat gain shape even without using any costly gain flattening techniques.

For the validity of HOA (in this case, the hybrid Raman-EDFA is used), a system constituting 160 DWDM channels deploying continuous wave lasers in the frequency range of 187 to 190.975 THz, with a channel spacing of 25 GHz has been considered. This system is investigated at different input laser powers (P_{in}) of 3, 5, and 15 mW; the details can be found in Ref. 42.

From Fig. 3, it can be seen that the gain variation over the effective bandwidth, i.e., 3.97 THz (33.37 nm), increases with respect to the increment in input power; this is because of the nonlinearities in the fiber. A better performance in terms of the gain flatness (4.5 dB) is achieved with an input power level at 3 mW.[39,53] On the other hand, the gain variation increases to 5.4 and 11.6 dB for 5 and 15 mW of input power/channel, respectively. This large variation along the fiber length is due to local gain variations or a local inversion introduced by the pump power. Amplifier saturation due to high-input power is also a major reason behind the large gain variation.

The gain flatness can be improved by using various gain flattening techniques (such as filters, DCF, FBG, and so on) but this leads to an expensive system. For a cost effective solution, we have optimized the various parameters of a

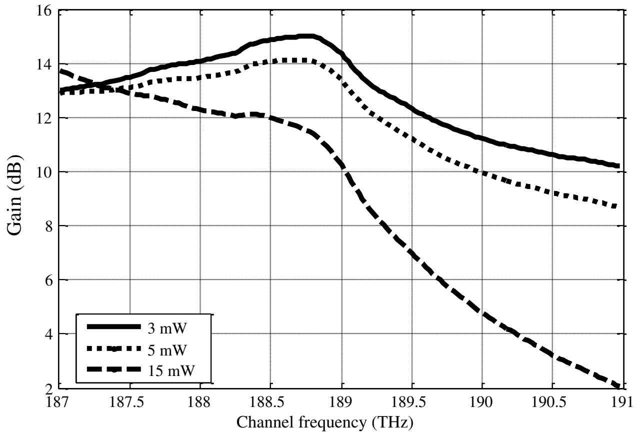

Fig. 3 Gain spectra (with $P_{in} = 3,5$, and 15 mW) of Raman-EDFA HOA.[42]

hybrid EDF-Raman amplifier using a genetic algorithm to attain better gain flatness.[44] Figure 4 shows the gain and an NF spectrum of the optimized EDFA-Raman HOA over a 100 channel DWDM system. The variation of the gain with wavelength is not uniform as each amplifier induces its own nonlinearities and ASE noise. It can be observed that each frequency has a gain of more than 18 dB. With an optimized HOA, a flat gain of >18 dB is obtained from a frequency region of 187 to 189.5 THz with a gain variation of less than 1.35 dB without using any gain flattening technique. The obtained NF is also the lowest value (<2 dB/channel) ever reported for a proposed HOA at a reduced channel spacing (25 GHz).

4.2 *Transient Effect*

In saturated amplifiers, transient crosstalk is generated between adjacent channels. This is due to the abrupt changes in average power of the optical amplifier due to sudden fiber cuts, add-drop operations, reconfigurability, and so on. This type of crosstalk can be a serious problem in today's reconfigurable networks where reconfigurable optical add/drop multiplexers and optical cross connects (OXCs) are used for dynamic routing and switching of individual channels. In general, transients are always unwanted in a system, as they impair the receiver sensitivity, can cause potential damage to system components, and can increase the effect from system nonlinearities during transmission. On the other hand, the optical networks are also moving toward the switching systems (such as packet or burst switching). As a result of the switching techniques, the power per channel varies and this variation will cause the transients on other channels propagating over the same amplifier. To suppress this phenomenon, Chang et al.[12] presented the transient effect in a Raman-EDF HOA during channel add-drop processes to observe the combined dynamics of Raman and EDFA. Further, using the gain control technique in the Raman-EDFA HOA, the transient response is successfully suppressed. It was reported that if the optical switching speed is carefully chosen then the transient effect can be suppressed to the level on which the proposed Raman-EDFA HOA is proven to be enough for the WDM networks, including a reconfigurable optical add-drop multiplexer (OADM) and OXC.

For better clarity, the transient effect of Raman-EDF HOA is presented in which the eight-channel laser sources are used, while a few channels were modulated with a Mach–Zehnder modulator to introduce an add/drop operation. The power excursion is present for all the surviving channels when the add/drop operation is activated. The power fluctuations for each of the surviving channels were essentially identical.[54] Figure 5 shows the power fluctuation in channel 1, when the last 2, 4, or 6 channels are added or dropped, respectively. The large power excursion is observed when many channels are added or dropped, as is also reported in Ref. 15. This is because the input power of the Raman-EDF HOA is decreased when the last 2, 4, and 6 channels are dropped, respectively, and vice versa when they are added.

It can also be observed that the response time of the Raman-EDFA HOA is governed by the response of the EDFA because it has the fastest response time.[55] The output power deviation of the HOA is mainly dependent on the dynamics of EDFA rather than DRA because of its high-output power. As the power variation after the Raman amplifier is smaller than that after EDFA and the transients after Raman are relatively slower than those after EDFA, there are input-power conditions that mandate that the power of the surviving channel can be controlled by adjusting the

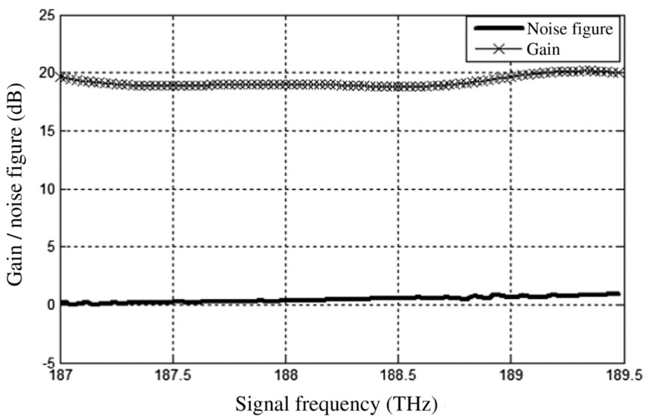

Fig. 4 Gain and noise figure characterization of optimized EDF-Raman HOA.[44]

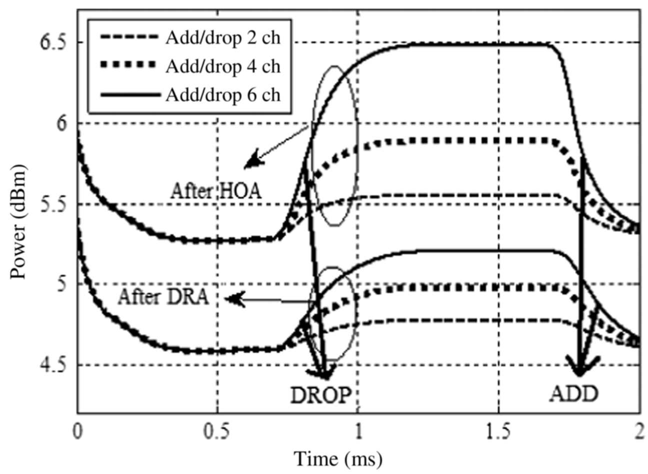

Fig. 5 Output power of the surviving channel after distributed Raman amplifier, and HOA when 2, 4, and 6 channels are added and dropped.[15]

parameters of the EDFA only. In Ref. 15, it is observed that the power variation (peak-to-peak power excursion) is reduced with a decrease in the EDFA pump power and an increase in the EDFA length.

4.3 *Crosstalk Effect*

In literature, various HOAs are designed, but the distortion in data pulses is still present because of the crosstalk between the transmitted symbols. There are various reasons for the crosstalk: (1) it is induced due to the rapid gain excursion of optical amplifiers.[56] (2) It is induced due to amplifier nonlinearities [such as stimulated Raman scattering (SRS), FWM, SPM, XPM, and so on] which change the parameters of the transmitting signal since it depends on the remaining optical signals propagating through the same fiber.[57,58,59] Where SRS is a nonlinear optical process in which a pump photon is absorbed and immediately re-emitted in the form of a phonon and a signal photon; FWM is the nonlinear process in which the undesired beat frequency is generated due to existing multiple frequencies; SPM is a nonlinear phenomenon in which nonlinear phase modulation is self-induced, which is undesired; and XPM occurs when two or more optical channels are transmitted simultaneously inside an optical fiber using the WDM technique. In such systems, the nonlinear phase shift for a specific channel depends not only on the power of that channel but also on the power of the other channels. Therefore, it is mandatory to investigate the level of crosstalk before the implantation of the proposed amplifiers in various applications. In a Raman amplifier, the closely spaced channels are affected by the SRS, which yields undesired nonlinear crosstalk. The power level of bit "1" in the individual pattern is changed due to amplification or attenuation as a result of SRS, which degrades the BER performance.[60]

For better clarity, we have investigated the crosstalk effect on the effective wavelength grid as used in Fig. 6. Due to the gain dynamics induced by EDF-Raman HOA, the distortion of pulse shapes and crosstalk between the symbols is present. These crosstalk effects are due to induced nonlinearities such as SRS, FWM, self- and cross-phase modulation, and so on. The induced crosstalk directly affects the BER performance of the system. In Fig. 6, the variation of BER among the

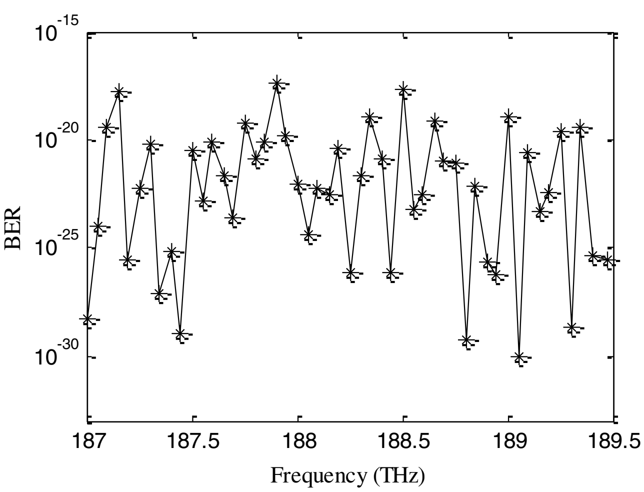

Fig. 6 Bit error rate (BER) versus dense wavelength division multiplexed signals after transmission over EDF-Raman HOA.[17]

selected DWDM channels is detected due to crosstalk between the data symbols. However, the proposed system provides good BER ($<1 \times 10^{-16}$) over the effective bandwidth.

Therefore, according to the above discussion, it can be observed that the HOAs can provide a better gain flatness without using any expensive gain flattening techniques while the other performance parameters (such as gain, NF, BER, transience) are also in an acceptable range.

5 Future Prospects

Work continues apace on optical amplifiers, driven by the enormous potential benefits of HOAs. The large gain over a broad bandwidth with large channel spacing is now relatively well understood, and while the undesired effects (such as nonlinearities, transient, crosstalk, and so on) of an ultra-DWDM system remain problematic, new combinations of Raman amplifiers with another rare doped amplifier should be explored for covering a much wider gain bandwidth product.

Despite the wide range of HOAs that have been used to attain gain variation over a large gain bandwidth with a better performance, no on chip hybrid waveguide amplifier has yet been proposed which can offer a small footprint and low-mass production cost. The increased deployment of local-area DWDM necessitates the development of cheap planar gain elements. In this field, work continues on the production of planar waveguide devices using silica, fluorides, tellurites, polymers, and chalcogenides. While concentration quenching limits the ultimate gain achievable from doped materials, careful design of wave guide geometries can help to mitigate these effects.

Because HOAs have applications in wide area networks as inline amplifiers, the placement of optimum HOAs in different optical network topologies can be studied. The HOAs' placement can also be explored in other broadcast topologies including multilevel topologies. Additionally, in extension of a previous work reported in Ref. 61, the HOAs can be used for an ultralong haul communication system even at high speed with reduced channel spacing.

The leading challenges of HOAs in the coming years will continue to be to achieve the lowest power efficiency of the amplifier, to lower the high cost of the pumps, and to solve issues related to the safety and risks of having high-optical powers in the field. The latter could be a major problem of access and fibers to home networks, where optical fibers are located in much more accessible areas (cable masts and interior boxes in houses) and human interaction with the fiber is more likely. Security and monitoring of these systems will be essential for a more widespread use of the HOAs in the coming years.

6 Conclusion

The field of HOAs remains a lively and rapidly developing one. The HOAs are one of the possible ways to amplify the broad gain bandwidth product with a minimum gain variation among the channels. These amplifiers have been presented with the purpose of identifying new applications and limitations for its use in future optical communication systems. This article presented the recent developments in HOAs and various current problems (such as the transient phenomena, gain variation, gain bandwidth product, crosstalk, and so on) have also been presented; the solution of these issues will increase the capacity and flexibility of a DWDM communication system at a reduced channel spacing. The HOAs are recommended for a high-capacity DWDM system having a large gain bandwidth and/or large gain flatness with less error. There remains a strong emphasis on telecommunications compatible wavelengths, though there are a number of novel solutions aimed at extending the capabilities of HOAs to satisfy the ever-increasing demand for gain bandwidth in this area.

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