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Introductory Chapter: A Revisit to Optical Amplifiers

Pankaj Kumar Choudhury

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1. Introduction

The modern age of information may be regarded as the era of fast- and high-bandwidth communication, which exploits fiber-optic communication system. Transmission of signals spanning distances of over thousands of kilometers essentially cause signal degradation. Due to varieties of loss mechanisms in the medium (the optical channel used for transmission), there happens gradual attenuation in the power of signals being transmitted, as those propagate through a communication channel. Clearly, the attenuation imposed by the medium remains a serious issue that affects light propagating ultra-long distances through a fiber-optic cable (the communication link). The degradation of signal must be overcome, which makes the utilization of the process of amplification (of signal) vital. Further, in order for the information carried by a signal to be detectable at the receiving end, there must be a minimum amount of threshold power, which the signal must possess. As such, optical amplifiers, which would incorporate optical fibers and/or waveguides, remain indispensable in fiber-optic communication systems owing to the limitations imposed by the transmission channels/systems. These limitations would arrive in the form of fiber loss and dispersion, which are usually overcome by exploiting varieties of amplifiers. In reality, loss and dispersion are related to each other [1], which can be well-understood upon giving a thought to a pulse shape—more broad a pulse becomes (causing dispersion), more will be the decrease in power (causing loss), and vice-versa.

In earlier days, optoelectronic repeaters were in use for the purpose of amplification, wherein the optical signal is first converted into an electric current, and then regenerated using a transmitter [2]. However, the process of regeneration used to be quite complex and expensive, in particular, when multichannel optical systems are in use. As such, the exploitation of optical amplifier evolved as the alternative approach for amplifying optical signals during transmission. It is a device that directly amplifies an optical signal, without the need of conversion to an electrical signal—the feature needed in the *so-called* repeaters.

2. The mechanism involved

To the very fundamental level, optical amplifiers amplify the incident light through the process of stimulated emission—the mechanism similar to what exploited in the operation of lasers. One would say that optical amplifiers are, in fact, lasers without feedback mechanism, and the optical gain is realized when the amplifier is pumped to achieve population inversion [3]. The achieved optical gain depends not only on the frequency of the incident optical signal, but also, the local beam intensity at any point inside the amplifier. As such, the bandwidth of an amplifier remains greatly important as it determines the frequency and intensity dependence of the optical gain (of an amplifier).

3. A few different amplifier types

Optical amplifiers can be of varieties of forms ranging from the solid-state type to the fiber-based ones [2]. Usually the operation of an optical amplifier relies on the process of feedback, which essentially yields enough gain corresponding to the frequency of signal. An optical amplifier can also be without feedback—the category addressed as traveling wave amplifiers [4]. In these, the amplified signal travels in the forward direction only. In solid-state kind of amplifiers, the resonator is generally made of certain solid materials (e.g., semiconductors), the shape and structure of which tailor the gain parameter. On the other hand, fiber-based amplifiers would rely on the phenomenon of inelastic scattering of light, and/or certain dopants (in the fiber) would make the guide itself an *all-optical* type of structure to yield the required amount of gain. In this section, a few different types of optical amplifiers are touched upon in cursory form.

3.1. Semiconductor optical amplifiers

Semiconductor optical amplifiers (SOAs) fall in the category of solid-state amplifier, wherein semiconductor lasers are used [5]. These experience a relatively large amount of feedback because of multiple reflections (of light) occurring at the cleaved facets of the Fabry-Perot (FP) kind of laser cavity. As such, SOAs can be used as amplifiers when biased below threshold. These amplifiers are easy to fabricate, but the optical signal gain remains highly sensitive to the variations in temperature (of amplifier) and the input optical frequency.

If the SOA is to be of the traveling wave type, the feedback due to reflection from the end facets is to be suppressed. A simple way to reduce the reflectivity would be to coat the facets with a kind of antireflection coating. Indeed, the reflectivity of one of the facets must be extremely small ($<0.1\%$) for the SOA to be operated as a traveling wave amplifier. The minimum amount reflectivity would depend on the amplifier gain. However, it remains almost impossible to realize low reflectivity values of facets in a predictable form—the feature that motivated to investigate other possibilities to achieve the same. Within the context, one of the possibilities would be to use a tilted resonator cavity in laser. In such a kind of laser structure, the angled-facet

makes the reflected light to be physically separated from the light propagating in the forward direction. However, to attain a vanishing amount of feedback is almost impossible, due to the physical properties of light propagating in a guiding channel. Apart from this kind of structure, another form would be to use a window-facet structure, wherein a *transparent* window is implanted between the ends of active region and the facets. Losses take place in such structures due to the spreading of signal in the window section—the feature that causes to minimize the reflectivity.

3.2. Fiber Raman amplifiers

It has been known that the response of any dielectric medium to light becomes nonlinear in the case of high electric fields. Such nonlinearities would result in nonlinear (or inelastic) scattering, and the frequency of the scattered light would be downshifted, thereby resulting into a kind of loss (in the fiber). As such, the scattering of photon contributes to the loss of power at the incident frequency. However, corresponding to low incident power levels, the scattering cross-sections remain very small, and therefore, the loss becomes negligible. On the other hand, for high incident optical fields, the nonlinear phenomenon of stimulated Raman scattering (SRS) takes place that leads to a considerable amount of loss. Once the incident optical power exceeds a threshold value, the intensity of the scattered light grows exponentially.

In fiber Raman amplifiers, SRS takes place in silica fibers in the case, when an intense optical pump signal propagates through it [6]. Here the incident pump photon gives up its energy to create another photon of reduced energy at a lower frequency. The remaining amount of energy is absorbed by the medium in the form of molecular vibrations, thereby generating optical phonons. As such, fiber Raman amplifiers are pumped optically to achieve gain. The difference in energy is known as Stokes shift. The pump and signal frequencies are injected into a fiber, and the energy is *transferred* from the pump beam to the signal beam through the process of SRS, as the two beams co-propagate along the fiber. The pump and signal beams can also be injected into the fiber in such a way that they would counter-propagate (inside the fiber). Indeed, it depends on the pumping configurations used to achieve the required amount of gain with certain merits and demerits.

Fiber Raman amplifiers exhibit broad bandwidth—the feature which remains useful for amplifying several channels simultaneously, and also, short optical pulses [7]. These amplifiers can also be used to overcome fiber loss in soliton-based communication systems, and therefore, highly recommended for distributed amplification. However, these suffer from the drawback of the need of high-power lasers for optical pumping, thereby making the communication not enough cost-effective.

3.3. Fiber Brillouin amplifiers

Fiber Brillouin amplifiers operate similarly to fiber Raman amplifiers except that the gain in this case is provided by the process of stimulated Brillouin scattering (SBS), instead of SRS. When such amplifiers are pumped optically, a part of the pump power is transferred to the signal through SBS [8–13]. Each pump photon uses most of its energy to create a signal photon,

and the remaining amount of energy is used to excite an acoustic phonon. As such, the amplifier system relies on acoustic phonons, instead of optical phonons, as we come across in the case of fiber Raman amplifiers [14, 15]. The phenomenon of SBS differs from SRS in the following forms:

- In SBS, amplification occurs only when the signal beam propagates in a direction opposite to that of the pump beam (backward pumping configuration), whereas in the case of SRS, both kinds of configurations would be exploited.
- The Stokes shift in SBS is smaller (nearly 10 GHz) by three orders of magnitude compared with that obtained in SRS.
- The Brillouin gain spectrum is narrow (less than 100 MHz).

This much amount of narrow bandwidth results into low gain-bandwidth product provided by fiber Brillouin amplifiers, which is the prime disadvantage of this kind of device for the usage in amplifying optical signals in lightwave communication systems. As such, better usage of Fiber Brillouin amplifier would be as preamplifier to improve the receiver sensitivity. In addition, the *noise figure* of such amplifiers is quite large (over 15 dB).

3.4. Doped-fiber amplifiers

Doped-fiber amplifiers make use of rare earth elements (namely erbium, holmium, neodymium, samarium, thulium and ytterbium) as a gain medium (i.e., the cavity resonator). Such elements are doped in usual silica fibers, and therefore, the characteristics of these amplifiers are determined by the dopants rather than by the silica fiber [2]; the latter one plays the role of host medium only. The use of different types of dopants makes the fiber amplifier to operate in different wavelengths covering a range of 0.5–3.5 μm . Among the others, the erbium-doped fiber amplifiers (EDFAs) are greatly attractive as these operate near 1.55 μm wavelength, corresponding to which the fiber loss remains minimum [16, 17]. The key element in EDFA is erbium — a rare earth element in the lanthanide series.

Erbium was a relatively unimportant element in the past, but now it has been postulated that what silicon is to the semiconductor technology, erbium will be to the photonics technology. According to Emmanuel Desurvire [18], small amount of erbium doping in optical fibers — *“makes it possible to distribute the gain over the fiber itself, thereby minimizing the power excursion of the signal. Such an approach makes possible virtually lossless signal transmission from one fiber network to the next.”*

EDFAs can be designed to operate in such a way that the pump and signal beams propagate along the same direction (unidirectional pumping configuration). In bidirectional pumping, the amplifier is pumped in both directions simultaneously by using two semiconductor lasers located at the two fiber ends. Both the types of configurations have their relative merits and demerits. Some of such relevant configurations have been reported before in Refs. [19–21].

The gain characteristics of EDFAs depend on the pumping scheme as well as the other co-dopants, such as germania and alumina—the materials that remain present in the fiber core.

The amorphous nature of silica broadens the energy levels of Er^{3+} ions into Er^{3+} bands—the feature facilitating different possible transitions that can be used to pump the EDFA. Structural disorders lead to inhomogeneous broadening of the EDFA gain profile, whereas Stark splitting of various energy levels is responsible for homogeneous broadening. The addition of alumina to the core broadens the gain spectrum even more.

Efficient EDFA pumping generally requires semiconductor lasers operating near 0.98 and 1.48 μm . The required amount of pump power can be reduced by using silica fibers doped with aluminum and phosphorous or by using fluorophosphate fibers. Within the context, the EDFA gain spectrum can vary from amplifier to amplifier even when the core composition is the same. This is because the EDFA gain also depends on the length of amplifier, that is, the size of FP cavity resonator wherein multiple reflections take place. Gain essentially depends on both the absorption and emission cross-sections, which have distinct spectral characteristics. Apart from these, other device as well as operational parameters, such as Er^{3+} ion concentration, amplifier length, core radius and pump power, also play vital roles to determine EDFA gain spectrum.

EDFAs exhibit relatively low noise levels, making them suitable for applications in lightwave communication systems. Nevertheless, long haul fiber-optic communication systems employing multiple EDFAs suffer from the issues related to amplifier noise. Such problems become severe when the system operates in the anomalous dispersion region of fiber. This happens primarily due to the fact that the nonlinear phenomenon, known as modulation instability, plays a prime role to enhance the amplifier noise, thereby degrading the spectral characteristics of signal.

As stated before, EDFAs are ideal for lightwave communication systems operating near 1.55 μm wavelength. However, worldwide telecommunication network contains huge span of communication link optimized for operations at other wavelengths as well, at 1.3 μm . Clearly, signal amplification in such communication networks needs other forms of amplifiers. Within the context, silica fibers, doped with neodymium ions, would provide fiber amplifiers that can be operated in the 1.30–1.36 μm wavelength span. However, such amplifiers suffer from the undesirable effects, such as excited-state absorption and radiative transitions, thereby limiting the performance characteristics. To overcome the issues, varieties of other forms of amplifiers, such as Nd^{3+} ion-doped fluoride fibers, ZBLAN ($\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-NaF}$) fibers doped with praseodymium (Pr^{3+}) ions, ytterbium-doped fibers, etc., were investigated with their relative merits and demerits [2].

4. Applications

There can be various forms of applications of optical amplifiers. For example, as stated earlier, the use of optical amplifiers is particularly attractive for multichannel systems since they can amplify all channels simultaneously. The use of SOAs as preamplifiers increases the sensitivity of optical receivers. In such a kind of application, the signal is optically amplified before it falls on the receiver. The preamplifier boosts the signal to a level that the receiver performance is

improved in terms of noise figure. Such amplifiers are used in local area networks (LANs) as well in order to compensate the loss due to the distribution of signal. SOAs can also be used as power amplifiers to boost the signal power. Further, a power amplifier can increase the distance of optical transmission by 100 km or more. However, it essentially depends on the amplifier gain and channel loss. Finally, the purpose of using amplifiers in transmission links is to boost the propagating power [2].

After all these different types of applications of SOA, it must be emphasized that these suffer from many drawbacks, namely polarization sensitivity, interchannel cross-talk, and large coupling loss, which essentially limit their usage as in-line amplifiers. Fiber amplifiers do not suffer from such severe issues and can be exploited satisfactorily for signal amplification in the 1.55 μm -based communication links. However, as to the 1.3 μm -based lightwave systems, SOAs remain better alternative because fiber amplifiers do not perform well in this wavelength. Furthermore, SOAs can be used as wavelength converter and fast switch for wavelength routing in wavelength-division-multiplexed (WDM) networks [22].

5. Current scenario

Varieties of optical amplifiers have been put forward by the investigators that are capable for usages based on specific needs. The scope of the present introductory chapter remains out of accounting all those in concise forms. Just to state a few, one may focus on the organic semiconductor lasers, which contribute to major advances in the area of organic light emitting diodes (LEDs). Such semiconductors exhibit high absorption and broadband spectra. Further, their operations in the visible spectrum regime make them highly prudent for many applications [23]. These amplifiers are pumped optically, and day-by-day, the pumping scheme has seen improvements to the extent that compact sources, such as microchip lasers [24], have been in use with high efficiency. High absorption yields large gain, and therefore, the gain-bandwidth product becomes very large for such solid-state amplifiers [25]. Furthermore, these amplifiers exhibit good compatibility with polymer-based optical fibers.

The communication schemes currently employ WDM systems, and therefore, optical amplifiers are designed accordingly so that all the channels with different wavelengths can be simultaneously amplified. As such, the demand remains for optical amplifiers with better performance, in terms of optical nonlinearities, channel crosstalk, gain flatness, large gain-bandwidth product, etc. Meeting these specifications only would make the amplifier suitable for dense-WDM systems. Within the context, hybrid optical amplifiers (HOAs) are of promising use as these are suitably applicable for high-speed broadband applications in cost-effective ways [26]. In fact, the combination of more than one optical amplifier in any configuration is termed as HOA. The implementation of such scheme has the potential benefits of large gain over a broad bandwidth with large channel spacing and reduced nonlinear losses. However, these also suffer from cross talk, noise and nonlinear losses. HOA can be used in DWDM systems where high gain and/or gain bandwidth with less variation is required. However, relative merits and demerits of different configurations have been making the investigators engaged in coming up with new ideas to design such amplifiers with enhanced efficiencies [27–31].

6. Summary

Optical amplifiers are the key components in the present-day distant communication systems, wherein fiber-based networks are vigorously exploited under the principle of WDM. Indeed, merits and demerits remain in adopting different configurations, which essentially depend on the need of operation. The very basic principles of some of the forms of optical amplifiers are discussed in this introductory chapter. This is made primarily with the aim of creating the background before authors read the contributions by the different authors in this Book. Apart from this chapter, there are six other chapters included—all of which are dedicated to the recent advancements in the area of optical amplifiers; the introductory chapter would make the understanding of the remaining part (of the Book) fairly simpler. With such thoughts, the editor of the Book expects the volume to be of help for graduate students as well as established scientists—the former group of readers would generate their own ideas, where the latter ones would foster own research with having glimpse of the ongoing investigations in the relevant field.

Author details

Pankaj Kumar Choudhury

Address all correspondence to: pankaj@ukm.edu.my

Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, UKM, Bangi, Selangor, Malaysia

References

- [1] Kaiser G. *Optical Fiber Communications*. Singapore: McGraw-Hill; 2000
- [2] Agrawal G. *Fiber-Optic Communication Systems*. New York: Academic Press; 2002
- [3] Quimby RS. *Photonics and Lasers: An Introduction*. New York: Wiley; 2006
- [4] Desurvire E, Simpson JR, Becker PC. High-gain erbium-doped traveling-wave fiber amplifier. *Optics Letters*. 1987;**12**:888-890
- [5] Liu JM. *Photonic Devices*. New York: Cambridge; 2005
- [6] Aoki Y. Properties of fiber Raman amplifiers and their applicability to digital optical communication systems. *Journal of Lightwave Technology*. 1988;**6**:1225-1239
- [7] Han B, Zhang X, Zhang G, Lu Z, Yang G. Composite broad-band fiber Raman amplifiers using incoherent pumping. *Optics Express*. 2005;**13**:6023-6032
- [8] Nasir MNM, Al-Mansoori MH, Abdul Rashid HA, Choudhury PK, Yusoff Z. Multi-wavelength Brillouin erbium fiber laser incorporating a fiber Bragg grating filter. *Laser Physics*. 2008;**18**:446-448

- [9] Nasir MNM, Yusoff Z, Al-Mansoori MH, Abdul Rashid HA, Choudhury PK. Broadly tunable multi-wavelength Brillouin-erbium fiber laser in a Fabry-Perot cavity. *Laser Physics Letters*. 2008;**5**:812-816
- [10] Nasir MNM, Yusoff Z, Al-Mansoori MH, Abdul Rashid HA, Choudhury PK. Low threshold and efficient multi-wavelength Brillouin-erbium fiber laser incorporating a fiber Bragg grating filter with intra-cavity pre-amplified Brillouin pump. *Laser Physics Letters*. 2009;**6**:54-58
- [11] Nasir MNM, Yusoff Z, Al-Mansoori MH, Abdul Rashid HA, Choudhury PK. Widely tunable multi-wavelength Brillouin-erbium fiber laser utilizing low SBS threshold photonic crystal fiber. *Optics Express*. 2009;**7**:12829-12834
- [12] Johari MI, Adamiat A, Shahabuddin NS, Yusoff Z, Abdul Rashid HA, Al-Mansoori MH, Choudhury PK. Ring cavity multiwavelength Brillouin-erbium fiber laser with a partially reflective fiber Bragg grating. *Journal of the Optical Society of America B*. 2009;**26**:1675-1678
- [13] Nasir MNM, Yusoff Z, Al-Mansoori MH, Abdul Rashid HA, Choudhury PK. On the pre-amplified linear cavity multi-wavelength Brillouin-erbium fiber laser with low SBS threshold highly nonlinear photonic crystal fiber. *Laser Physics*. 2009;**19**:2027-2030
- [14] Song KY, Hotate K. 25 GHz bandwidth Brillouin slow light in optical fibers. *Optics Letters*. 2007;**32**:217-219
- [15] Xing L, Zhan L, Luo S, Xia Y. High-power low-noise fiber Brillouin amplifier for tunable slow-light delay buffer. *IEEE Journal of Quantum Electronics*. 2008;**44**:1133-1138
- [16] Desurvire E, Giles CR, Simpson JR, Zyskind JL. Efficient erbium-doped fiber amplifier at a 1.53 μm wavelength with a high output saturation power. *Optics Letters*. 1989;**14**:1266-1268
- [17] Desurvire E, Simpson JR. Amplification of spontaneous emission in erbium-doped single-mode fibers. *IEEE Journal of Lightwave Technology*. 1989;**7**:835-845
- [18] Desurvire E. *Erbium-Doped Fiber Amplifiers*. New York: Wiley; 1994
- [19] Pathmanathan SS, Abdul-Rashid HA, Choudhury PK. An experimental investigation of double-pass erbium-doped optical amplifier with tunable band-pass filter. *Asian Journal of Physics*. 2008;**17**:241-244
- [20] Pathmanathan SS, Abdul-Rashid HA, Choudhury PK. An experimental investigation of Er^{+3} -doped optical amplifiers with very low 1480 nm pump power. *International journal of microwave and optical. Technology*. 2008;**3**:134-138
- [21] Pathmanathan SS, Muhd-Yassin SZ, Abdul-Rashid HA, Choudhury PK. An experimental investigation of the gain spectrum of erbium-doped fiber amplifiers under various system configurations. *Optik*. 2010;**121**:184-187
- [22] Willner AE, Xie Y. Wavelength domain multiplexed (WDM) fiber-optic communication networks. In: Bass M, Van Stryland EW, editors. *Fiber Optics Handbook—Fiber, Devices and Systems for Optical Communications*. New York: McGraw-Hill; 2002. pp. 13.1-13.31

- [23] Tessler N. Lasers based on semiconducting organic materials. *Advanced Materials*. 1999; **11**:363-370
- [24] Turnbull GA, Andrew P, Barnes WL, Samuel IDW. Operating characteristics of a semiconducting polymer laser pumped by a microchip laser. *Applied Physics Letters*. 2003;**82**:313-315
- [25] Lawrence JR, Turnbull GA, Samuel IDW. Broadband optical amplifier based on a conjugated polymer. *Applied Physics Letters*. 2002;**8**:3036-3038
- [26] Lee JH, Chang YM, Han YG, Chung H, Kim SH, Lee SB. A detailed experimental study on single-pump Raman/EDFA hybrid amplifiers: Static, dynamic, and system performance comparison. *Journal of Lightwave Technology*. 2005;**23**:3484-3493
- [27] Tiwari U, Rajan K, Thyagarajan K. Multi-channel gain and noise figure evaluation of Raman/EDFA hybrid amplifiers. *Optics Communications*. 2008;**281**:1593-1597
- [28] Singh S, Kaler RS. Investigation of hybrid optical amplifiers for dense wavelength division multiplexed system with reduced spacing at higher bit rates. *Fiber and Integrated Optics*. 2012;**31**:208-220
- [29] Rocha AM, Nogueira RN. Flexible single pump hybrid fiber amplifier for the S+C bands. *Optics Communications*. 2014;**320**:105-108
- [30] Singh S, Kaler RS. Novel optical flat gain hybrid amplifier for dense wavelength division multiplexed system. *IEEE Photonics Technology Letters*. 2014;**26**:173-176
- [31] Singh S, Kaler RS. Performance optimization of EDFA-Raman hybrid optical amplifier using genetic algorithm. *Optics and Laser Technology*. 2015;**68**:89-95

