Light Speed:
Catch Me If You Can


PROFESSOR DR. MOHD ADZIR MAHDI

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ABSTRACT

Optical communications have been vigorously touted as the future of communications due to its many benefits such as amazing speed, enormous capacity and low transmission loss. The emergence of the optical wavelength-division multiplexing (WDM) scheme has further strengthened its position as the premier communication method to date. Nevertheless, optical communication is still hindered by a number of weaknesses, in particular the accumulated loss in long distance transmission and the need for multi-wavelength laser sources for WDM systems.

The advent of various types of optical amplifiers strives to counter transmission attenuation in optical fiber. The two main players in the field are the erbium-doped fiber amplifiers and the Raman amplifiers, with their own individual advantages and weaknesses. Resourceful researchers have been able to combine both types to create hybrid amplifiers that enjoy the best features of both while downplaying their drawbacks. Additionally, the introduction of the remote pumping scheme has eliminated geographical and infrastructural obstacles which were strongly associated with optical amplifiers in the past.

The Optical WDM system necessitates the employment of a multi-wavelength laser source that can provide multiple channels at high output. Multi-wavelength fiber lasers have been able to fill this need very well by generating lasers with low noise and smaller channel spacing, which allows more channel per transmission. These fiber lasers have taken advantage of the scattering effect in optical fiber, mainly the Brillouin scattering which enables the generation of multiple laser channels with small spacing of 0.089 nm. The integration of fiber lasers with erbium and modifications of the structure have allowed for a higher number of channels with wider tuning range. Such improvements have elevated the status of

fiber lasers as an efficient and cost effective choice for deployment in optical WDM communications.

Optical communication has already displayed great ability at this early stage and promises even more. This lecture serves to portray the current state of the technology and the significant contributions that have led to its current prominence and promise of an outstanding future.

INTRODUCTION

The North-South Expressway is the longest expressway is Malaysia, running 772 kilometers, from Bukit Kayu Hitam to Johor Bahru. If one were to drive along this expressway using the SSC Ultimate Aero, currently the fastest production car in the world, at the car's maximum speed of 411 km/h, it would take approximately 1 hour and 53 minutes to traverse the entire highway. On the other hand, a light signal propagated through an optical fiber of similar length would require just slightly above 3.8 milliseconds to travel from end-to-end. A race between the light signal and the SSC Ultimate Aero would probably be over even before the engine of the RM 2.29 million car has a chance to start! Such is the astonishing speed of light passing through an optical fiber, going as fast as around 200 thousand kilometers per second at the fiber core. It is even more amazing when you take note that the optical signal is actually already impeded by the refractive index of the fiber material which lowers its original speed in a vacuum (around 300,000 km/s).

Nevertheless, speed alone will not give optical communication an advantage over its predecessor, electrical signals over copper wires. In reality, electrical signals passing through a copper wire is only marginally slower than an optical signal via optical fiber. What makes optical transmission so vigorously hyped as the future of communication is its huge bandwidth and low attenuation. Fiber optics is capable of transmitting data in excess of 10 Gbps, dwarfing the meager 1.54 Mbps data provided by a single copper wire. As a matter of fact, just recently in 2010 the record for fiber capacity was broken, when researchers achieved up to 69.1 Tbps on a single optical fiber over a distance of 240 km [1]. Its advantage in terms of bandwidth can also be looked at from another aspect, which is its size. Due to its amazingly small and lightweight form (thinner than a strand of human hair), a single fiber optic strand can transmit the same amount of data equivalent to 33 tons of copper cables. Its small size also allows for easy handling, making fiber installations and repairs considerably easier.

Apart from the extremely high bandwidth, fiber optics also possess very low and constant attenuation. A single-mode fiber has maximum attenuation of around 0.4 dB per km while typical copper wire attenuation is measured in dB per meter and is also directly proportional to the frequency of the transmission. This means that at a distance of only a few hundred meters, an electrical signal could already be subjected to a sizeable amount of attenuation and the attenuation escalates with higher frequency. In contrast, an optical signal of any wavelength can propagate up to tens of kilometers without suffering any substantial loss of power.

These features are not the only advantages of optical communication. Invulnerability to electromagnetic interference, secure data transmission and no risk from high voltage transmissions are just a few of the numerous other beneficial traits of optical fibers. What makes it so much more appealing is that current researches are only at the tip of the iceberg. There are many facets of optical communication that have yet to be explored and discovered. Limitation of transmission span due to accumulation of fiber loss has triggered the advent of optical amplifiers, which boost the distance between spans by up to several hundred kilometers. The demand for higher capacity brought about optical wavelength-division multiplexing (WDM), consequently generating the need for multi-channel laser sources. Both innovations are fast-growing, emerging technological fields in which various opportunities for research exist.

HISTORY OF OPTICAL FIBERS

Due to the fact that light basically travels in a straight line, a receiver needs to be in line-of-sight to the transmitter in order to successfully receive the signal. Unfortunately, the world does not comprise of flat and unobstructed land and thus a way to bend light around corners and turns is needed if optical communication is to be realized. In the past, scientists have experimented with the use of mirrors and special tubes but none of these methods were practical enough to warrant serious attention. This, however, changed when John Tyndall rose to prominence. Tyndall is an acclaimed physicist credited as the founder of the science of light scattering. In 1870, Tyndall demonstrated to the members of the prestigious British Royal Society how a light beam can be confined and guided. In the said demonstration, Tyndall let out a stream of water from a tank into a collection pan placed on the floor. He then directed a bright light into the stream of water where it was seen that the light beam was trapped and traveled in a zigzag path within the curved path of the water until it reached the collection pan below.

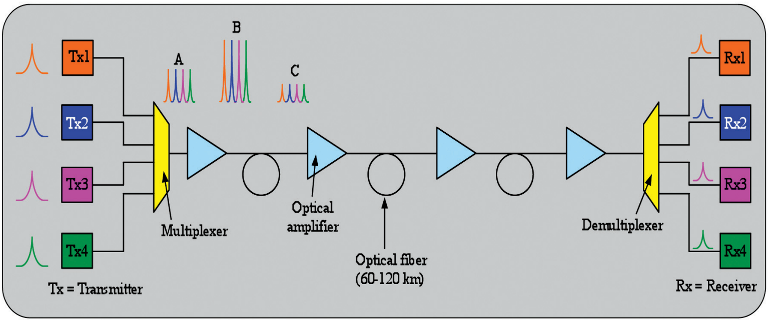
Tyndall's finding later became the basis for the creation of the optical fiber, which took 82 years to be accomplished. The inventor was Narinder Singh Kapany, an Indian born American physicist who was dubbed "The Father of Fiber Optics". During his younger days, he was vehemently told by a teacher that light can only travel in straight lines. Kapany felt that the statement was inaccurate and from that day onwards he was obsessed with finding a way to bend light. Kapany eventually succeeded in 1952, creating the first practical all-glass fiber, and also coining the term 'fiber optic'. Kapany's primary objective of devising the fiber optic at that time was for the medical endoscope and thus not many other uses were developed for fiber optics particularly due to the extremely high loss in the fiber.

OPTICAL FIBER COMMUNICATIONS

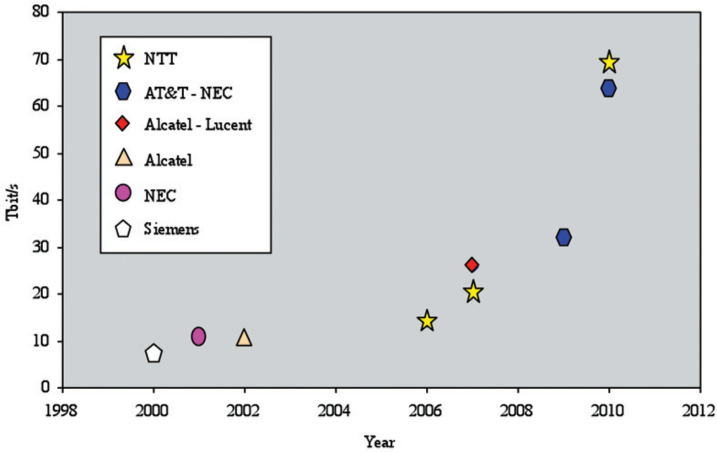
Until 1966, it was unthinkable to utilize fiber optics for communication purposes due to the high attenuation of light signals propagating in the fiber, which severely limited the distance of optical transmissions. Researchers at the time attributed this drawback to the presence of fundamental physics phenomena such as scattering. Charles K. Kao however, suggested that the high attenuation problem was largely due to impurities present in glass used in the fiber. The removal of such impurities would allow optical signals to propagate in long distance optical fiber, thereby making it suitable for communications. The results validating this theory were published in January and July 1966 by Kao and his counterpart, George Hockham. Kao's work was rewarded with half a Noble Prize in 2009 and earned him the nickname 'Father of Optical Communication'. This breakthrough opened up a new paradigm in optical fiber communications and the race to fabricate low loss optical fibers began.

In 1970, Corning Glass Works announced its success in producing low loss fibers with less than 20 dB/km [2]. Later another important accomplishment was reported by a group at Bell Laboratories, where an optical fiber with 1.1 dB/km loss was successfully fabricated [3]. Advancements in technology have enabled the fabrication of optical fibers with losses of around 0.22 dB/km, that are suitable for communications.

In order to satisfy bandwidth hunger, WDM technology was introduced and has emerged as the champion in providing high-capacity transmission systems as shown in Figure 1. The fascination with WDM stems from its use of individual segments of the optical spectrum to multiplex channels into a single strand of fiber, as illustrated by spectrum A in Figure 1(a). As a result, the total bandwidth is the product of each individual signal multiplied by its data rate. Due to this, the bandwidth can be easily tailored by controlling the number of signals with regard to availability of the amplification band. After these signals are combined via multiplexer, their power levels are amplified by optical amplifier before propagating into a few tenths (up to hundredths) kilometer of fiber optic (spectrum B). Owing to the nature of material absorption, bending and scattering losses in optical fibers, the initial signal power level cannot be sustained at the end of each fiber span as indicated by spectrum C. Thus, the signals must be further amplified to boost their power before experiencing another cycle of propagation loss in the subsequent fiber span. This superior multiplexing technology merged with sophisticated optical amplification comprising of rare-earth doped fiber amplifiers and Raman amplifiers have resulted in Terabits transmissions as summarized in Figure 1 (b).



(a)



(b)

Figure 1 (a) Typical WDM transmission system and (b) evolution of ultra high bit rate transmissions from the year of 2000 up to date.

Figure 1, shows that since the year 2000, there has been exponential growth in the trend of successful experiments on ultra high bit rate transmission. Within this period, the total transmission rate has elevated from 7 to 69 Tbit/s. The advancement of these transmission systems was supported by rapid development of amplifiers and also signal modulation schemes. The current world record holder (69 Tbit/s) utilizes as many as 432 channels at 171 Gbps (data rate per channel) with wideband amplifiers of approximately 88 nm bandwidth [1].

OPTICAL FIBER AMPLIFIERS

Optical fibers, one of several kinds of transport media for telecommunications, can carry an enormous amount of information for broadband applications between widely separated transmitters and receivers. Although low transmission loss is the main advantage of optical fibers over other transport media, regeneration is still needed to compensate for transmission losses in long haul point-to-point transmission systems and for splitting losses in networking systems. In 1987, the discovery of erbium-doped fiber amplifiers (EDFAs) cultivated a new dimension of signal amplification in optical fibers [4]. In addition to this discovery, breakthrough research in multiple wavelengths transportation riding on EDFA has nurtured the most powerful technology in the history of optical fiber communications; renowned as the WDM system.

The first analysis of rare-earth doped fiber was demonstrated by C. J. Koester and E. Snitzer [5] in 1964, using Nd^{3+} as an active material. The analysis of erbium-doped fiber as a laser and an amplifier was demonstrated in 1987 [4, 6] and since then, the development of the erbium-doped fiber has been extensively studied [7-19].

Principle of Optical Amplification

Erbium is one of the rare-earth materials that have been investigated for the purpose of optical amplification. For rare-earth doped fiber amplifiers, the fiber core is doped with erbium that has the appropriate energy levels in their atomic structures to amplify light within a low-loss transmission window of optical fibers.

For doped glass, each free ion of erbium exhibits discrete energy levels. The energy level refers to an amount of particular energy contained by the ion either corresponding to absorbtion or emission of the energy. Amplification in erbium doped fiber is closely related to changes in the energy level of the erbium ions. Absorbing energy will increase its energy level and vice versa for emitting energy. In amplification terms, emitting light is associated with emitting photons. Figure 2 shows the fundamental interactions of light with matter. The amplification energy is injected by external pump sources (electrical or optical) through an absorption process as illustrated in Figure 2(a).

On the other hand, emission can occur in two ways:

i. A spontaneous emission where excited ions return to the lower energy level in a random manner as depicted in Figure 2(b). According to quantum mechanics theory, spontaneous emission always involves transition from a higher energy state to a lower energy state. The emitted spontaneous emission becomes the noise generated by the amplifier and is referred to as amplified spontaneous emission (ASE).

ii. As shown in Figure 2(c), when a photon having energy equal to the energy difference between E_2 and E_1 interacts with the atoms in E_2, causing them to return to E_1 along with the creation of more photons, it is called ‘stimulated emission’. Photons produced by this process generally possess identical energy to the ones that caused it and hence, the light associated with them is of the same frequency, phase and polarization.

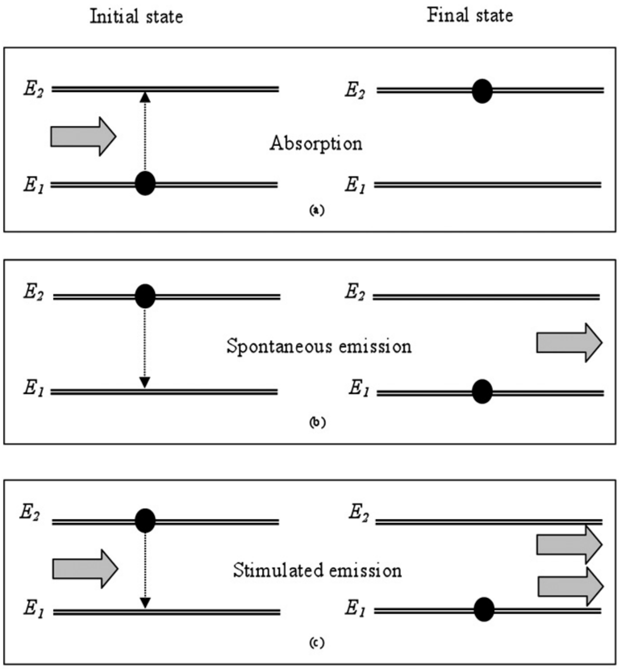


Figure 2 Schematic representations of absorption and emission between energy level 1 and 2: (a) absorption (b) spontaneous emission (c) stimulated emission.

Figure 3 shows possible energy levels for Erbium ions as well as possible pumping bands. Absorption of pump photons excites erbium ions to higher energy states. At higher energy levels, the ions may dissipate energy radiatively by releasing photons or converting the energy into heat. According to ion energy structure, a number of Stark levels are present at any particular energy level. Each ion experiences a different field strength and orientation due to randomness in the glass molecular structure, resulting in different Stark-splitting. The splitting causes a large gain bandwidth of rare-earth doped fiber amplifier. The number of Stark split lines for each level are 7 and 8 for $^4I_{13/2}$ and $^4I_{15/2}$, respectively, resulting in 56 possible transitions between those lines spreading across a 1550 nm band at low temperature.

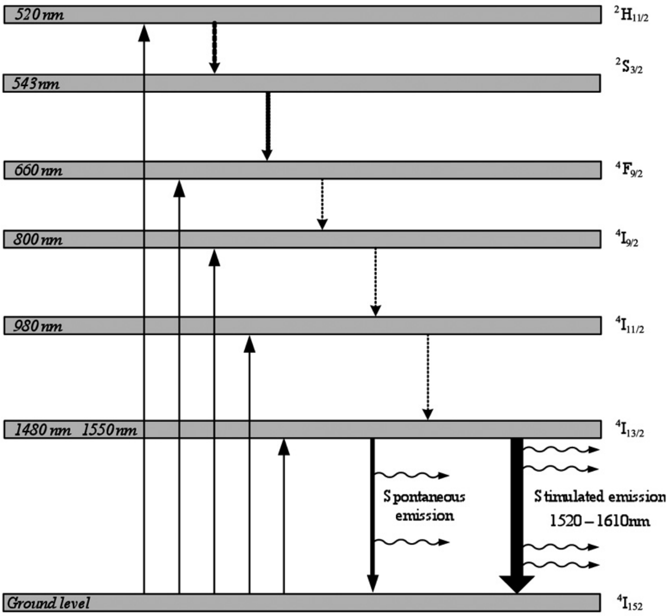


Figure 3 Energy levels of erbium ions with possible pump bands.

At 300 K temperature, the bands overlap sufficiently for smooth and continuous transition. The increases in energy gap between levels will also increase the tendency of photon radiation when jumping to lower energy levels. Thus the transition between $^4I_{13/2}$ and $^4I_{15/2}$ is predominantly radiative resulting in the 1550 nm wavelength region. Spectroscopy studies on erbium glass show that pump wavelengths at 520, 620, 800, 980 and 1480 nm can be utilized for amplification. Availability and maturity of pump laser diodes for 980 and 1480 nm lead these pump wavelengths to be widely deployed.

The 980 nm pump band offers low noise characteristics but also requires stringent requirements of pump wavelength accuracy due to its narrow absorption band. However, this problem was rectified when the pump wavelength was locked to the specified wavelength through the advent of fiber Bragg gratings [20]. On the other hand, the 1480 nm pump laser has better power conversion efficiency though it is at the expense of power consumption requirements [21].

Referring to Figure 3, discrete energy values are separated by energy gaps, which follow the law of quantum physics whereby the transition of atoms between energy levels occurs discretely. Ground level E_1 ($^4I_{15/2}$) indicates the lowest level and E_2 ($^4I_{13/2}$) indicates the first level. The difference of energy ΔE, at which the atom moves from upper to lower level, releases photons as a quantum of energy. The photon carries energy of *Ep* and is defined as [21];

$$Ep = hf = E_2 - E_1 \tag{1}$$

E_2 and E_1 refer to the atom's discrete energy during transition between levels, where $h = 6.626 \times 10^{-34}$ J.s is a Planck's constant and photon frequency denoted by *f*. Changes of atomic energy levels from lower to higher levels require external energy. The atom absorbs this energy and jumps to the higher level. The process of providing an atom with external energy, referred to as pumping, is depicted in Figure 4(a).

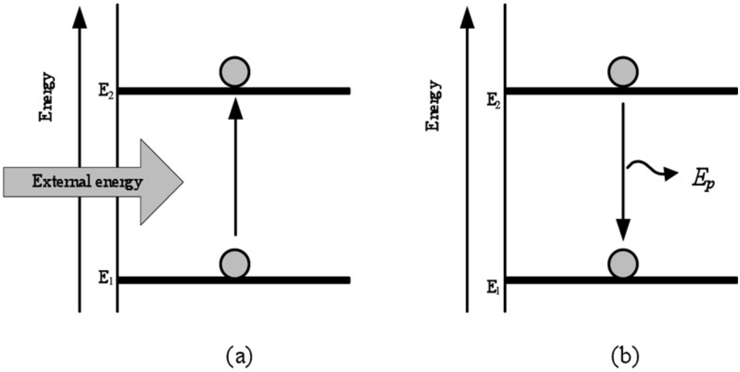


Figure 4 Atom with respective energy levels (a) light absorption and (b) light emission.

Initially the atom relaxes at E_1 which is the lowest energy level. Applied external energy is absorbed by the atom, causing it to jump to an upper level, E_2. This condition is known as light absorption. By nature an atom always tries to get to its lowest possible energy level. Figure 4(b) shows light emission occurring when the atom goes down from E_2 to the lower energy level and emits photons.

Population Inversion

In atomic systems with thermal equilibrium, the atom density in each energy level obeys the Boltzmann distribution given by Desurvire [21];

$$\frac{N_2}{N_1} = e^{-\left(\frac{E_2 - E_1}{KT}\right)} = e^{-\left(\frac{hf}{KT}\right)} \tag{2}$$

N_1 and N_2 are atom densities for energy levels E_1 and E_2 respectively, K is the Boltzmann constant, T is the absolute temperature, f is the frequency and *h* is Planck's constant. According to the above equation, N_2 is much smaller than N_1 in a normal atomic system at thermal equilibrium. Hence, the absorption is dominant compared to the spontaneous/stimulated emission.

A condition where thermal equilibrium is achieved is where the lower level energy contains more atoms than the upper level, at room temperature. A non-equilibrium distribution of atoms where a population of atoms at upper energy level is greater than the lower is necessary to have optical amplification. The condition is commonly known as population inversion, with $N_2 > N_1$ where both N_2 and N_1 represent the density of atoms in energy levels E_2 and E_1. Through population inversion, N_2 will become much larger than N_1, resulting in a system with dominant stimulated emission. Population inversion is achieved by injecting power into the system through an external energy source, which is known as pumping, as described previously.

Spectroscopic Properties

Understanding absorption characteristics is important to study potential pump wavelengths for the erbium ion as shown in Figure 5 [22]. Erbium ions have absorption transition of photon energy for wavelengths at 520, 620, 800, 980 and 1480 nm. However, the 980 and 1480 nm pumping bands are widely used due to their technological maturity. Furthermore, these pumping bands are more suitable for single-mode signal propagation in optical fibers.

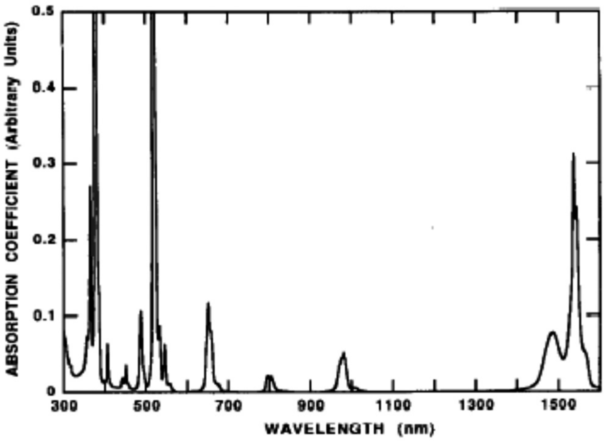


Figure 5 Absorption spectrum of erbium ion in silicate glass [22].

The typical optical properties are shown in Figure 6 for the 980 nm absorption band and the 1550 nm absorption/emission bands. The 980 nm absorption peaked at 978 nm with Lorentzian-like response, as depicted in Figure 6(a). Since there is no emission transition within the 980 nm wavelength range, all the excited atoms are available for amplifications, which is normally considered as full inversion. However, as seen in Figure 6(b), there is an emission transition in the 1480 nm band, making the condition of full inversion impossible. This contributes to the deterioration of amplifier noise pumped by the 1480 nm pumping band. Despite this drawback, the amplifier performance is also dependent on the power conversion efficiency where the 1480 nm pumping is much better than the 980 nm pumping.

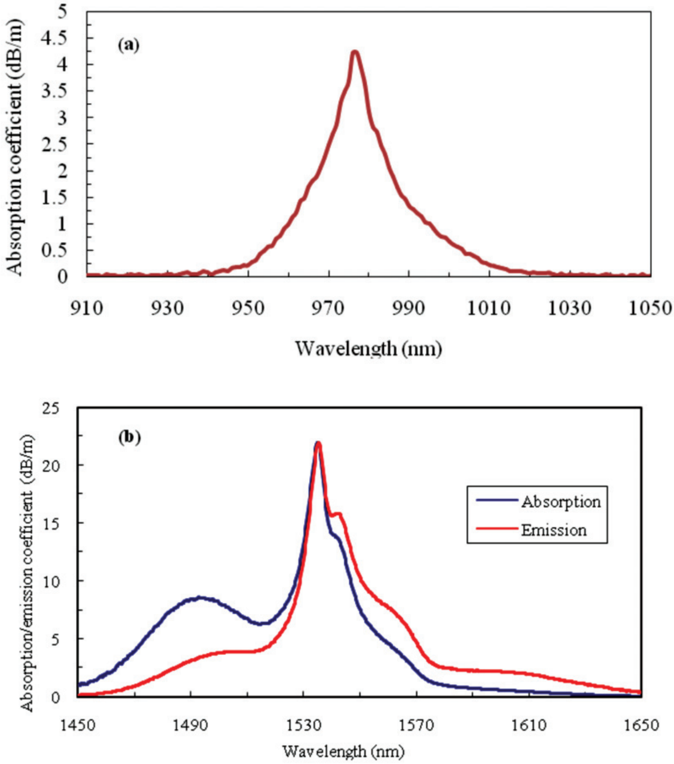
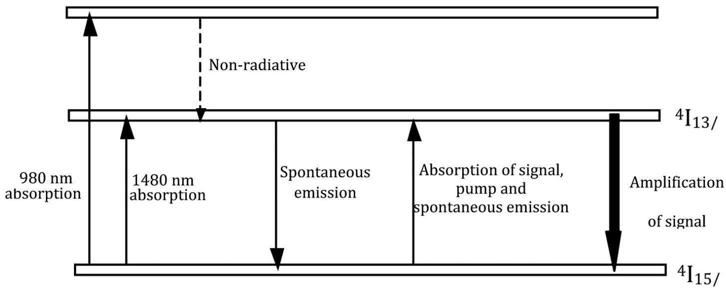


Figure 6 (a) Absorption coefficient of 980 nm band and (b) emission/ absorption coefficient of 1550 nm

Pumping Scheme

The erbium-ion is described through the energy level diagram shown in Figure 7(a). When pumping at 980 nm, the EDFA acts as a three-level laser system. This means that the Er^{3+} ions are excited from the ground state level ($^4I_{15/2}$) to a third level ($^4I_{11/2}$) from which it rapidly decays, mainly non-radiative emission to a lower energy level ($^4I_{13/2}$) metastable state with relatively longer lifetime. For a two-level laser system, normally the erbium-doped fiber (EDF) is pumped by 1480 nm pump lasers. Figure 7(b) depicts the emission of green fluorescence when the EDF is pumped by 980 nm pump lasers. This effect is known as excited state absorption, whereby the pump light is not only absorbed from the ground level ($^4I_{15/2}$) but also from an excited state level ($^4I_{11/2}$) due to the existence of a third energy level with an energy gap between these two levels closely matching the pump photons energy. Then, these excited ions naturally drop to ground level to release photon energy of around 510 nm (green light).



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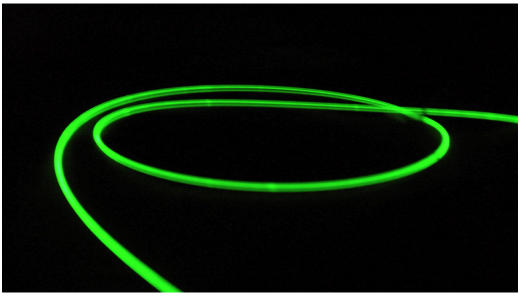


(b)

Figure 7 (a) Pumping scheme of erbium-doped fiber; three- and two-level laser systems and (b) green fluorescence from EDF pumped with 980 nm light.

Amplifier Configuration in Transmission Systems

The invention of EDFA transformed the landscape of optical transmission systems. Figure 8 shows specific applications of EDFA in typical optical transmission systems which correspond to distinct operating regimes of the EDFA. Practically, there are three regimes: small signal regime for pre-amplifiers, saturation regime for in-line amplifiers and deep saturation regime for high power amplifiers. The location of an amplifier depends on the intended application in a specific transmission system. Thus, the pre-amplifier is located just before a receiver (Rx) where the input signal level is extremely low and accordingly the pre-amplifier is designed to have an extremely low noise figure. An in-line amplifier, which is located between the transmitter (Tx) and receiver along the trunk fiber lines, normally has characteristics of high gain, high output power and low noise figure. Finally, power amplifiers are designed mainly to boost the input signal power from Tx so as to provide very high output power for long haul transmission systems and are located just after a transmitter.

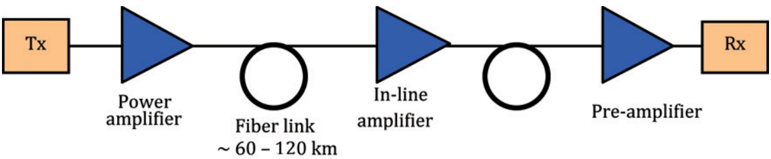
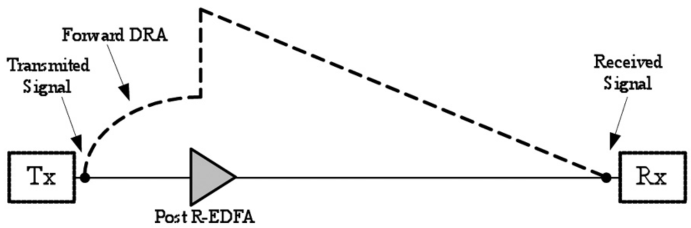


Figure 8 Applications of EDFA in a standard optical fiber transmission system.

Besides conventional designs of EDFA, there is another type of optical amplifier. This class is called a remotely-pumped EDFA (R-EDFA). The R-EDFA surmounted the geographical obstruction problem faced by the discrete pump EDFA and enabled utilization of longer span length. The difference between the discrete pump EDFA and R-EDFA is that the pump no longer needs to be in proximity with the EDFA. In R-EDFA architecture, the pump can be located at either the transmitter or the receiver. A schematic drawing of the repeaterless optical transmission system setup is shown in Figure 9. This configuration includes most of the technologies that have enabled significant progress in transmission distance.

A post EDFA boosts the signal level to launch it into post-length fiber span. The boosted signal is also amplified by a distributed Raman amplifier (DRA) which is the natural cause of nonlinear effect in optical fiber when the pump power is above a certain threshold value. A post R-EDFA is located after this section of fiber for additional signal amplification. Figure 9(a) shows signal power evolution, represented by a dashed line along the transmission distance, using forward DRA and R-EDFA. On the other hand, a pre-R-EDFA can also be located closer to a receiver as depicted in Figure 9(b). In this configuration, the backward DRA is utilized to improve signal power for better detection level at Rx.



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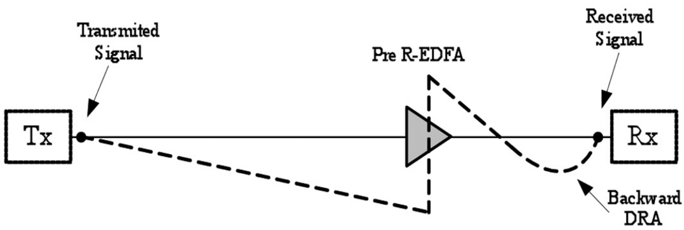


(b)

Figure 9 Signal power evolution experienced by (a) forward DRA and Post R-EDFA, and (b) backward DRA and pre R-EDFA.

Figure 10 illustrates the progression of a repeaterless system employing several configurations of remotely-pumped optical amplifiers. The longest achievable transmission system is possible with the inclusion of the effect of distributed Raman amplification as depicted in Figure 10(g).

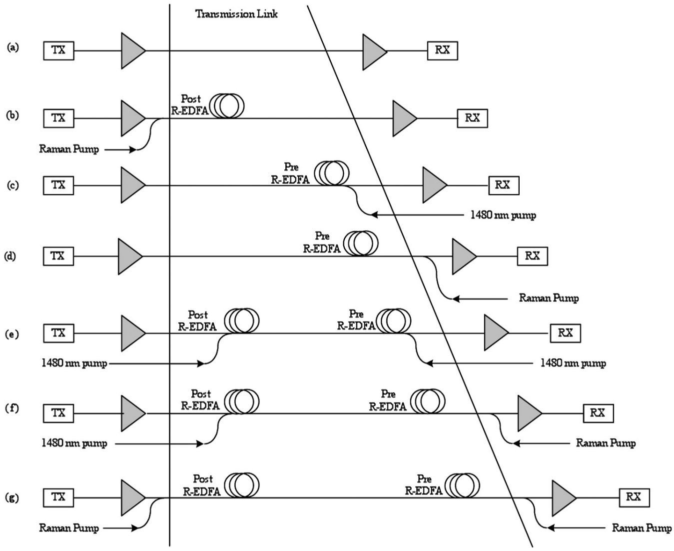
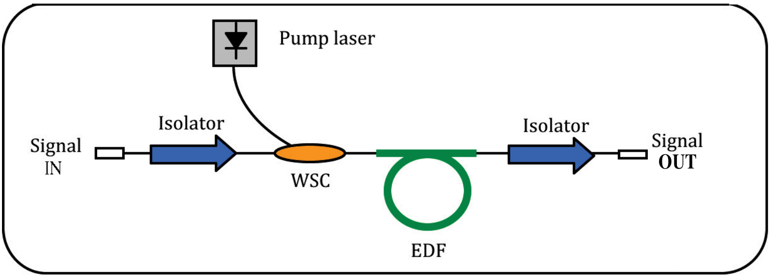


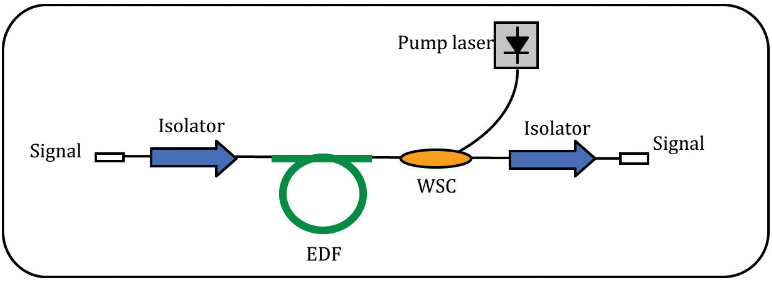
Figure 10 Various configurations of repeaterless transmission systems.

Optical Amplifier Architectures

Basically, an EDFA can be constructed using three different configurations as shown in Figure 11. The pump laser used is either a 980 or 1480 nm laser diode (LD) to inject energy for ions excitation to create population inversion in a length of erbium-doped fiber (EDF) for amplification. Wavelength selective couplers (WSCs) are utilized as pump and signal light multiplexers/demultiplexers. These couplers are made using fused fiber technology. Isolators are deployed as a unidirectional component which allows one-way direction of light while blocking any light from the opposite direction.



(a)



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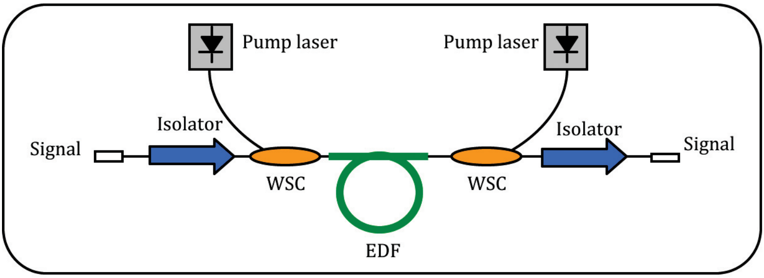


(c)

Figure 11 EDFA can be designed in (a) forward-pumped, (b) backward-pumped and (c) bi-directionally-pumped configurations.

The forward-pumped configuration is defined as that where the pump and signal lights propagate in the same direction along the erbium-doped fibers, whereas the backward-pumped configuration is constructed such that the pump and signal lights propagate in the opposite direction. On the other hand, the bi-directional pump scheme utilizes two pump lasers at both ends of the EDF where the propagating signal encounters pump lights in both directions.

Optical Amplification Band

Fiber attenuations play an essential role in determining the assignment of optical band in transmission systems. Optical signals experience loss mainly due to material absorptions and scatterings. A typical fiber attenuation curve (solid line) is shown in Figure 12 where there is an absorption peak of around 1400 nm owing to strong absorptions of O-H ions. Advancement in optical fiber technology has led to the development of new fiber types which suppress the OH peak, as represented by the dashed line illustrated in Figure 12. This breakthrough has enabled data transmission from 1290 to 1700 nm (410 nm bandwidth). Referring to Figure 12, band allocations for these transmission windows are namely O, E, S, S+, C, L and U bands. In order to rectify this attenuation problem, optical amplifiers are needed to cover the whole transmission band. Practically, the praseodymium-doped fiber amplifier (PDFA) covers O-bands from 1290 to 1320 nm. Thulium-doped fiber amplifiers (TDFAs) are utilized to amplify signals from 1420 to 1500 nm (S- and S+-band). Finally, EDFA can be used to combat attenuation in the range of 1500-1620 nm [11, 23, 24]. Apart from rare-earth doped amplifiers, Raman fiber amplifiers (RFAs) can also be designed to operate in a wide range of transmission windows, subject to the availability of pump lasers [25-28].

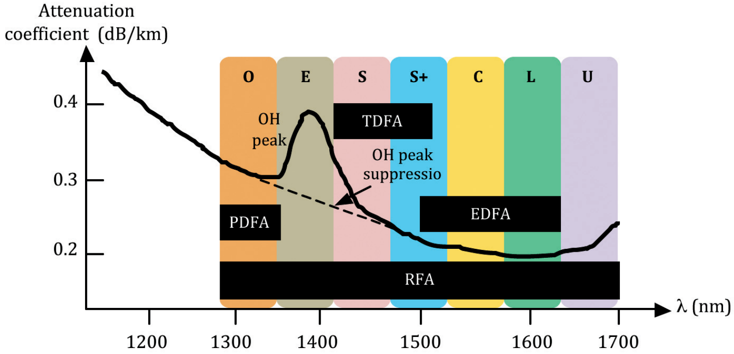


Figure 12 Transmission band assignment with respect to fiber attenuation and available optical amplifier technologies.

Since the amplification bandwidth of EDFA is perfectly overlapped with the lowest attenuation window of optical fibers, this enabling technology continues to be extensively investigated. Together with Raman amplifiers, these two amplification gadgets shape the landscape of optical communication industries around the globe.

WIDEBAND OPTICAL AMPLIFIERS

In optical fiber communications, WDM systems are the enabling technology to increase transmission capacities. This allows the capacity of a single fiber to be increased while managing both component performance and optical impairments that limit amplifier spacing and total link length. Additionally, higher optical channel counts may extend the economic benefits of managing traffic in the optical layer by providing access to signals at a finer level of granularity. Hence, optical amplifiers must be able to cope with the requirement of having a higher number of channel counts. In this case, broadband optical amplifiers are the essential optical engine to support WDM systems especially in the wavelength range of C- and L-bands.

C-band Optical Amplifiers

Acquiring high gain in the C-band transmission window is simpler owing to the fact that the erbium emission spectrum is substantially high in that region, as seen in Figure 6(b). The drawback in C-band amplification is that the difference in the emission spectrum across the C-band region is significantly high which generates a 'hump' (around 1530 nm) in the amplification spectrum, as depicted in Figure 13. This in turn causes variation in the gain experienced by the signals in multi-channel transmission. The effect of dispersion in optical fiber has to be considered as well, since longer transmission distance will lead to higher accumulated dispersion. While the existence of dispersion is welcome in some ways; particularly in reducing the effect of four-wave mixing in WDM systems, uncontrolled dispersion will cause severe distortion to the transmitted signals, rendering the data incomprehensible.

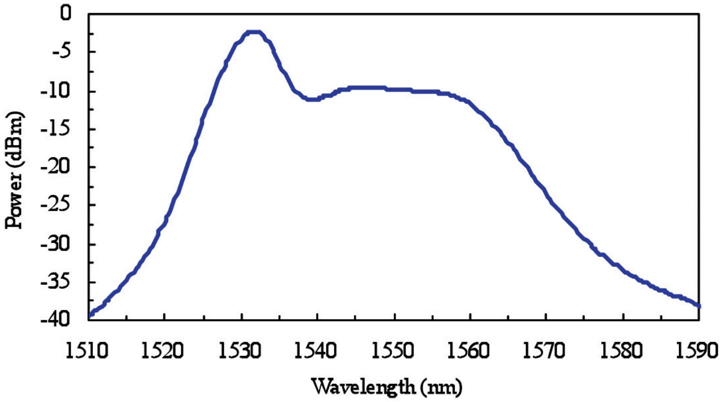
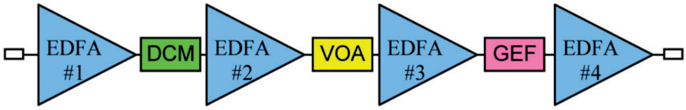
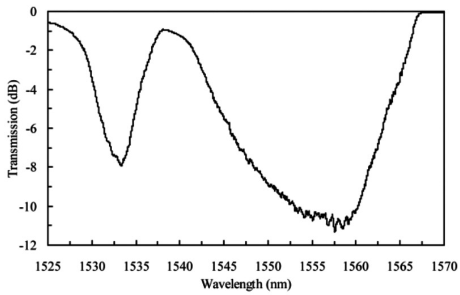


Figure 13 Typical gain spectrum of C-band EDFA.

The use of amplifiers in optical communication systems has to take into account the problems due to the said effect. Referring to Figure 14(a), the amplifier design consists of four amplifier stages that distribute losses of three core optical devices: dispersion compensating module (DCM), variable optical attenuator (VOA) and gain-equalizing filter (GEF). The DCM is used to compensate for the_accumulated fiber dispersion within a transmission span. Since the loss of DCM has variations, thus the maximum allowable mid-stage loss is fixed at 10 dB. This is critical in order to maintain the gain-flattened operation of the amplifier. On the other hand, the VOA is utilized to vary the operating gain-flattened value from 15 dB to 30 dB, and finally the GEF is employed to have a flat gain with tolerance of about $\pm$ 0.75 dB. The transmission spectrum of the GEF is shown in Figure 14(b). The maximum loss of the GEF is about 11 dB around the 1557 nm wavelength range. In general, the transmission spectrum of GEF is matched to the inverted gain spectrum of the amplifier.



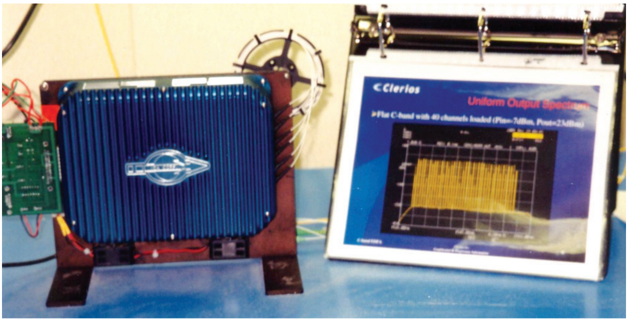
(a)



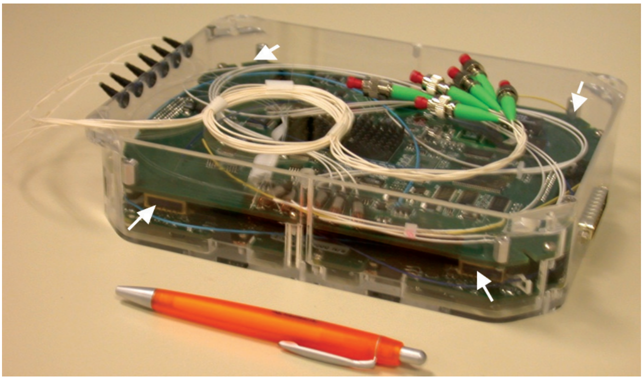
(b)

Figure 14 (a) Block diagram of the 4-stage Erbium-doped fiber amplifier and (b) transmission spectrum of GEF used in the 4-stage EDFA.

The commercial prototype of this high end amplifier is depicted in Figure 15(a). The package consists of four separate pump lasers that are located at the corners (white arrows) to allow efficient heat distribution as shown in Figure 15(b). There are two separate electronics boards to control the entire operation of the optical amplifier.



(a)



(b)

Figure15 (a) Commercial prototype of the gain-flattened EDFA and (b) the electronic boards used to operate as the intelligent engine.

Referring to Figure 16, four different gain levels (15, 20, 25 and 30 dB) are measured from the gain-flattened EDFA. In addition, the extreme signal condition is tested by taking the input power equivalent to the minimum and maximum signal powers for each gain level. The average signal gain at the desired gain value was successfully obtained without any significant power penalty from the broadband noise of ASE. This was achieved by implementing our unique algorithm of ASE correction. This algorithm is very useful to compensate for the contribution of ASE on the amplified signals [29]. The gain variation of signals is due to the profile of GEF used in the 4-stage EDFA. For the 15 dB operating gain, the signal gains from 1530.33 nm to 1531.90 nm are slightly higher than the rest of the signals. This phenomenon is due to the effect of spectral hole burning as reported in [9, 30].

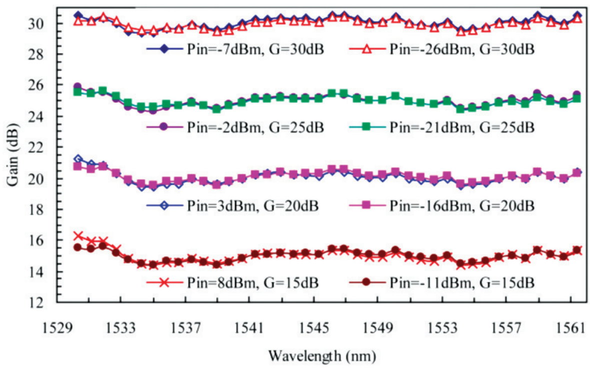


Figure 16 Gain performance of 4-stage EDFA with ASE compensation algorithm [29].

The output spectra of the variable gain-flattened EDFA are depicted in Figure 17. In this case, the total input powers are -19 and -26 dBm, and the operating gain is fixed to 30 dB. The output spectra are exceptionally flat even though the input signal power variation is applied to the amplifier. The developed algorithm is able to handle the power penalty problem induced by internally generated ASE.

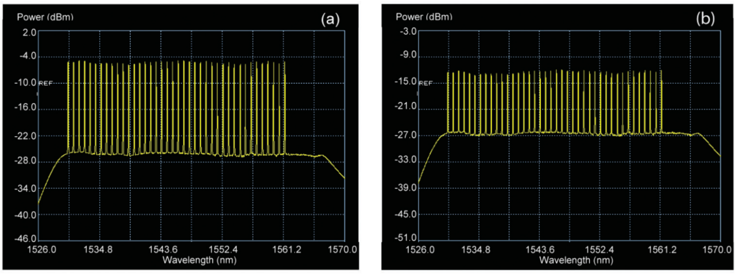


Figure 17 Output spectrum at 30 dB gain with (a) -19 dBm total signal power and (b) -26 dBm total signal power [29].

The wideband EDFA of 35 nm can be extended to 38 nm as shown in Figure 18. The wavelength range is from 1528 to 1566 nm and the operating gain is 28 dB. The impact of having broader amplification bandwidths is the transmission loss of GEF. This invites additional engineering problems in GEF fabrication and higher internal gain of EDF by increasing the length of active gain medium and also its pump power requirements.

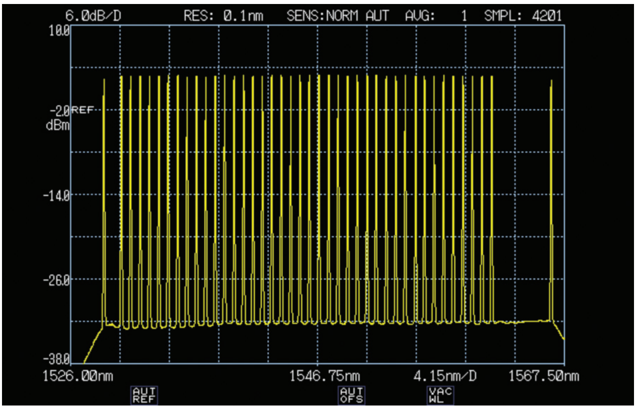


Figure 18 Output spectrum of gain-flattened EDFA at 28 dB gain with 38 nm amplification bandwidth.

L-band Optical Amplifiers

The rise of the WDM system in optical communications has increased the demand for more bandwidth, leading to the addition of the L-band transmission window. The use of the L-band region for optical transmissions has eliminated several problems associated with the C-band region, such as the uneven gain spectrum and the existence of four-wave mixing in systems utilizing dispersion-shifted fiber.

Figure 19 shows a schematic diagram of L-band amplification in a long coil of EDF length. Strong ASE of 1550 nm is generated by 980 or 1480 nm band pump light at the input portion of the fiber. Due to the inadequate pump power for this long fiber, the 1550 nm band ASE is absorbed and emits longer wavelengths in the L-band. The gain band shifts from the 1550 nm band to the 1580 nm band with increment of EDF length. Thus, energy of long wavelengths is accumulated along the fiber length and is more pronounced if there is a lack of pump energy. A long fiber is needed because the gain coefficient of the L-band is smaller than that in the C-band. Similarly, EDF can be highly doped with erbium ion concentrations in order to get the same effect [31].

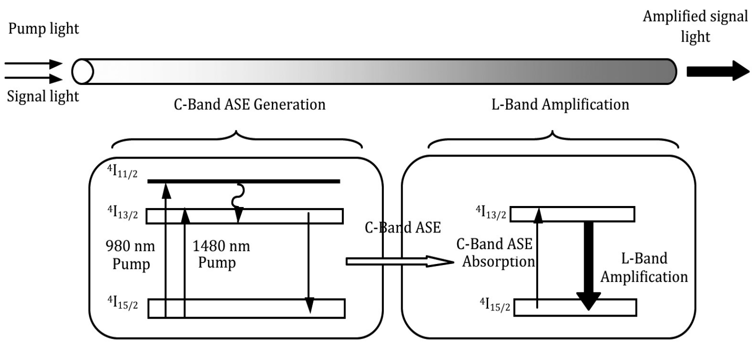


Figure 19 Schematic diagram of L-band amplification.

The L-band operating region falls at the edge of the erbium amplification window as shown in Figure 6(b). In this region, the absorption and emission coefficients are much lower as compared to the peak wavelength region of around 1530 nm. Unfortunately, these low coefficients cause low net gain coefficients. Therefore high inversion is required to obtain high-gain operations. However, in sustaining high inversion in this region, the flat-gain property of the L-band cannot be utilized. In order to relate the gain coefficient and level of inversion, a simple mathematical derivation is performed as follows:

$$G_C(\lambda) = g(\lambda)N_2 - \alpha(\lambda)N_1 \quad (3)$$

where G_c is the gain coefficient, g is the emission coefficient, α is the absorption coefficient and $N_{1,2}$ is the fractional ion density at level 1 and 2 respectively. However,

$$N_1 = 1 - N_2 \quad (4)$$

and yields,

$$G_C = \left(g(\lambda) + \alpha(\lambda)\right)N_2 - \alpha(\lambda) \quad (5)$$

where N_2 is known as the inversion factor that can take on values in the range of 0 – 1. Then, gain coefficient versus wavelength is plotted as shown in Figure 20(a), in order to make use of the inherent flat-gain response of the L-band, where the average inversion along the fiber should be maintained at around 40%. The nominal output spectrum of the L-band amplifier under these conditions is depicted in Figure 20(b)

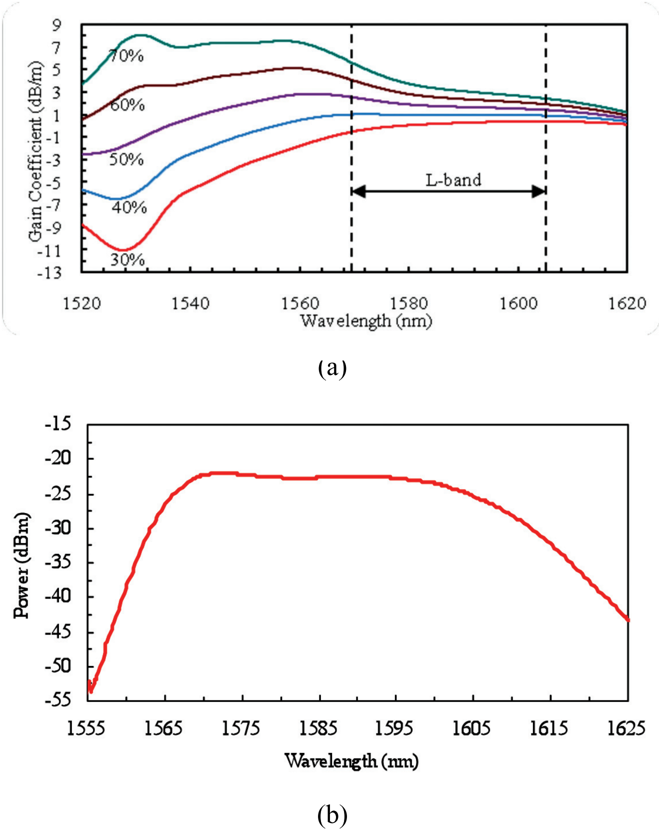


Figure 20 (a) Gain coefficient spectra at different inversion levels in L-band and (b) typical gain spectrum of L-band EDFA at 40% population inversion.

It can be seen that signal wavelengths cannot exceed 1605 nm in order to have good gain flatness in the L-band. The L-band gain coefficient of about 0.26 dB/m is 6 to 8 times lower than that in the C-band region. Hence, longer lengths of EDF are needed to obtain reasonably flat-gain values. As an example, if a 100 m long EDF is used, the flat-gain value is around 26 dB. Since the length requirement for the L-band amplification is significant, research activities have been centered on gain enhancement techniques for the L-band, as summarized in Table 1.

Table 1 Significant reports on techniques to improve L-band gain

Method	Brief description	Year	Ref.
Reflective amplifier	Insertion of fiber Bragg gratings to reflect the input signal back into the gain medium for another amplification trip.	1996	[32]
Internal C-band seeding	Employment of fiber Bragg grating to reflect a portion of backward ASE back into the EDFA and to act as a secondary pump.	1998	[33]
Passive EDF	A section of passive EDF placed to utilize backward ASE from the L-band amplifier.	1999	[34]
Pump detuning	Detuning of 980 nm pump to avoid peak absorption wavelength and enhance power conversion efficiency.	1999	[35]
Backward ASE pumping	A feedback system is implemented in a dual-stage amplifier where the backward ASE from the first amplifier is fed to the second amplifier for pumping purposes.	2001	[13]
Internal C-band seeding	Employment of ring-cavity laser structure to convert backward ASE to C-band seed.	2001	[36]
Internal C-band seeding	Employment of linear-cavity laser structure to convert backward ASE to C-band seed.	2001	[37]
C-band pumping scheme	The use of 1530 nm pumping band for L-band amplifier to increase gain coefficient.	2001	[38]

Broadband reflective amplifier	Employment of double-pass amplification of L-band signals to reduce the EDF length.	2001	[39]
Advanced glass materials	Phosphorous silicate glass for extended L-band amplification.	2002	[40]
Advanced glass materials	Antimony silicate glass for broader amplification in L-band.	2002	[41]
Advanced glass materials	Bismuth glass host is used for higher erbium ion concentration.	2003	[42]
Advanced fiber design	The modification of fiber geometry to enable cladding-guided pump light.	2003	[43]
Hybrid EDF/ Raman amplifier	Remote EDFA combined with Raman effect for higher cumulative gain.	2003	[44]

The application of L-band EDFAs for wideband amplification is quite interesting because it can offer wider bandwidths as compared to its counterpart the C-band [45]. Therefore, new transmission networks can be deployed using this extended L-band as a result of more channels being available to support WDM systems. The amplifier architecture of the extended L-band (43 nm) is depicted in Figure 21(a) [17].

A dual-stage amplifier structure is used with midway isolators and GEF. 1480 nm pump lasers are chosen due to the fact that the 1480 nm pumping scheme produces better power conversion efficiency when compared to the 980 nm pumping scheme. Since the extended L-band amplifier is designed to operate in conjunction with Raman amplifiers, the input signal powers into this amplifier are high. Thus, the 1480 nm pump lasers are used because of their higher power conversion efficiency that translates to higher gain values. The isolator in the middle functions to avoid reflection of the detrimental backward propagating ASE from the second-stage amplifier.

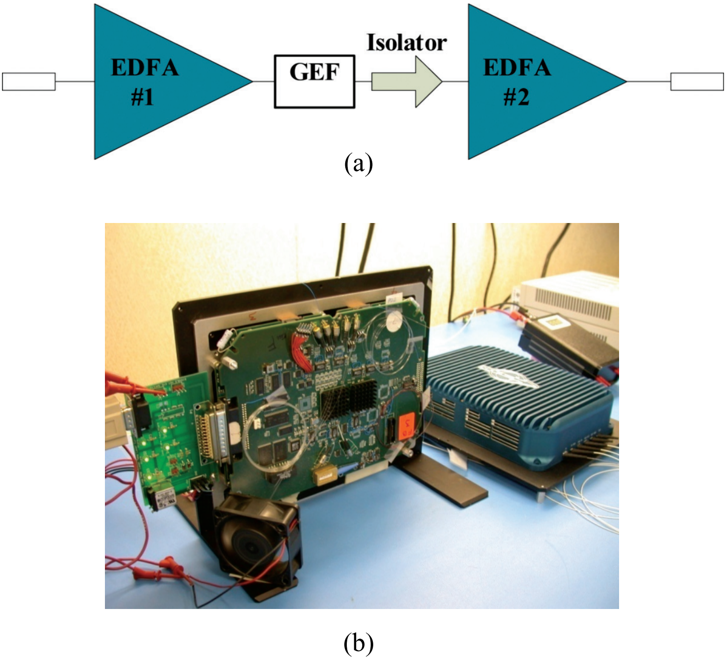


Figure 21 (a) Configuration of extended L-band amplifier and (b) its engineering prototype.

The gain of 13 dB with gain flatness of less than 1 dB is achieved using the GEF made from the fiber Bragg grating technology as depicted in Figure 22. The output power is 20 dBm. Power conversion efficiency of 25.6% is obtained from the proposed amplifier structure, higher than the 18.4% reported in [46]. For extended L-band EDFA, widest bandwidth of 55 nm was reported with the use of advanced materials, in year 2000 [47].

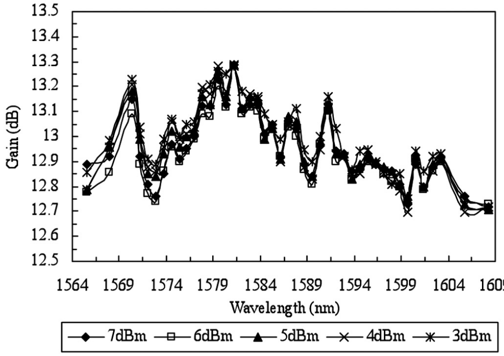


Figure 22 Flat-gain response against wavelength at different input powers from 3dBm to 7dBm, the gain-control value is fixed at 13dB [17].

Figure 23 shows the impact of the four-wave-mixing (FWM) product in the amplifier system. The total signal power is set at 4 dBm and the output power is 17 dBm. The signal at 1586.96 nm is turned-off in order to observe the presence of the FWM product. The difference between the peak signal and the FWM product was around 43 dB. Since the length of EDF is only 40 m, the effective length for nonlinear interaction is reduced significantly.

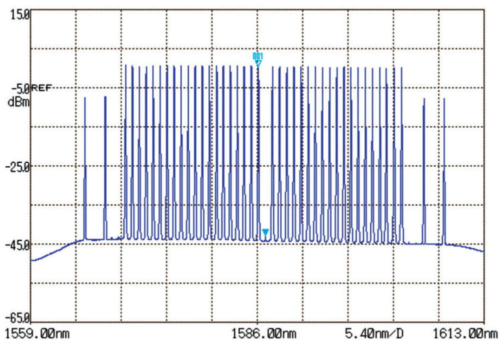


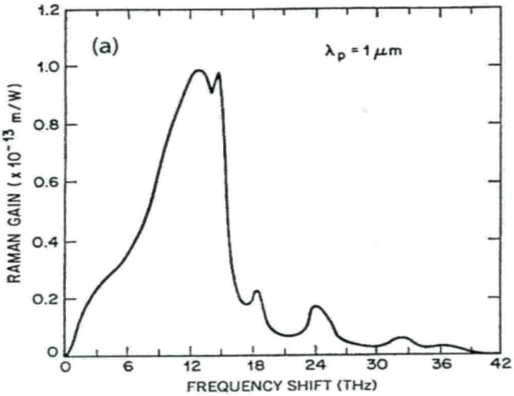
Figure 23 FWM component at 1586.96 nm for input power of 4 dBm and the total output power of 17 dBm [17].

Raman Fiber Amplifiers

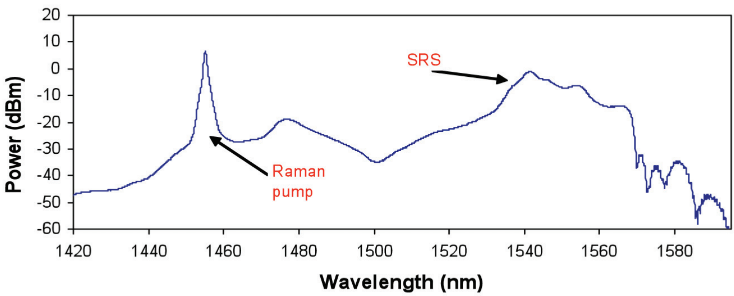
Raman amplification in optical fibers was first demonstrated by Stolen and Ippen in 1972 [48]. However, lack of efficient power conversion or high power pumps throughout the 1970s and the first half of the 1980s, caused Raman amplifiers to remain primarily as laboratory curiosities. In the mid 1980s, many research papers looked into the promise of Raman amplifiers, but this was overtaken by interests in EDFAs. In the mid 1990s, there was an abrupt increase of interest in Raman amplification. This trend was due to the increased understanding of Raman efficiency with respect to gain media and fiber optics, and the arrival of more efficient, high power optical pumping lasers in conjunction with the exploding growth of WDM transmission systems [25].

The Raman scattering process becomes stimulated if the pump power exceeds a threshold value. Stimulated Raman scattering (SRS) can occur in both forward and backward directions in optical fibers. Physically speaking, the beating of the pump and scattered light in these two directions create a frequency component at the beat frequency ω_p - ω_s, which acts as a source that derives molecular oscillations. Since the amplitude of the scattered wave increases in response to these oscillations, a positive feedback loop sets in.

The spectrum of Raman gain depends on the decay time associated with the excited vibrational state. In the case of optical fibers, the bandwidth exceeds 10 THz. Figure 24 shows the Raman-gain spectrum of silica fibers. The broadband and multipeak nature of the spectrum is due to the amorphous nature of glass. More specifically, the vibration energy levels of silica molecules merge together to form a band. As a result, the Stokes frequency ω_s can differ from pump frequency ω_p over a wide range. Maximum gain occurs when the Raman shift $\Omega_R \equiv \omega_p - \omega_s$ is about 13 THz.



(a)



(b)

Figure 24 (a) Raman gain spectrum of fused silica at pump wavelength of 1µm [49] and (b) experimental result of SRS and its pump light at 1455 nm.

For SRS, the incident pump photon gives up its energy to create another photon of reduced energy at a lower frequency, while the remaining energy is absorbed by the medium in the form of molecular vibrations (optical phonons). The energy level diagram is represented in Figure 25. This virtual state energy can occur in any glass medium that creates the benefits of Raman amplification in optical communication systems. Thus, any transmission fibers can be utilized as the Raman gain medium and the operating band can be easily tailored by choosing the appropriate pump wavelengths. By combining a few pump wavelengths, 100 nm bandwidth has been demonstrated as reported in [50]. This technology is normally considered as distributed Raman amplification (DRA) (Refer to Figure 26).

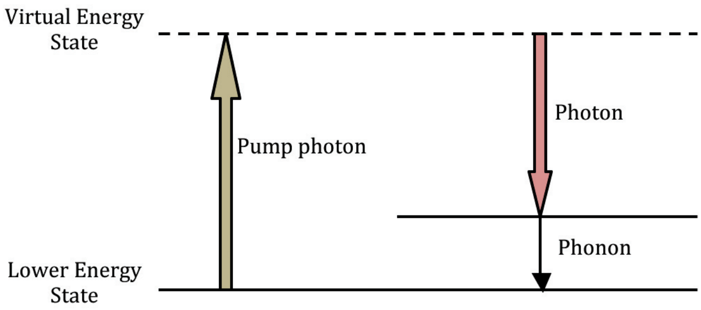


Figure 25 Energy level diagram representative of the Raman process, which takes a higher energy pump photon and splits it into a lower-energy signal photon and a phonon.

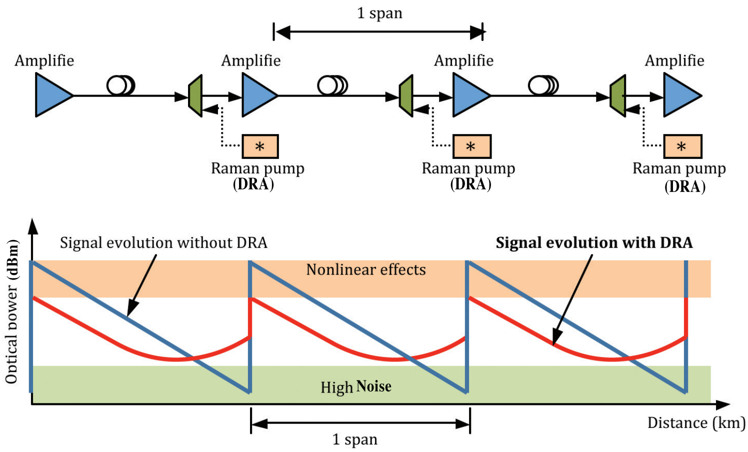


Figure 26 Distributed Raman amplification technology in transmission systems and signal power evolution along the transmission fibers.

Referring to Figure 26, there are two optical power boundaries that influence the signal performance in transmission systems, for both large and small signals. Large signals have a tendency to induce nonlinear effects such as stimulated Brillouin scattering (SBS), four wave mixing and self-phase modulation [49]. If the signal power which reaches the amplifier input is very low, the ASE from the amplifier is dominant, which leads to deterioration of signal quality in terms of optical signal-to-noise ratio (OSNR). By having DRA in the transmission systems, the maximum power can be reduced below its nonlinear effect threshold, as the maximum signal power per channel is normally about 5 dBm. In addition to this, the signal power at the amplifier input is enhanced and as a result, signal quality is greatly improved (better OSNR).

Figure 27 Engineering prototype of the Raman pump unit.

The impact of DRA can be observed in the experimental findings illustrated in Figure 28, which shows the 44-channel spectrum for wavelengths from 1530.33 to 1568.78 nm, when the Raman pump is turned off and on. It is worth noting that four channels at longer wavelengths have higher insertion loss as compared to the group of 40 channels. Thus the signal power is lower as depicted in Figure 28. However, this issue does not impact the measurement since the gain characteristics are taken into account. The total input power is 14 dBm and the average Raman on-off gain of 10 dB is set as the target value. The flat signal spectrum is observed for all the channels after travelling through 100 km of transmission fiber with gain variation of less than 1.1 dB.

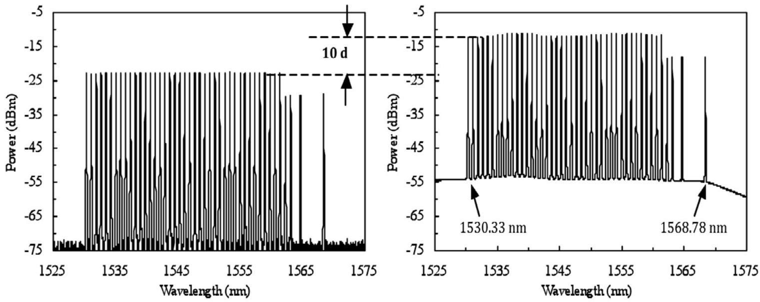


Figure 28 Spectrum of 44-channel WDM when the Raman pump is turned off (left) and on (right) at the end of the transmission fiber.

To verify the benefit of DRA in the transmission system, the Raman pump unit is disabled and the EDFA alone activated to compensate the span loss of 28 dB, as depicted in Figure 29. Then, the gain of the EDFA is adjusted to 18 dB in order to give some room for Raman amplification of 10 dB. Still, total gain is maintained at 28 dB to fully compensate for transmission loss. The output spectrum of the hybrid Raman/EDFA transmission system is shown by the green curve. The gain flatness is maintained at around 1.2 dB for both transmission systems i.e. EDFA alone and hybrid Raman/EDFA. It is obvious that the noise floor is reduced by 5 dB in the hybrid Raman/EDFA system and the OSNR is improved. Reduction of the accumulated noise is beneficial to enhance the bit error rate performance of the transmission systems and thus, push towards longer transmission distances.

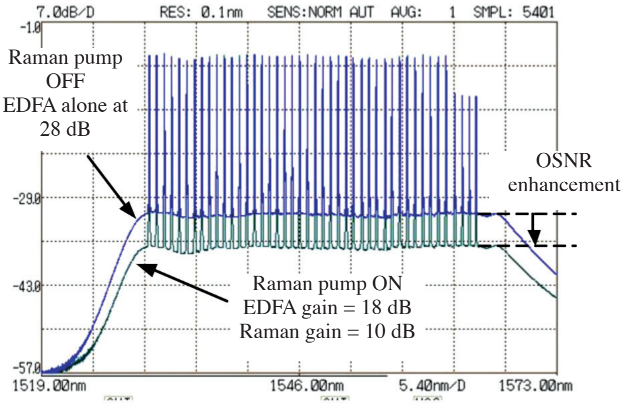


Figure 29 The output spectra of 44 WDM channels through a 100 km span of fiber amplified with a conventional EDFA and a hybrid Raman/ EDFA. The peak power is the same while the noise floor is 5 dB for the hybrid Raman/EDFA system.

FIBER LASERS

Fiber lasers are referred to as lasers with optical rare-earth doped fibers as gain media. Many different rare-earth ions, such as erbium, neodymium, and ytterbium, can be used to make fiber lasers capable of operating over a wide wavelength range extending from 0.4 to 4 μm . Fiber lasers have many advantages as compared to other types of lasers. They are compact, easy to build and manipulate and can be pumped with diodes. Compared to laser diodes, fiber lasers are spectrally cleaner and can be modulated with less chirp and signal distortion. Moreover, fiber-to-fiber compatibility is a distinct advantage in optical communication systems. The first fiber laser was demonstrated by Snitzer [51] as early as in 1961, by using a neodymium (Nd)-doped fiber with a 300 μm core diameter. Late in 1965, Snitzer together with R. Woodcock [52], investigated a glass doped with both Erbium and ytterbium and achieved lasing action at 1.54 µm. Low loss silica fibers were used to make diode-laser pumped fiber lasers in 1973 soon after such fibers became available [53]. Although there was some research activity in between, it was not until the late 1980s that fiber lasers were fully developed. Among rare-earth doped fiber lasers, Erbium-doped fiber lasers in the 1.5 µm region attracts the most attention because it coincides with the least-loss (as low as 0.2 dB/Km) region of silica fibers used for lightwave communications. The first Erbium doped fiber laser was reported by Mears [54] in 1986. It had a threshold of 30 mW absorbed pump power and slope of efficiency of 0.6%. In 1987, a low threshold (2.5 mW) CW operation of EDFL was demonstrated, pumped by a dye laser at 807 nm [6].

Laser Cavity

Several types of optical resonators have been used in designing fiber lasers. The various configurations of optical resonators are based on two types of cavities, linear cavity (bi-directional oscillation) and ring cavity (unidirectional oscillation), as illustrated in Figure 30. Linear cavity is realized by placing the active gain medium between two high reflecting mirrors as depicted in Figure 30(a). Ring cavity is often used for lasers since it is easy to fabricate in practice by forming a loop with the doped fiber and a coupler. The amount of output power is defined by the x% of coupling ratio as shown in Figure 30(b). Normally fiber lasers are constructed together with an appropriate filter to select the desired lasing wavelength. This filter is an external optical device that can generate either single lasing wavelength or multiple lasing wavelengths [55-57]. Instead of this, the filtering mechanism can also be performed by combining inherent scattering effects in optical fibers which is a more attractive solution to generate multiple wavelength lasers [58-67].

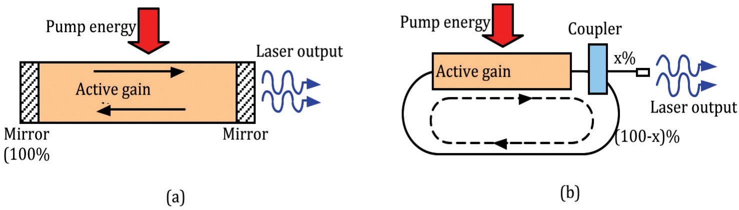


Figure 30 Structure of fiber laser based on (a) linear cavity and (b) ring cavity.

Principle of Laser

The word laser is an acronym for *Light Amplification by Stimulated Emission of Radiation*. A laser is composed of an optical cavity in which light can circulate, a gain medium which serves to amplify the light and a pumping mechanism. The latter two elements are made from the same structure as optical amplifiers. Therefore optical amplifiers can easily be upgraded to lasers by designing an optical cavity that allows oscillation of light generated by the gain medium. The same optical amplification principle is also applied to lasers, as depicted in Figure 31. With reference to Figure 31(b), it is seen that spontaneous emission occurs when the excited atoms from upper level, E_2 drop down to the lower energy level, E_1. When this spontaneous emission is pushed to circulate in the same gain medium, then it becomes an incoming photon that stimulates excited atoms to drop from E_2 to E_1 to generate identical photons. These photons, in turn, can serve to stimulate the emission of additional photons. This process will continue and the result is coherent light amplification (photon multiplication). When the gain obtained after one round-trip is larger than the cavity losses, laser threshold is reached and laser light is emitted out of the laser cavity [68]. Once laser effect is achieved, only specific wavelengths can be supported in the optical resonant cavity, called the longitudinal modes of oscillation. The choice of emitted wavelengths depends on the spectroscopic properties of the active gain medium.

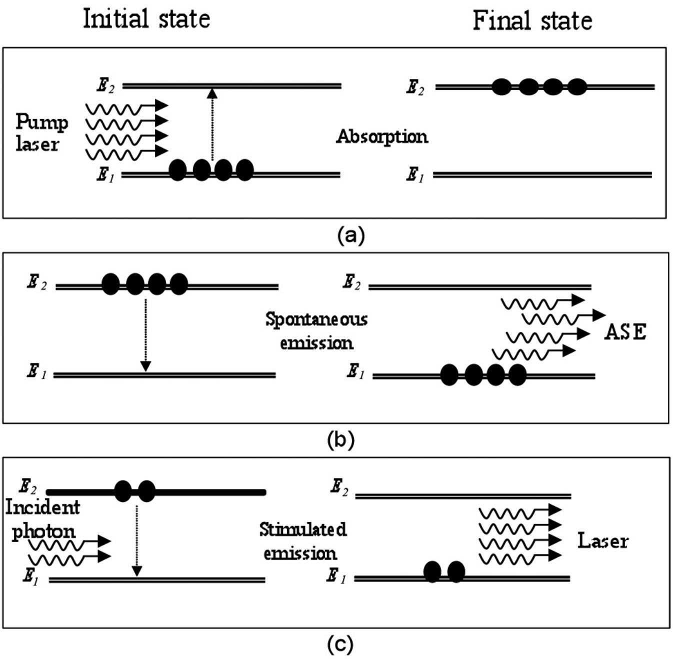


Figure 31 Two level laser system representing the process of absorption and emission between energy level E_1 and E_2: (a) absorption (b) spontaneous emission (c) stimulated emission.

MULTIWAVELENGTH FIBER LASERS

Fiber laser can be used for emitting light at several wavelengths simultaneously, and several schemes have been developed by a number of researchers [69-72]. Linear and ring resonator configurations have been investigated by using one or more filters to define the multiple lasing wavelengths. Such filters may have different forms, such as fiber Bragg gratings, bandpass filters, fabry perot etalons and comb filters based on mode beating, either in a birefringent fiber or a multimode fiber [55, 69, 73-76].

Besides using physical mirrors, nonlinear effects in optical fibers can be utilized to generate multiple wavelengths such as four wave mixing and supercontinuum generation [77-80]. In addition, the filtering mechanism can also be performed by combining inherent scattering effects in optical fibers, which is a more attractive solution to generate multiple wavelength lasers [58-67]. In any optical fibers, the scattering effects cannot be avoided and these unwanted lights can be utilized to generate multiple wavelengths.

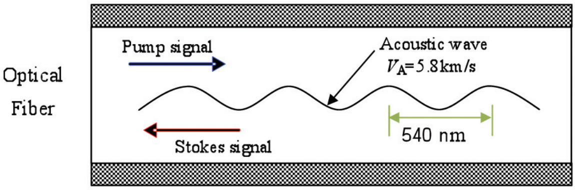
Scattering Phenomena in Optical Fibers

It is well known that when light is transmitted in any media, reflection, absorption and scattering may occur due to interaction between light and media. The cross-sectional area of the core of single-mode optical fibers is very small and as such large light intensities can be reached at relatively low input powers. Thus, a number of scattering phenomena can be observed in optical fibers that include Rayleigh, Raman and Brillouin scattering. In all of these cases scattering is due to fluctuations in the refractive index of the fiber core. The inelastic interaction between optical photons and acoustic phonons leads to a frequency shift of the scattered phonons directly dependent on the characteristic of the sound velocity of the medium.

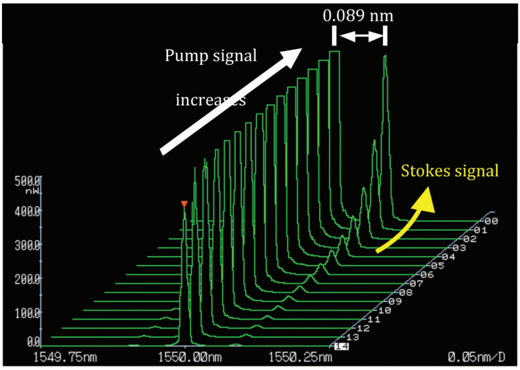
Stimulated Brillouin Scattering

Stimulated Brillouin scattering (SBS) is a nonlinear process that can occur when the optical power launched into the fiber exceeds a threshold level [49]. It manifests through the generation of backward-propagating Stokes wave whose frequency is downshifted from that of incident light by an amount set by the nonlinear medium. The first demonstration of SBS in optical fibers was reported in 1972 by Ippen and Stolen [81]. A single mode fiber with a large loss of about 1300 dB/km was used along with a pulsed high power narrowband xenon laser operating at 535.5 nm. As a result of the high fiber loss and short fiber lengths, ~20 m, the SBS threshold was high at 1 W of injected optical power. Since then a number of groups have reported Brillouin scattering in optical fiber with both pulsed and CW pump lasers [82-85]

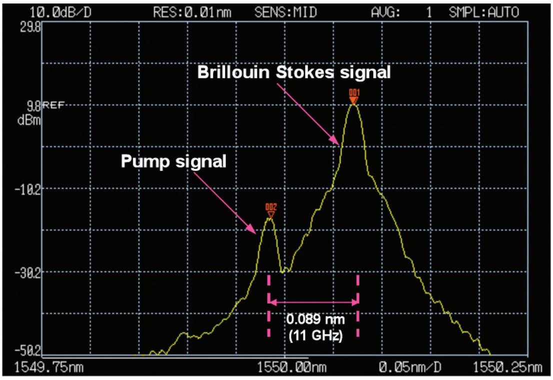
The physical process of SBS can be explained as a three-wave interaction in the optical fiber core. Laser light propagating through the fiber acts as a pump wave and induces an acoustic wave through the process of electrostriction, where the density of the glass is affected by the applied optical field [49]. The acoustic wave causes different periodic variations in the material density that result in periodic variations in the refractive index. This pump-induced index grating scatters the pump light through the Bragg diffraction process. The scattered light is down shifted in frequency because of Doppler shift associated with grating moving at the acoustic velocity (K_A) as shown in Figure 32(a). According to quantum mechanics, the scattering process can be thought of as the annihilation of a pump photon that creates an anti-Stokes photon, while the creation of an acoustic phonon creates a Stokes photon. The intensity of the Stokes signal increases in tandem with the pump signal above its threshold power, as portrayed in Figure 32(b). The separation between the pump and Stokes signal is around 0.089 nm for silica optical fibers as shown in Figure 32(c).



(a)



(b)



(c)

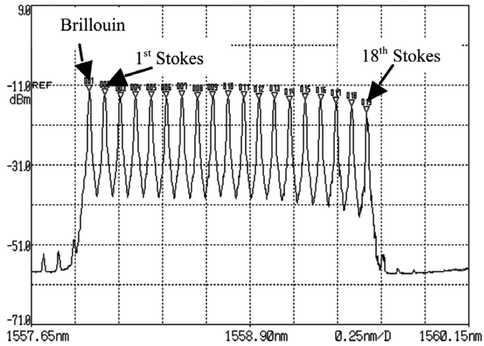
Figure 32 (a) Process of stimulated Brillouin scattering in optical fibers, (b) spectral information of Stokes signal with respect to the increment of pump signal power and (c) optical spectrum of Brillouin Stokes and its pump signals.

Brillouin-Erbium Fiber Laser

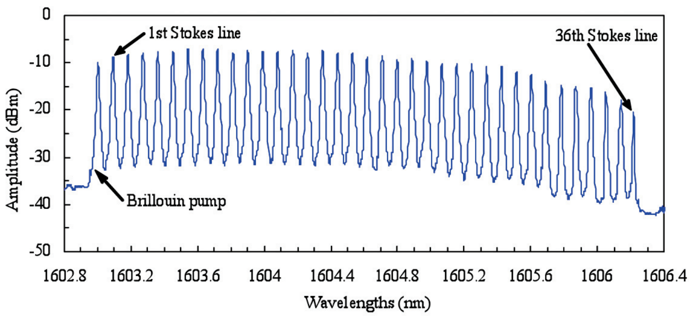
The generation of Brillouin Stokes line in optical fiber has been utilized as a single longitudinal fiber laser [86-88]. Since the Brillouin gain in optical fiber is low, it is difficult to achieve efficient operation of a fiber laser with its own cavity [49]. Thus, the SBS effect must be integrated with another amplifying medium to allow large output powers and avoid requirement for a critically coupled resonator. The amplifying medium provides a primary gain to compensate cavity loss and SBS is utilized as the frequency-shifted mechanism. This idea was successfully demonstrated by combining the SBS effect with the Erbium gain medium to create a ring fiber laser with reasonable output powers [89]. In this case, only one channel was obtained from the proposed ring fiber laser structure.

This hybrid technique led to the development of multi-wavelength Brillouin-Erbium fiber lasers (BEFLs) by feeding back the Brillouin Stokes lines into the laser cavity via the non-resonant direction; famously known as the reverse-S-shaped fiber section [90]. In this enhanced architecture of BEFL, two 3-dB couplers were deployed to tap a portion of the oscillating lasers to be injected into the single-mode fiber. However, the construction of the reverse-S-shaped fiber section was achieved at the expense of higher cavity loss. Therefore, the total output power was low for this type of BEFL. In order to enhance BEFL performance, an Erbium-doped fiber amplifier (EDFA) was inserted in the reverse-S-shaped fiber section to enhance the lasers' intensity as the subsequent Brillouin pump (BP) [91]. Two EDFA sections were required to achieve the objective, which increased operational complexity. All previous research works were based on the ring-cavity laser system.

The first linear cavity BEFL structure was reported in 2004, as in [59]. The efficiency of Brillouin Stokes signal generation and its amplification is greatly increased because mode oscillation occurs in both directions. As a result, the proposed linear cavity BEFL produces greater channel counts as compared to its predecessor, the ring-cavity lasers. Figure 33 shows the output spectrum of the proposed linear cavity BEFL that consists of 18 Stokes lines (C-band) and 36 Stokes lines (L-band).



(a)



(b)

Figure 33 Output spectrum of the linear cavity BEFL in (a) C-band [59] and (b) L-band [66].

The main drawback of BEFL is the generation of Brillouin Stokes lines in a wide tuning range and the interference of these lines with the self-lasing cavity modes. These modes are the natural effect of standing waves formation for any laser structure. These unwanted self-lasing cavity modes can be suppressed by injecting adequate amount of BP power into the BEFL cavity. Thus this technique is only efficient when the BP is injected in the region of peak oscillation. When the injected BP wavelength is beyond this range, the self-lasing cavity modes appear at the peak oscillation region by extracting energy from the group of cascaded Brillouin Stokes lines.

To overcome the tunability limitation, various approaches have been implemented to develop a tunable BEFL [92-94]. The wide tuning range of up to 14.5 nm with the generation of up to 12 lines are obtained by incorporating a Sagnac loop filter into the fiber ring [95]. However, the manipulation of spectral loss to flatten the cavity gain has led to lower output power. On the other hand, the use of high external BP power to suppress self-lasing cavity modes is achieved at the expense of additional optical amplifiers to boost the Brillouin pump [93]. Despite the large tuning range given by self-seeded BEFL, its major disadvantage is the OSNR of lasers [94].

We have investigated the BEFL tuning range using the single-pass amplification technique to pre-amplify BP power within the laser cavity before entering the single-mode fiber [96]. In the experiment, the EDF gain block is forced to operate in a deep saturation regime with respect to the Brillouin pump intensity. As a result, the self-lasing cavity modes experience gain compression and consequently, these unwanted cavity modes are efficiently suppressed in a wider wavelength range. Hence, homogeneous saturation of the EDF gain plays a dominant role in attaining wider tuning range and stable laser operation.

The output spectra comparison between BP direct injection and intra-cavity BP pre-amplification are depicted in Figure 34. Figure 34(a) shows the superimposed optical spectra for the BP direct-injection technique for BP wavelength of 1602 nm and 1608 nm. For both conditions, the presence of self-lasing cavity modes is clearly recorded at around 1605-1606 nm (laser cavity peak gain). On the other hand, these eccentrically oscillation modes are completely suppressed for the intra-cavity BP pre-amplification technique as clearly shown in Figure 34(b).

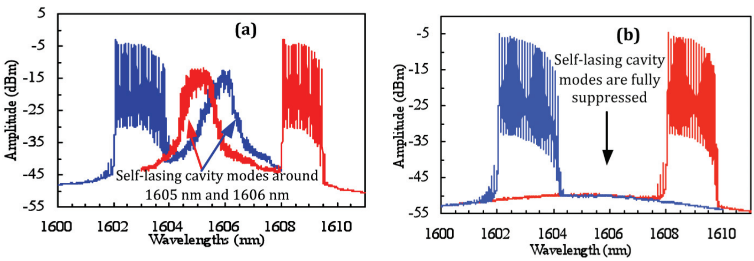
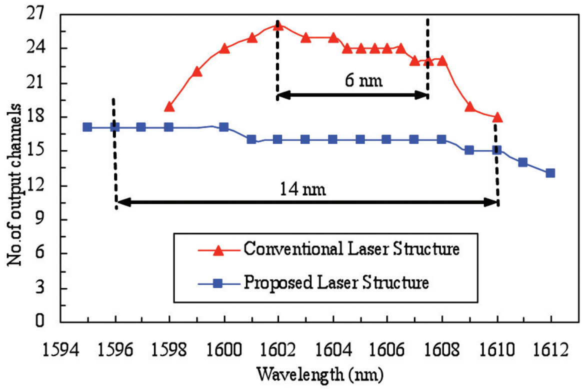


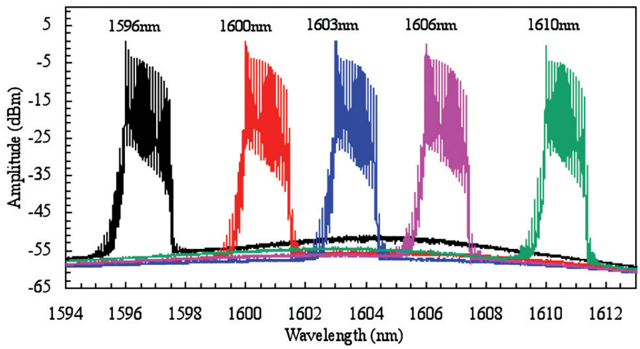
Figure 34 Output spectrum of the BEFL utilizing (a) BP direct-injection technique and (b) BP pre-amplification technique for the pump power of 90 mW and BP power of 1.1 mW. BP wavelength is set at 1602 nm (blue curve) and 1608 nm (red curve) [96].

An enhanced multiwavelength BEFL with double-pass BP preamplified technique within the linear cavity was proposed and experimentally demonstrated in [97]. The main innovative step in this approach is the use of the internal EDFA to amplify the BP power twice within the laser cavity before entering the single-mode fiber. Therefore, the proposed fiber laser eliminates the requirement for high external BP power to create the Brillouin gain and achieve low threshold power. Contrary to the direct-injection and single-pass preamplification of BP into the single-mode fiber, the tuning range of the proposed fiber laser is widened.

Referring to Figure 35(a), the number of output channels without any free-running cavity modes varies between 23 channels and 25 channels within 6 nm for the conventional laser structure. On the other hand, the number of output channels varies between 15 channels and 17 channels, within 14 nm for the proposed laser structure. As BP power increases, the tuning range of output channels (without free-running cavity modes) increases at the expense of the number of output channels generated. This is due to the fact that more effective power conversion from the pre-amplified BP signal to Brillouin Stokes signals is induced with deeper EDF gain saturation of the BP signal in the peak gain bandwidth. Consequently, the generated Brillouin Stokes signal achieves its saturation level faster because of its higher gain when higher BP power and EDF pump power are used. In addition, this is also because of the effect of Brillouin gain saturation in which higher threshold power is required to create a higher order Stokes signal to lase in the laser cavity. The output spectra of the proposed laser structure are depicted in Figure 35(b). It is clearly seen that there are no free-running cavity modes appearing around the 1605 nm wavelength range (the peak gain of laser cavity). In contrast to the results reported in Ref. [95], no filtering and careful adjustment of polarization controllers are needed to control the shape of the gain in the laser cavity. Thus, in the proposed laser structure, the oscillating cavity modes experience gain compression as a result of higher Stokes signal peak power and consequently, these unwanted cavity modes are efficiently suppressed in a wider wavelength range as depicted in Figure 35(b).



(a)



(b)

Figure 35 (a) Number of output channels versus BP wavelengths at 120 mW EDF pump power and 3.5 mW BP power for the two BEFL structures and (b) tunability of output channels at 120 mW pump power and 3.5 mW BP power for the proposed laser structure (BP pre-amplification technique) [97].

A major disadvantage of BEFL however, is limited wavelength tunability owing to its self-lasing cavity modes. Schemes employed to overcome this limitation, include; spectrum filtering [92, 95], BP amplification technique [96, 97] and a variable optical attenuator used to control the cavity mode's oscillations [98]. Although the previous schemes were able to improve the tunability in BEFL, the self-lasing cavity modes cannot be completely suppressed in the laser cavity. We demonstrated the concept of virtual reflectivity (generated through the use of a spool of fiber) in a ring cavity BEFL that overcomes the tuning range limitation, but the structure provides a low number of output channels [99].

The output spectra of the tunable laser system at selected wavelength of 1530 nm, 1538 nm, 1550 nm, 1562 nm and 1570 nm are shown in Figure 36. These wavelengths are preferred to show the BP wavelengths at the beginning, centre and end of the tuning range. It can be seen that the spectrum is devoid of any self-lasing cavity modes within the BEFL cavity for any BP wavelength within the selected tuning range of 40 nm. All through the 40 nm tuning range, the first 10 channels have individual power levels above -10 dBm. Also, by comparing the channel's peak power to the highest noise floor level, good OSNR above 20 dB is maintained by all the channels throughout the 40 nm tuning range.

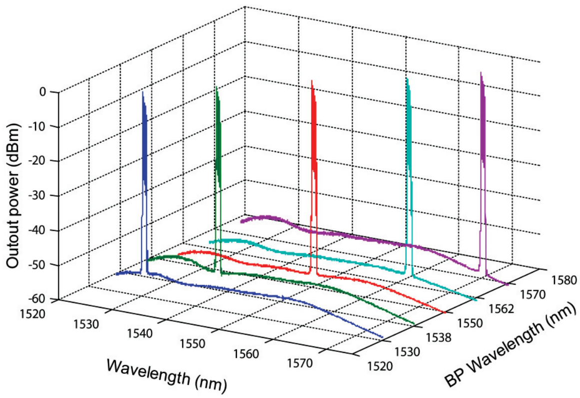


Figure 36 Output spectra of the BEFL at BP power of 2 mW and PP of 130 mW, showing the generated channels at selected wavelengths [100].

Brillouin-Raman Fiber Laser

Brillouin-Raman fiber lasers combine Brillouin gain as used in Brillouin fiber lasers with Raman gain generated in optical fibers. Raman gain uses the principles of Raman scattering to amplify optical signals. The advantages of Raman amplification is that they can be made to work in any wavelength band by simply choosing the appropriate pump wavelength. Unlike erbium – doped fiber amplifiers that work on the principles of population inversion between energy levels of the erbium ions and thus have restricted bandwidth, Raman amplifiers have a very large bandwidth. Apart from this, the fiber section that is used in the generation of Brillouin gain can also be used to generate the Raman gain. When a high power light beam is launched into an optical fiber, Raman scattering, normally referred to as spontaneous Raman scattering, takes place. In addition to the high power beam, if a weak light beam, normally called a signal beam, is launched into the same fiber, with the wavelength of the signal beam lying within the band of the spontaneous Raman scattering, it leads to stimulated Raman scattering. If this happens, the pump and signal wavelength are coherently coupled by the Raman scattering process. The coherent nature of the process implies that the incident light gets coherently amplified by the stimulated Raman scattering. This is the same process that is employed in the building of Raman gain assisted Brillouin fiber lasers. In most reported multiple wavelength Brillouin/Raman fiber lasers [62, 64, 101, 102], the Stokes cascading process relies on Rayleigh scattering rather than feedback loops as used in Brillouin/erbium fiber lasers.

In the early stages, the distributed Rayleigh scattering effect was manipulated as the cavity mirror to assist laser-cavity feedback as a means of providing reflections to the Brillouin Stokes lines [103]. This effect was successfully measured to indicate the Rayleigh scattering contribution on the line narrowing effect that enhances the stimulated Brillouin scattering (SBS) process [104]. In another experiment, discrepancy between the odd and even channel profiles of Brillouin Stokes lines was observed, indicating a significant coupling contribution from the Rayleigh scattering to the SBS effect [105]. Owing to the process of Rayleigh scattering, this virtual mirror has weak reflectivity compared to the physical mirror. Thus, the proposed laser cavity is driven into deep saturation to push the Rayleigh component to reach the same saturation level set by the Brillouin components. On the other hand, distinctive power level discrepancy is clearly observed when the Brillouin-Raman fiber laser cavity is constructed from two virtual mirrors (no physical mirror at both cavity ends) [106].

In order to investigate this phenomenon further, a new fiber laser structure of Brillouin-Raman fiber laser is proposed in which both ends of the laser cavity are terminated with the high reflectivity mirrors [62]. Figure 37 shows the first few Stokes lines near the BP wavelength of 1534 nm with a resolution bandwidth of 0.01 nm, the operating point at the highest Brillouin Stokes number. It can be seen clearly that the odd and even Brillouin Stokes are almost the same in terms of power level, OSNR and line width. It is worth highlighting that the OSNR is measured at around 18 dB for each Brillouin Stokes. These characteristics mark an improvement over the ones previously reported due to complete lasing oscillation experienced by each Brillouin Stokes in the linear cavity.

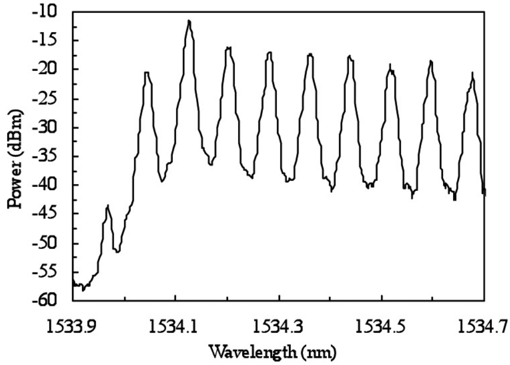


Figure 37 A magnified output spectrum of a few Brillouin Stokes closer to the BP wavelength of 1534 nm [62].

The processes of Raman amplification, Brillouin shift and Rayleigh scattering are blended in the proposed laser structure. For BP wavelengths far away from the laser cavity gain, the generation of cascaded Brillouin Stokes lines is dominated by Rayleigh scattering and these Stokes lines are relatively weaker than other Stokes lines within the laser cavity bandwidth as shown in Figure 38. As a result, the output power is also not flat over the whole wavelength range owing to this low saturation effect. The flat-amplitude Stokes lines are defined by 3-dB peak power fluctuations across the whole spectrum regardless of the Stokes lines' location. Referring to Figure 38, the flat-amplitude bandwidth is obtained from 1549.5 to 1558.6 nm, which is about 10.5 nm bandwidth. It is also important to note that the flat-amplitude region occurs in the range of the Raman peak gain. In addition, the noise envelope follows the Raman gain spectrum exactly, which indicates that the oscillating Brillouin Stokes lines are not strong enough to suppress the noise generation from the stimulated Raman scattering.

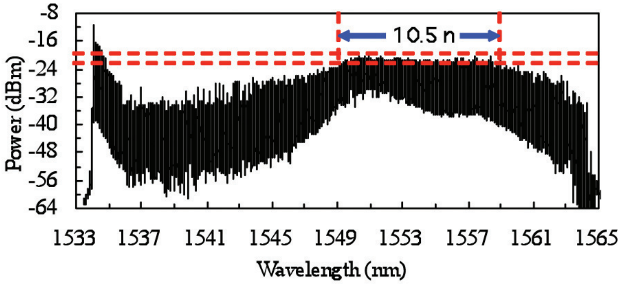


Figure 38 Measured output spectrum for 1534 nm BP wavelength at 10 mW power, the pump power is fixed at 300 mW [64].

Since the Raman amplification is gradually increased from short wavelengths to longer wavelengths, thus the amplification of Brillouin Stokes lines is also increased within this wavelength range. Therefore, the injection of BP into the laser cavity gets this benefit by selecting a wavelength lower than the Raman peak gain. The widest flat-amplitude bandwidth is obtained when the BP wavelength is set at 1540 nm and its power is cranked up to 10 mW. The measured flat-amplitude bandwidth is from 1542.8 to 1559.2 nm, which is about 17.1 nm bandwidth, as shown in Figure 39.

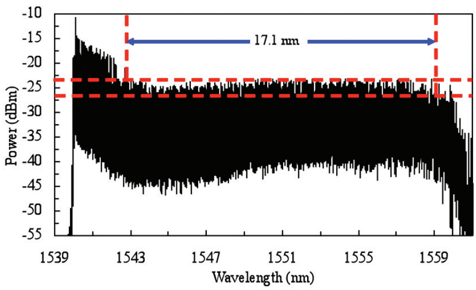


Figure 39 Output spectrum following a proper optimization of BP wavelength (1540 nm) and power (10 mW), the Raman pump power is fixed at 300 mW [64].

In order to widen the flat-amplitude bandwidth, the laser cavity must be pumped by another Raman pump wavelength to improve its Raman gain bandwidth. Based on our analysis of the results, other Raman pump lasers at 1435 nm are activated to achieve the aforementioned objective. The pump power from the RPU is carefully adjusted concurrently with the optimization of BP wavelength and power. As a result, optimized output spectrum is obtained, which has flat-amplitude Stokes lines as depicted in Figure 40. Under this condition, the BP wavelength is set at 1527 nm and its power is tuned to 4.14 mW. In addition, the RPU is configured as follows: 1435 nm (200 mW) and 1450 nm (120 mW). The flat-amplitude bandwidth is obtained from 1527.32 to 1558.02 nm, which is about 30.7 nm bandwidth (357 Stokes lines with 0.086 nm spacing).

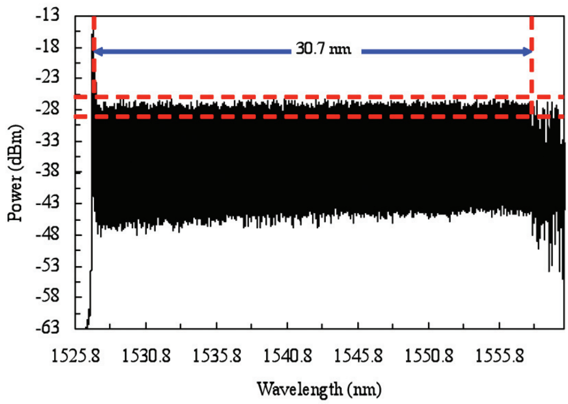


Figure 40 The optimized flat-amplitude spectrum of 30.7 nm bandwidth [64].

CONCLUSION

The vast benefits of the optical communication system have more than justified the hype surrounding this amazing technology. Although the system is not without flaws, the exceptional performance accorded through its utilization far outweighs its drawbacks, and further emphasizes its superiority over other communication methods.

Looking at the current communication landscape where optical communication systems are in rapid deployment worldwide, it is tempting to think that current innovations of optical amplifiers and multi-wavelength laser sources -serve the requirements of WDM communication schemes well. However, one has to remember that this technology is just slightly over 40 years of age and in a way, still in its infancy. The race to Petabit/s (10^{15} bit/s) transmission systems is wide open and global telecommunication players are actively pursuing related research in a quest to become the first in recording this significant achievement. This target is in-line with the anticipated unprecedented growth in demand for bandwidth to support transparent networks in the near future.

The potential for further research in this area is immense, where the target is still for wideband amplifiers with improved gain, better signal quality and flatter gain spectrum, in addition to laser sources with high output power and more channels. These two research flavors are the foundation to support ultra high bit rate transmission systems. It is heartening to note that our local researchers are already in the thick of things with their noteworthy findings being published in high impact journals.

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BIOGRAPHY

Mohd Adzir Mahdi was born in Kuala Lumpur, Malaysia on June 4, 1972, exactly on the first anniversary of his parents' wedding. He obtained his early education at Sekolah Kebangsaan Serdang. He then completed his secondary school education at Maktab Rendah Sains MARA, Kuantan. Adzir received a Bachelor's degree with first class honors in Electrical, Electronics and Systems Engineering from Universiti Kebangsaan Malaysia, in 1996. Later, he received his Master and Ph.D. degrees with distinctions in Optical Fiber Communications from Universiti Malaya in 1999 and 2002, respectively.

In 1996, upon graduation, he joined a pioneer photonics research group called *Telekom Malaysia Photonics Research Center*. Armed with a strong belief in the technology and equipped with sound skills, Adzir confidently plunged into the world of optics where he became fascinated by Erbium-doped fiber amplifiers and lasers. In the year 2001, he was offered a dream job in the United States of America during the period of the dotcom bubble. For the sake of knowledge advancement, he accepted the offer from Pine Photonics Communications, a start-up company in Fremont, California. Soon after he opted to join IOA Corporation, another start-up company in Sunnyvale, California, to further sharpen his skills and strengthen his understanding in research areas related to optical amplifiers. Finally, Adzir joined the Department of Computer and Communication Systems Engineering at the Faculty of Engineering in Universiti Putra Malaysia on January 21, 2003, as an Associate Professor. He was appointed to the rank of full professor in October 2008. Along the way, he garnered experience as a visiting researcher at Marconi SpA (Italy), Monash University (Australia) and Georgia Institute of Technology (USA).

During his research tenure, Adzir authored and co-authored over 150 journal papers and 150 conference papers. At present, his published papers have been cited over 400 times and his current h-index is 11, based on the Thomson ISI database. His notable research finding on L-band optical amplifiers was reprinted in *WDM Solutions,* an international professional magazine, in March 2002. In addition, he is credited with two issued patents and seven pending patents.

He has supervised over 28 postgraduate students over the past seven years, with three PhD and nine Master students successfully graduating. Several of his graduated students are now academicians and researchers attached to various organizations such as TMRnD, UIA, UNITEN, UniMAP, etc. His present postgraduate students are undertaking diverse researches into photonics such as optical amplifiers, fiber lasers, optical devices, nonlinear optics and optical materials.

In recognition of his contributions in this research area, Adzir has been awarded the IEEE LEOS Graduate-Student Fellowship, the IEEE LEOS Best Student Paper Award, the Australia-Malaysia Institute Research Fellowship, the Leading Scientists and Engineers of OIC Member States (COMSTECH) Award and the TWAS Young Affiliate Fellowship.

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