SEAMLESS GLOBAL CONNECTIVITY AT THE SPEED OF LIGHT: Converting Intrinsic Undesirable Phenomena in Optical Fibres to Capacity Increase

BAYERO UNIVERSITY KANO
PROFESSORIAL INAUGURAL LECTURE
NO. 34

Mohammed Ajiya
Professor of Electrical Engineering,
Department of Electrical Engineering,
Faculty of Engineering,
Bayero University, Kano.

DATE: 18th October 2018

BAYERO
UNIVERSITY PRESS

Published 2018 by:
Bayero University Press,
Main Library Building,
Bayero University Kano,
New Site, Gwarzo Road,
P.M.B. 3011.
Kano.

Website:*www.buk.edu.ng*
E-mail: *info.bukpress@buk.edu.ng*

ISBN 978-978-56076-9-7

PRINTED BY BAYERO UNIVERSITY PRESS KANO, NIGERIA.

Mohammed Ajiya

B. Eng, M.Eng (BUK), PhD (UPM), FHEA (UK), FIICA, R.Eng (COREN), MNSE, MOSA, MIEEE, MSPIE (USA)

Professor of Electrical Engineering,

SUMMARY OF PRESENTER'S BIODATA

Mohammed Ajiya was born in Misau, Bauchi State on Tuesday, 17th September 1963. He obtained his primary education at Central Primary School Misau between 1970 and 1976. Between 1976 and 1981, Mohammed completed his secondary education at General Murtala Mohammed College, Yola. In 1984, he received National Diploma in Electrical Engineering from Kaduna Polytechnic and later obtained Bachelor of Engineering Degree in Electrical Engineering in April 1994 from Bayero University Kano (BUK). In 2002, Mohammed received Master of Engineering Degree in Electrical Engineering also from BUK. In 2007, Mohammed enrolled at University Putra Malaysia (UPM) and later in 2009 submitted his PhD thesis for examination. In January 2010, Mohammed obtained his PhD degree in Optical Communication Engineering from UPM. In 2011, he obtained the Postgraduate Certificate in Advanced Studies in Academic Practice (PgCASAP) from Newcastle University, United Kingdom. The PgCASAP contributed immensely in his being admitted as a Fellow of the Higher Education Academy (FHEA) of the United Kingdom that certify him to teach in any tertiary institution, particularly universities in the United Kingdom.

Mohammed started his working career in 1984 as Assistant Technical Officer (Electrical) in the Bauchi State civil service. In March 1987, Mohammed joined Arewa Ceramics Limited Misau as Technical Officer. He rose through the ranks and became the General Manager/Chief Executive Officer of the Company in June 2000. In 2002, he was appointed the pioneer Managing Director/CEO of Bauchi Plastics Company Limited. On 2nd January 2004, Mohammed joined his alma mater, BUK as Lecturer II and rose to reach the pinnacle of his career in 2016, when the Governing Council of BUK approved his promotion to the rank of a full Professor of Electrical Engineering.

Mohammed has taught over 20 different courses both at undergraduate and postgraduate levels and has supervised several undergraduate and postgraduate students. He is currently supervising 12 postgraduate students (5 PhD and 7 Masters students). He has internally and externally examined several Masters and PhD students.

In the area of research, Mohammed authored and co-authored over 70 academic articles in citation, non-citation journals and conferences. Presently, 9 of his papers are published in Q1, 7 in Q2 and 3 in Q3 journals. Based on 2016 ISI journal citation report (JCR), Mohammed's cumulative impact factor stood at 32.59 while his h – index is 12. Mohammed has over 400 citations to his credit. He has been granted a Malaysian and United States of America patents.

In recognition of his contributions to humanity, Mohammed received several awards and honours. Notable among them are:

1. One of 2000 Outstanding Intellectuals of the 21st Century by International Biographical Centre, Cambridge, England. UK.
2. One of Top 100 Global Engineers in the year 2011 Cambridge University, England. UK.
3. Certificate of Honour for valuable contribution to Nigerian Status in Malaysia by Nigerian Students' Community in Malaysia, International Islamic University, Malaysia.
4. Bayero University scholarship award for outstanding academic performance.
5. The International Einstein Award for Scientific Achievement by International Biographical Centre, Cambridge, England, UK.
6. Award of Excellence in recognition of immense contribution to societal transformation, educational and information development in northern Nigeria – Association of Northern Nigerian Students – January 2017.

Mohammed served as a member, Nigerian Trade Mission to South Africa, Botswana, Zimbabwe, Mozambique and the Central African Republic. He is a member, Inter – Agency Committee of the Professionals inaugurated by the Nigerian Communication Commission (NCC) to assess Telecommunication based innovations from the Academia in Nigeria and also a member of panel of experts inaugurated by the Board of NCC to design appropriate curriculum/blueprint for ICT research in Nigeria. He served as a member of COREN and NUC accreditation visitation panel to Engineering programmes in several Nigerian universities.

Mohammed was Head, Department of Electrical Engineering BUK from 2012 to 2015 and since 2015, Director, Centre for Information Technology, BUK.

Mohammed belongs to several professional bodies that include:

1. Registered Engineer – by the Council for the Regulation of Engineering in Nigeria (COREN)
2. Member, Nigerian Society of Engineers (MNSE)
3. Fellow, The Higher Education Academy, United Kingdom (FHEA)
4. Fellow, Institute of Industrialist and Corporate Administrators of Nigeria (FIICA)
5. Member, Institute of Electrical and Electronics Engineers, USA (MIEEE)
6. Member, Society of Photo – Optical Instrumentation Engineers of America, (MSPIE)
7. Member, Optical Society of America (MOSA)
8. Thomson Reuters Researcher
9. Member, Open Access Academy

SEAMLESS GLOBAL CONNECTIVITY AT THE SPEED OF LIGHT: Converting Intrinsic Undesirable Phenomena in Optical Fibres to Capacity Increase

Preamble

Optical Fibre Cable (OFC), a glass strand as thin as human hair, offers enormous bandwidth (information carrying capacity) and is thus used as a waveguide that transmits information from place to place. The several advantages of OFC include very high speed of transmission, non-susceptibility to electromagnetic waves interferences and low signal losses during transmission when compared to other transmission media. These advantages make the OFC to be touted as the information transmission medium of future generations. The emergence of wavelength-division-multiplexing (WDM) technique, which later transformed into dense wavelength-division-multiplexing (DWDM), further strengthened the position of OFC as the leading communication channel to date, particularly in long haul telecommunication systems. Despite the advantages associated with OFC, certain drawbacks hindered the deployment of OFC in particularly long distance communications. These drawbacks include accumulated losses when the information is transmitted over long distances and the need to employ multiple wavelength lasers to cater for the several DWDM channels.

It is therefore apparent that in long haul point – to – point optical communication, signals travelling in the OFC have to be compensated for losses suffered if the information is to be recovered at the receiving end. Introduction of optical amplifiers, especially advent of erbium doped fibre amplifier (EDFA) around 1982 allows signals in OFC to be amplified in the optical domain. Amplification spectrum of EDFA is substantially very high in the C-band transmission window. However, signals especially in DWDM systems suffer different erbium emission spectrum thereby causing variation in gain experienced by the signals. On the other hand, the DWDM systems necessitate the use of lasers with multiple wavelengths so as to provide multi channels carrier source for the signals. Optical fibre based lasers perfectly serves this need. Fibre based lasers produce multiple carrier sources from a single coherent light source. Thus, they allow for more channels per transmission. One of the most successful fibre-based laser is the Brillouin/Erbium fibre laser. However, it has an inherent disadvantage of limited wavelength tunability caused largely by the gain competition imposed by its cavity gain characteristics.

In this lecture, I intend to portray this amazing technology that revolutionized communication globally – optical communication engineering. I also intend, within the lecture to highlight our local contributions to the development of this astonishing technology that holds prominence in long haul communication systems and a promise of an outstanding future.

Introduction

Today's world is connected by largely hidden but highly complex information networks that carry information from one place to another. This is the communication system. If the information is to be transmitted over a very long distance, then it is known as *Telecommunication*. The information so transmitted could be vocal, pictorial, textual, numerical, video, audio or even codes. It is now possible to communicate between any two parts of the world within the fraction of a minute. The speed at which this interconnected environment evolves is both exhilarating and daunting. Such technology has the power to unite us, can address some of our most difficult problems, and allows previously unimaginable human achievements. The generic communication system is shown in Figure 1.

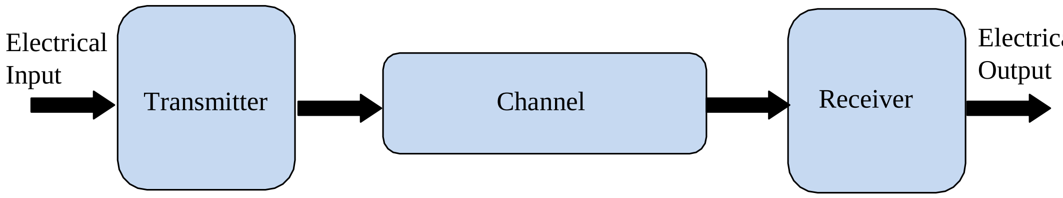


Fig. 1: *Generic Communication System*

The information to be transmitted is first converted to electrical signals and thereafter fed into the transmitter that transmits the electrical signals over a channel to a receiver at the receiving end. At the receiving end, the message signal is then converted back to its original form. The channel is a physical pathway that connects computers, other devices, and people on a communication network. Traditionally, there are three main categories of the channel:

Copper cable: This type of cable include unshielded twisted-pair (UTP), shielded twisted-pair (STP), and coaxial cable. Copper-based cables are inexpensive and easy to work with when compared to fibre-optic cable. However, a major disadvantage of copper cable is that it offers a rather limited bandwidth that cannot handle the advanced applications of today and the future, such as video conferencing, multimedia sharing and virtual reality.

Wireless: Wireless media include radio frequencies, microwave, satellite, and infrared. Deployment of wireless media is faster and less costly than deployment of cable. Wireless is also useful where environmental circumstances make it impossible or cost-prohibitive to use cable. There are a few disadvantages associated with wireless. Historically, wireless solutions support much lower data rates than do wired solutions. Wireless is also greatly affected by external impairments, such as the impact of adverse weather, thus reliability can be difficult to guarantee. Of course, one of the biggest concerns with wireless is security: Data must be secured in order to ensure privacy.

Fibre optics: Fibre offers enormous bandwidth, immunity to many types of interference and noise, and improved security. Therefore, fibre provides very clear communications and a relatively noise-free environment. The disadvantage of fibre is that it is costly to purchase and deploy because it requires specialized equipment and techniques. Typical advantages of each type of channel media is summarized in Table 1.

Table 1: *Characteristics of Communication Channel Types*

Media Type	**Bandwidth**	**Performance: Typical Error Rate**
Twisted-pair for analog voice applications	1MHz	Poor to fair (10^5)
Coaxial cable	1GHz	Good (10^7 to 10^9)
Microwave	100GHz	Good (10^9)
Satellite	100GHz	Good (10^9)
Fibre Optic	75THz	Great (10^{11} to 10^{13})

The electrical signals used in communication systems are first changed into optical (light) signals before they are transmitted in optical fibres. Therefore, in optical communications, signals are transmitted at the speed of light which is 3×10^8 meters per second in vacuum.

To understand this phenomena, consider the distance of Maiduguri from Lagos along the trunk A3 road, which is 1713.10 km [1].

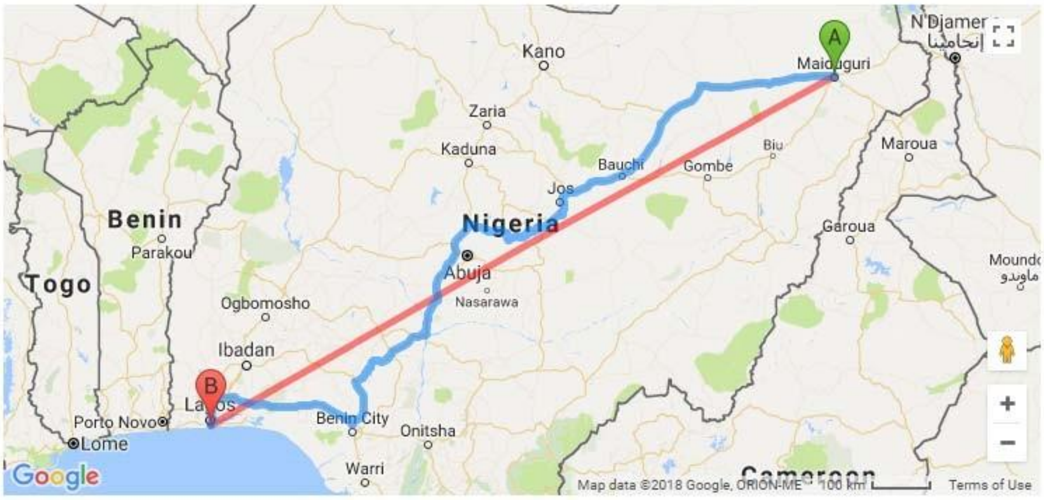


Fig. 2: *Distance between Lagos and Maiduguri along A3 trunk road*

If one is to traverse this distance using the 2017 fastest car in the world, ***Koenigsegg Agera RS*** [2], at its maximum speed of 447.19 km/h, it will take about 3 hours, 50 minutes. On the other hand, optical signal travelling in optical fibre will only take approximately 8.6 milliseconds (if one second is divided by 1000, it will take 8.6 parts only). The signal in optical fibre travels at a rate of approximately 200,000 km per second. This is even more amazing when it is noted that the speed of the optical signal in the optical fibre has been impeded by the refractive index of the fibre material that lowers its original speed in vacuum (about 300,000 km/s).

The speed of course is not the main advantage of transmitting signals optically. In fact, electrical signals being transmitted over copper wire is just marginally slower than the optical signal. The main advantage of optical transmission is its massive bandwidth. As it can be seen from Table 1, fibre optics affords the greatest bandwidth, some 75THz whereas twisted-pair affords the lowest bandwidth (i.e., the difference between the highest and lowest frequencies supported), a maximum of 1MHz.

Another important characteristic of a communication channel is a medium's susceptibility to noise and the consequent error rate. Again, twisted-pair suffers from much impairment. Coax and fibre have less impairment than twisted-pair because of how the cable is constructed, and fibre suffers the least because it is not affected by electrical interference. The error rate of wireless depends on the prevailing conditions, especially weather and the presence of obstacles, such as buildings.

In telecommunication systems, the power of signals being transmitted diminishes with distance. This phenomena is known as attenuation, which is largely characterized by the transmission environment. To overcome this problem, signals are required to be amplified after travelling for certain distance. The distance required between amplifiers, also known as repeaters in a communication channel is a major cost issue for those constructing and operating communication system networks. In the case of twisted-pair deployed as an analogue telephone channel, the distance between amplifiers is roughly 1.8 km. When twisted-pair is used in digital mode, the repeater spacing drops to about 550 m. Coaxial cable offers about a 25% increase in the distance between repeaters over twisted-pair. With microwave and satellite, the distance between repeaters depends on the operating frequency bands. In fibre optical communications, distance between repeaters or amplifiers is usually 100 km. Fibre optical cable has very low and constant attenuation. A standard single mode optical fibre has a maximum attenuation of 0.2 dB per kilometre while in typical copper wire, attenuation is measured in dB per meter and this is directly proportional to the frequency of transmission. This means that at a distance of few hundred meters, an electrical signal being transmitted over copper cable will experience sizeable amount of attenuation which escalates tremendously with higher frequencies of transmission. In contrast to electrical signals, optical signals can propagate for several tens of kilometres without suffering from substantial loss of power. This explains the required distance before installation of amplifiers in a communication channel.

Despite all the advantages of optical transmission and thus optical communication as highlighted so far, what makes it more appealing and thus vigorously touted [3] as the future of the communication industry is that current researches in optical communication are only at the tip of the iceberg. There are many facets of optical communication that are yet to be discovered.

In this lecture, I intend to portray the current state of the optical communication technology, its evolution, prominence and promise of an outstanding future. In the course of the lecture, I will also showcase our contributions to this great technology over the years as a postgraduate student, lecturer as well as a researcher.

History of Optical Fibres

For a very long time, scientists and engineers had realized that light could be used to carry information over long distances. They had long recognized that light could carry a great deal of information, however, there is no mechanism or a vehicle to transport and guide it. Many researchers investigated techniques by which this could be accomplished. The prominent methods at that time included the use of mirrors and special tubes [4-9]. Neither of these methods was found to be practical enough to warrant any serious attention.

In 1952, Narinder Singh Kapany, an Indian-born America physicist succeeded in creating the first practical all glass fibre and also coined the term "fibre optic". Kapany was dubbed 'The Father of Fibre Optics'. The basis of Kapany's invention was the demonstration of how a light beam can be confined and guided by John Tyndall in 1870. John Tyndall, an acclaimed physicist demonstrated to the prestigious British Royal Society the confining and guiding of light beam when he let out a stream of water from a tank onto a collection pan placed on a floor. Tyndall then directed a bright light into the stream of water where the light beam is seen to be trapped and travelled in zig-zag path within the curved path of the water until it reached the collection pan.

Kapany's creation, the fibre optic cable at that time was primarily for medical endoscopy and other applications that required short length of the fibre [10]. These fibres were characterized with very high signal loss such that only about 10% of light entering one end will emerge at the other end of a fibre that is only few meters long. Because of the high loss associated with these fibres at that time, engineers snubbed them for telecommunication applications, where signals will have to be transmitted over long distances.

In 1966, it was suggested by Kao and Hockham that the very high signal power loss in optical fibres is due to impurities in the silica sand material that was used in the fabrication of the fibres. They went further to demonstrate that by reducing the impurities in the silica, the losses of optical fibres could drastically be reduced and that such low-loss fibres might be the best choice for optical communications [11]. In fact, it was only in the year 2009 that Kao was recognized where he was awarded half Nobel price in physics "*for ground-breaking achievements concerning the transmission of light in fibres for optical communication"* [12].

The challenge of reducing fibre losses was taken by Corning, a company in New York, United States of America. It was only in 1970 that a breakthrough was recorded when scientists from Corning reported the reduction of fibre losses to about 20 dB per kilometre in the wavelength region near 630 nm. [13]. Two years later, in 1972, the same researchers from Corning reported producing a fibre with a loss of only 4 dB per kilometre. When this achievement was reported, so many research laboratories around the globe entered the race for reducing fibre loss even further. Research group at AT&T Bell Laboratories successfully fabricated an optical fibre with a loss of 1.1 dB per kilometre [14]. This race was won by a Japanese research group in 1979 when they reported reducing fibre loss to near 0.2 dB per kilometre in the wavelength region near 1550 nm.[15]. This value was very close to the intrinsic limit set by the phenomenon of Rayleigh scattering as indicated in Figure 3.

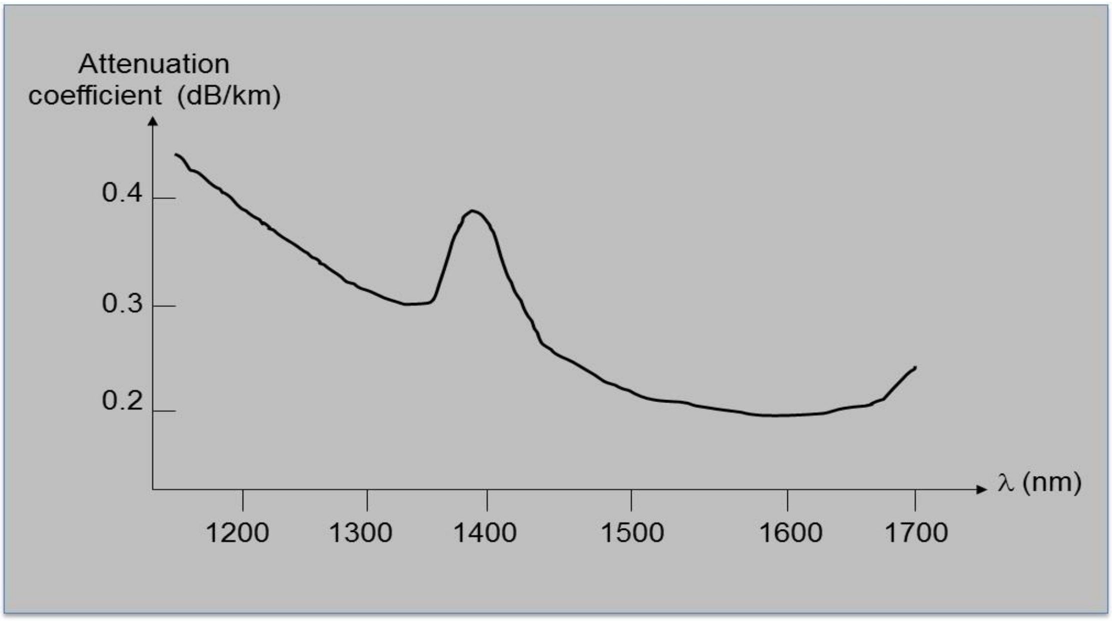


Fig. 3: *Intrinsic Attenuation in optical fibres*

Commercial fibre optical cables were installed in 1980. This achievement herald the arrival of fibre optical communication systems - the new breakthrough poised to revolutionize how humans live and interact in the globe. This became even more evident after the advent of the Internet in the 1990s.

The Start and Growth of Fibre Optical Communication

By the late 1960s, practical technique for the use of light to transmit information had not been found. Actually, the problems that mitigated the use of light for communication are two: neither carrier light source nor suitable transmission medium was available at that time. At the same time, the telecommunication service providers were facing the need for dramatically increased capacity.

The invention of the laser in the late 1960 provided the coherent light required to serve as carrier source thereby solving the first problem. The development of low-loss optical fibres, over a wide frequency range has led to world-wide effort for developing fibre optic communication that brought about tremendous revolution in communication systems. Fibre optical communication systems has now become the accepted technology for high speed data/information transmission medium for both the long haul systems and the local and metropolitan networks [16]. This is because the awesome bandwidth of the optical fibre is only limited by the electronics in the type of multiplexing/de-multiplexing scheme employed. The demand for more capacity over the last decades has soared. The spread and popularity of the Internet and the use of other high bandwidth required applications, particularly in the entertainment sector bolstered this growth. Capacity (bit rate) of optical fibre systems increased from 45 Mb/s in 1960 to 0.1 Gb/s in 1980 and to as well as over 10 Tb/s presently. This phenomenon of demand in capacity that is still very much relevant today, pushed the growing need for more communication capacity, both in terms of data rates and global coverage. Rapid and reliable transmission of voice, video and data signals are now more than ever before, critical to the continued growth of many aspects of modern life in research communities, industries, government and the society at large.

Commonly used figure of merit for communication systems is the bit – rate distance product, normally referred to as *BL,* where *B* stands for the bit – rate and *L* stands for the repeater spacing, the distance after which an optical signal have to be re-amplified in order to maintain its fidelity [17]. Figure 4 indicates the increase in *BL* for communication systems from the advent of electrical communication in 1840 to 2015 and projections to 2020 [18]. The red squares in Figure 4 indicate the emergence of new technologies. The acronyms WDM and SDM stand for wavelength – division – multiplexing and space – division – multiplexing respectively. These are techniques used in transmitting several message signals in a single optical fibre. We shall come to them later in the course of this lecture.

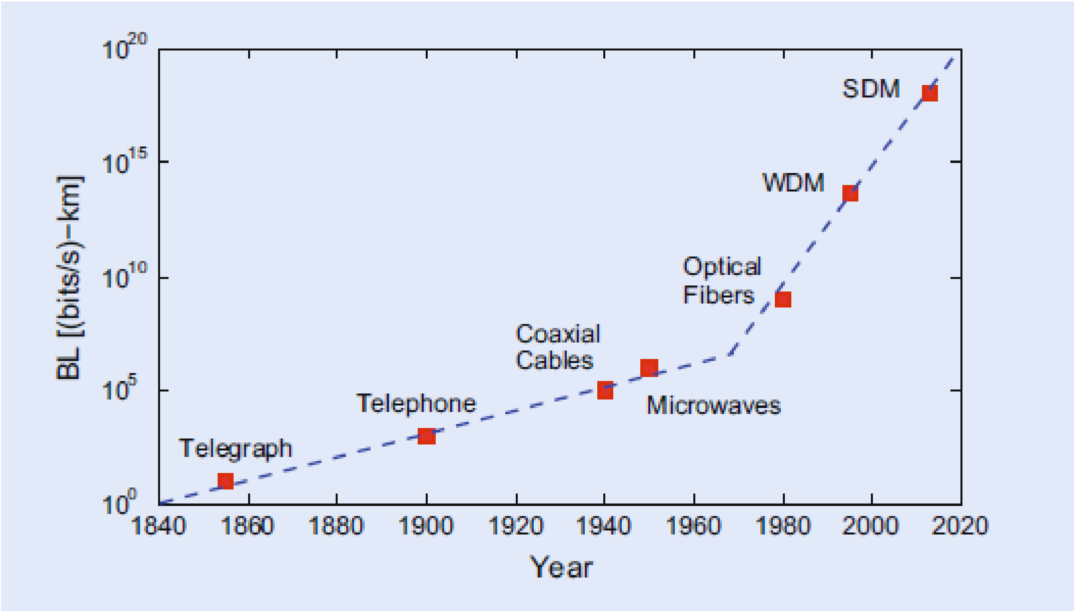


Fig. 4: *Indication of figure – of – merit for communication systems*

Basic Concept of Optical Communication

The basic concept of optical communication is not far different from the generic communication system as presented in Figure 1. In optical communication systems, the transmitter contains additional circuitry such that the electrical signal will be converted to optical signal. Suffice it to mention here again that any information that is required to be sent over optical fibre has to undergo conversion from the message signal format into electrical and later optical signals. The conversion process is accomplished at the transmitter. Another role of the transmitter is to launch the optical signal into the optical fibre. However, before launching the signal unto the fibre, it has to undergo modulation. Modulation is a process where the optical signal is superimposed onto a carrier signal, a coherent light signal that has a very high frequency, with a view to transporting the low frequency message signal to a far distance. Figure 5 shows the block diagram of an optical transmitter consisting of an optical source, a modulator and the necessary circuitry driving them.

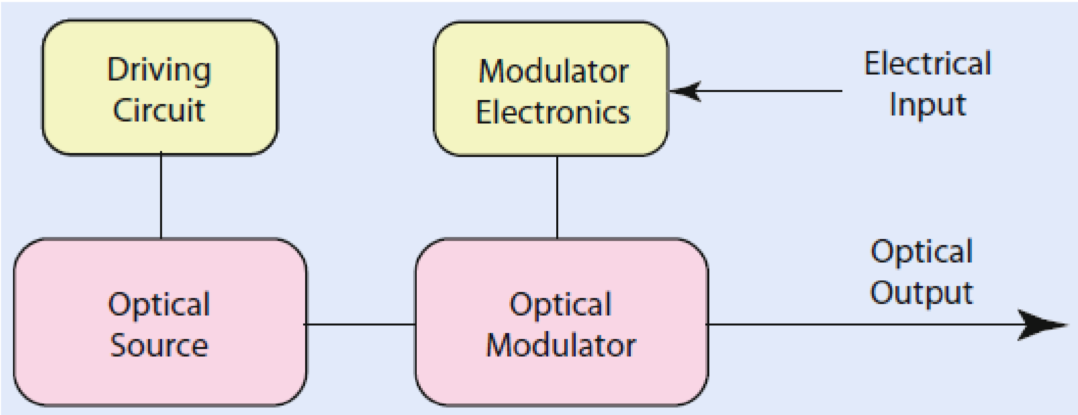


Fig. 5: *Block diagram of an optical transmitter*

The coherent light signal that is used as a carrier signal for telecommunication purposes is normally provided by lasers (an acronym that stands for Light Amplification by Stimulated Emission Radiation). However, in short distance communication, LEDs (light emitting diodes) could also be used as a source of coherent light signal.

Once an optical signal is launched into an optical fibre, the signal is confined within the fibre by a phenomenon known as *total internal reflection.*

The optical fibre, depicted in Figure 6, is as thin as one strand of human hair. It is made of glass although nowadays, it is also made out of polymers. The central portion—where most of the light travels—is called the core. Surrounding the core there is a region having a lower index of refraction, called the cladding. From a simple point of view, light trapped inside the core travels along the fibre by bouncing off the interfaces with the cladding, due to the effect of the total internal reflection. This will be explained later.

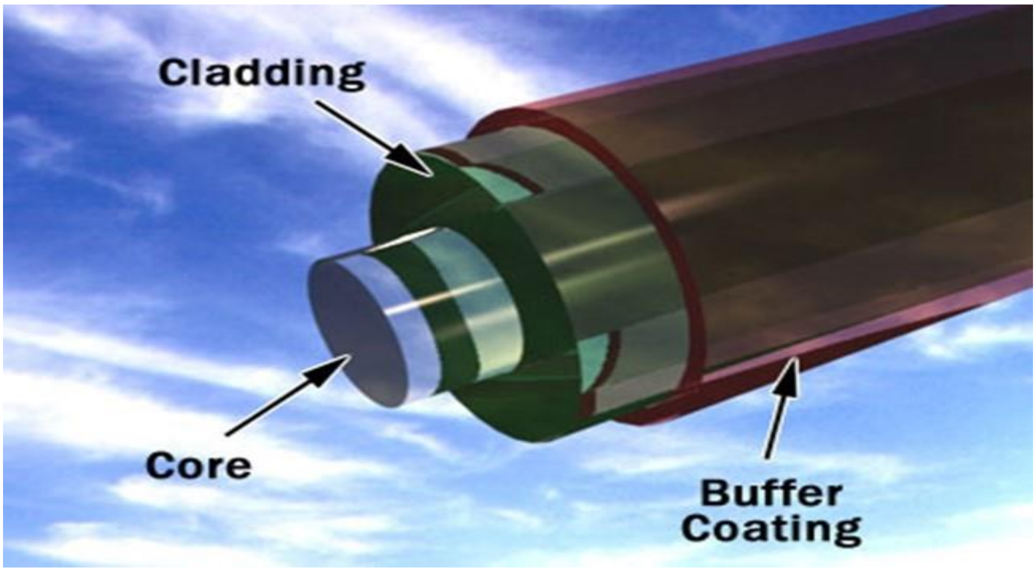


Fig. 6: *Structure of an optical fibre*

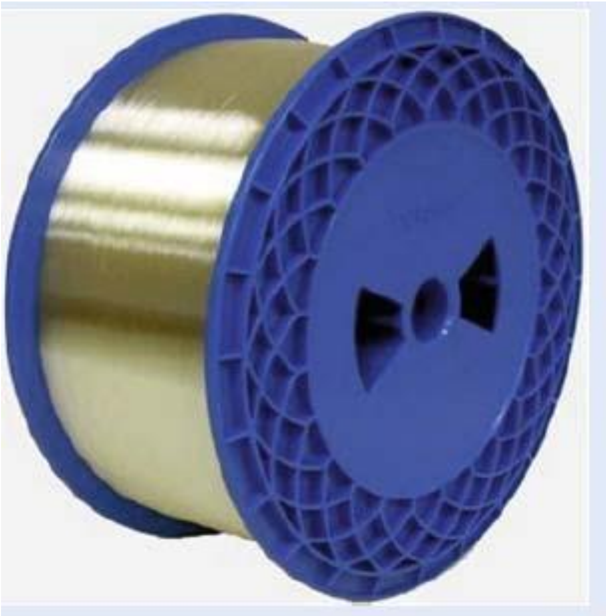


Fig. 7: *Fibre spool*

Optical signal in fibre also suffers from attenuation. This problem necessitates amplification of the signal after every100 kilometres.

At the receiver end, the message signal is normally recovered. The role of the optical receiver is to demodulate the optical signal and recover the original message signal in terms of electrical signal at the end of the communication channel, in this case the optical fibre. Block diagram of the optical receiver is shown in Figure 8. It consists of a photodetector, a demodulator and the necessary electronic circuitry required to drive them.

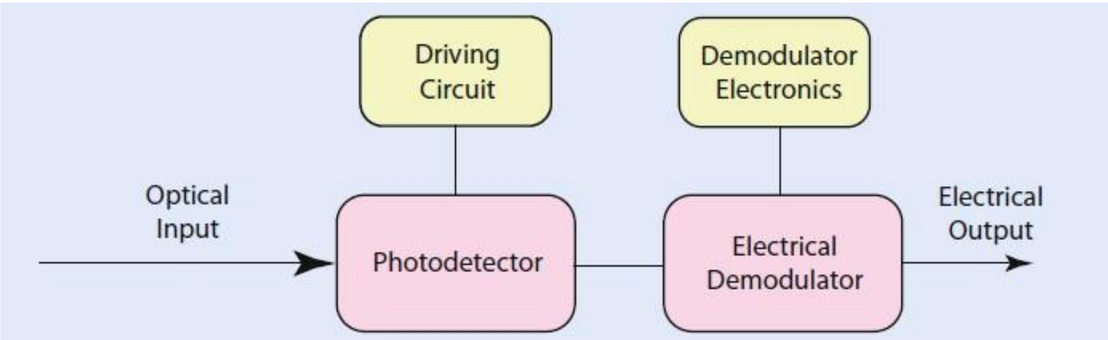


Fig. 8: *Block diagram of an optical receiver*

How Light is Confined in a Fibre

The waveguide geometry that confines light in optical fibres is due to the phenomenon of refraction. Note that the core and the cladding are made up of two materials with different refractive indices.

When a light ray is incident on the interface between two media with different refractive indices, refraction takes place and as a result, the direction of the light ray is changed as shown in Figures 9 and 10 [19].

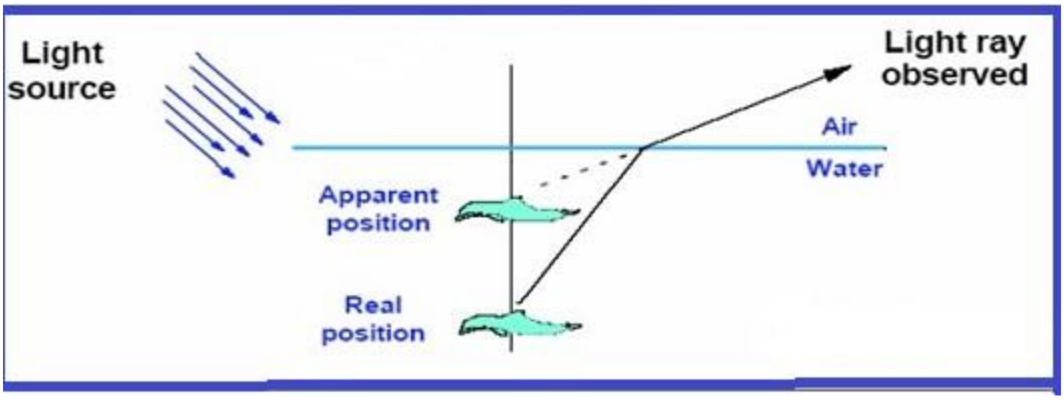


Fig. 9: *An example of refraction of light*

Fig. 10: *An example of a refraction: Straw in a class of water*

The refractive index of a medium is defined as "the ratio of the speed of light in vacuum to that in the medium" [20]. The refractive index in its simplest form is denoted by [21]:

$$n(\omega, I) = n_o(\omega) + n_2(I) \quad (1)$$

where n is the refractive index of the fibre, n_o the linear part, n_2 the nonlinear refractive index, I is the optical field intensity and ω is the angular frequency.

The relationship between refractive indices and the light ray angles is governed by Snell's law. For example, consider a ray travelling from one medium to another with different refractive indices as shown in Figure 11.

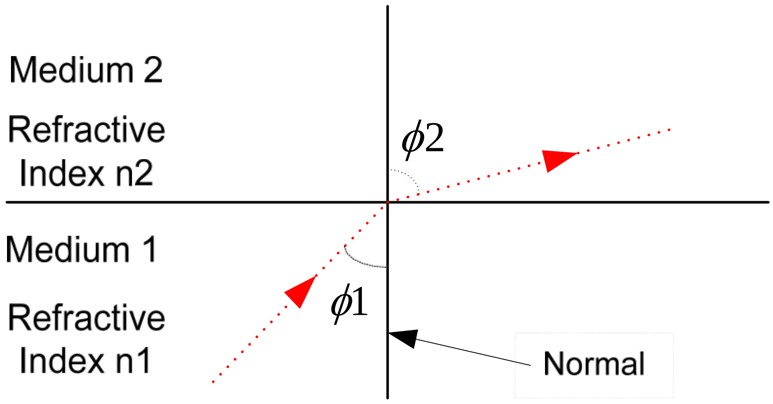


Fig. 11: *Ray of light incident on interface of two media*

Referring to Figure 11, suppose that n1 > n2 so that $\phi 2 > \phi 1$, then Snell's law states that $n1 \sin \phi 1 = n2 \sin \phi 2$.

What confines light ray in an optical fibre is the principles of total internal reflection (TIR). Consider the various scenarios as presented in Figure 12 where light is passing from a high refractive index medium to a lower refractive index medium. At some angle of incident $\phi 1$, called the critical angle ϕc, the angle of refraction ϕ2 is 90 degrees. When ϕ1 < ϕc, even though refraction is occurring, a certain portion of the incident ray is reflected. If the incident ray hits the boundary at ever-increasing angles, a value of ϕ1 = ϕc will be reached, at which no refraction will occur. The angle ϕc is called the critical angle. The refracted ray of light propagates along the interface, not penetrating into the lower-index medium. If ϕ1 is greater than the critical angle (ϕ1 > ϕc), then the ray of light is reflected back into the medium with high refractive index. This is the principle of total internal reflection that confines the ray in an optical fibre.

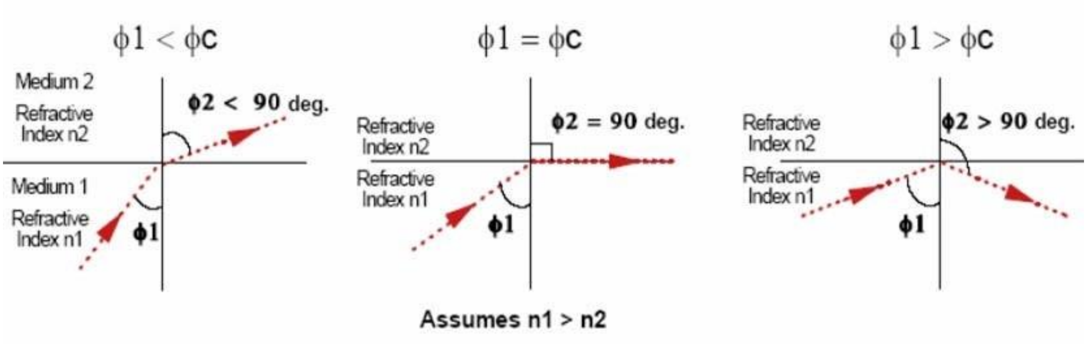


Fig.12: *Principle of Total Internal Reflection*

The critical angle is given by:

$$\sin\phi c = \frac{n2}{n1} \tag{2}$$

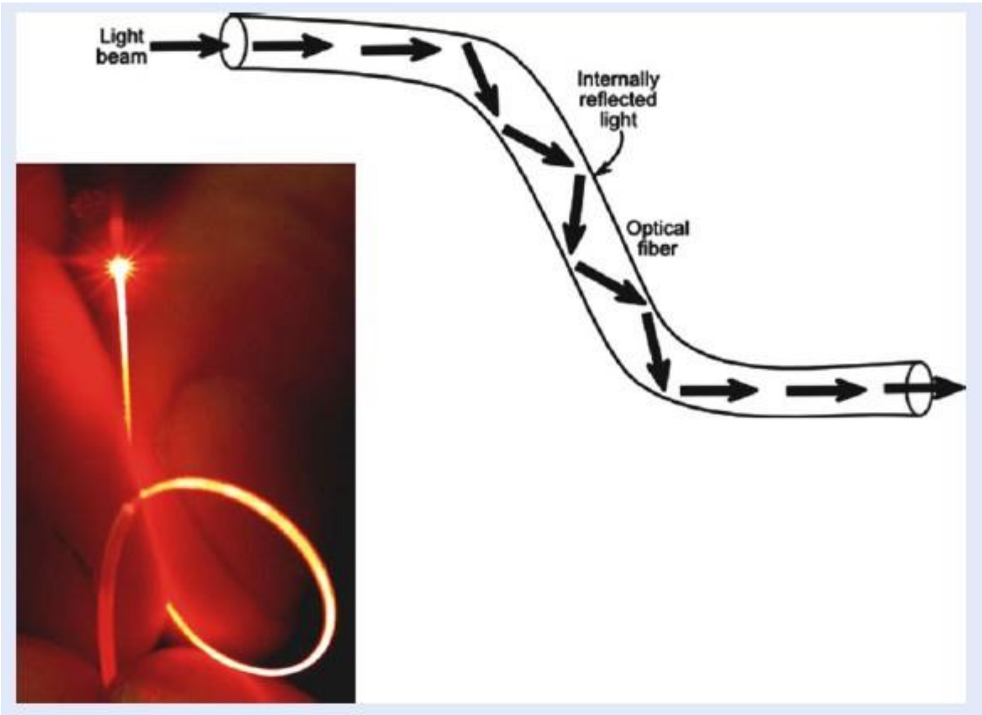


Fig. 13: *An optical fibre is able to guide light through the principle of total internal reflection. This guides the optical signals through any shape taken by the optical fibre* [22]

Wavelength Division Multiplexing (WDM)

The advent of the Internet around the late 1990s, generated significant traffic to international optical communication networks. This phenomenon that is still very much relevant today, pushed for the growing need for more communication capacity, both in terms of data rates and global coverage. Rapid and reliable transmission of voice, video and data signals is now, more than ever before, critical to the continued growth of many aspects of modern life in research communities, industries, government and the society at large. Wavelength-division multiplexing (WDM) systems that are based on the ability of an optical fibre to carry many different wavelengths of light simultaneously without mutual interference, evolved to utilize the massive bandwidth of the optical fibre. In this multiplexing technique, each wavelength represents an optical channel within the optical fibre as illustrated in Figure 14. This technology have developed to the point that channel separation can be very small, in most cases a fraction of a nanometer, giving rise to what is now known as dense wavelength division multiplexing (DWDM) systems.

Principles of Operation of WDM

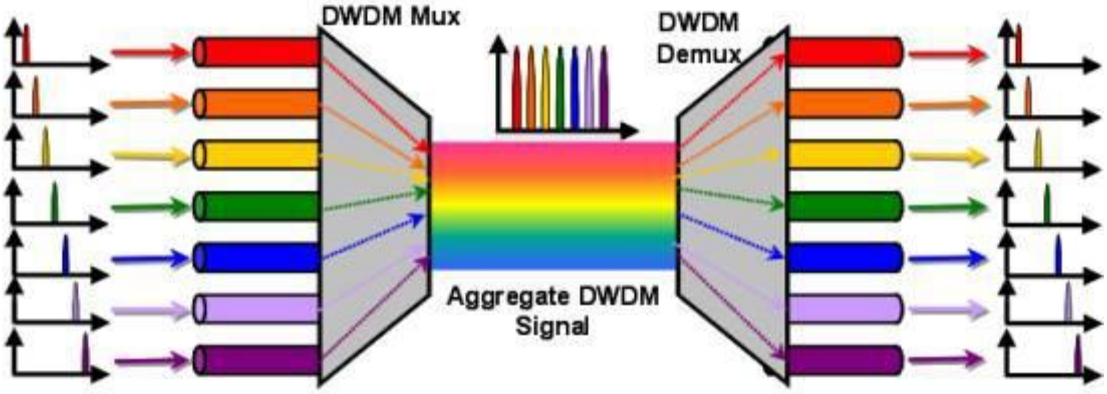


Fig. 14: *Principles of WDM*

In WDM systems, several signals carrying different data streams are multiplexed unto a single optical fibre. Each signal is transmitted at a different wavelength and at a different speed from other signals. Each of the multiple signals requires different wavelength lasers (called lambdas) in order to act as a carrier signal. Therefore, WDM systems require for its operation coherent light source with multiple wavelengths to cater for the many different channels involved. A promising technology for the generation of multiple wavelengths from a single wavelength light source is the fibre laser.

Optical Fibre Amplifiers

Optical amplifiers are a key element of long haul optical transmission systems and have significantly contributed to the success of optical communication systems. Although low transmission losses in optical fibres is a major advantage of optical transmission when compared to other signal transport media in telecommunication, amplification is still needed to compensate for attenuation (signal power losses) in long haul point-to-point transmission systems illustrated in Figure 15. Amplification is also required for the compensation of splitting and splicing losses in metropolitan network systems.

Fig. 15: *Attenuation in optical fibres*

Prior to 1987 when erbium – doped – fibre amplifier (EDFA) was discovered, optical signals have to undergo regeneration. In the regeneration process, optical-electrical-optical conversion takes place. The travelling optical signals are first converted into electrical signals, then the signals will now be amplified in the electrical domain and thereafter, the signals undergo another conversion into optical and then re-transmitted via the fibre. The discovery of the EDFA heralded a new dimension in optical signal amplification [23]. This discovery together with breakthrough research in multiple signals transportation in optical fibres nurtured the WDM technology.

C. J. Koester and E. Snitzer were the first researchers to demonstrate the use and analysis of rare-earth doped optical fibre in 1964 [24]. They used Neodymium (Nd^{+3}) as an active material. The use of Erbium ions (Er^{+3}) to doped optical fibre that is used as Laser, like its use as an amplifier was demonstrated in 1987 [25]. Since its demonstration, EDFA has been extensively studied [26-32].

Principles of Signal Amplification in Optical Fibres

Optical signals amplification in the optical domain is achieved when a section of the material used in the fabrication of the optical fibre, mostly silica glass is doped with rare-earth metals. Rare-earth metals or elements are set of the seventeen chemical elements in group 3 of the periodic table. Prominent among elements used in optical amplification include Neodymium, Praseodymium, Ytterbium and Erbium. However, Erbium doped fibre amplifiers are the most successful because the amplification bandwidth of the erbium ions naturally coincides perfectly with the low-loss spectral region of the optical transmission window centred on 1550 nm.

For erbium doped silica glass, each free ion of erbium exhibits discrete energy level. The energy level refers to an amount of particular energy contained by the ion either corresponding to absorption or emission of the energy. Therefore, amplification in erbium doped fibre is closely related to changes in the energy levels of the erbium ions. Absorbing energy will increase the energy level of the erbium ion while emitting energy will annihilate the energy of the erbium ion. In amplification terms, emitting light is closely associated with emitting photons, the smallest particle of light. The interaction of light with matter can take the form of absorption or emission of photons. This process is illustrated in Figure 16.

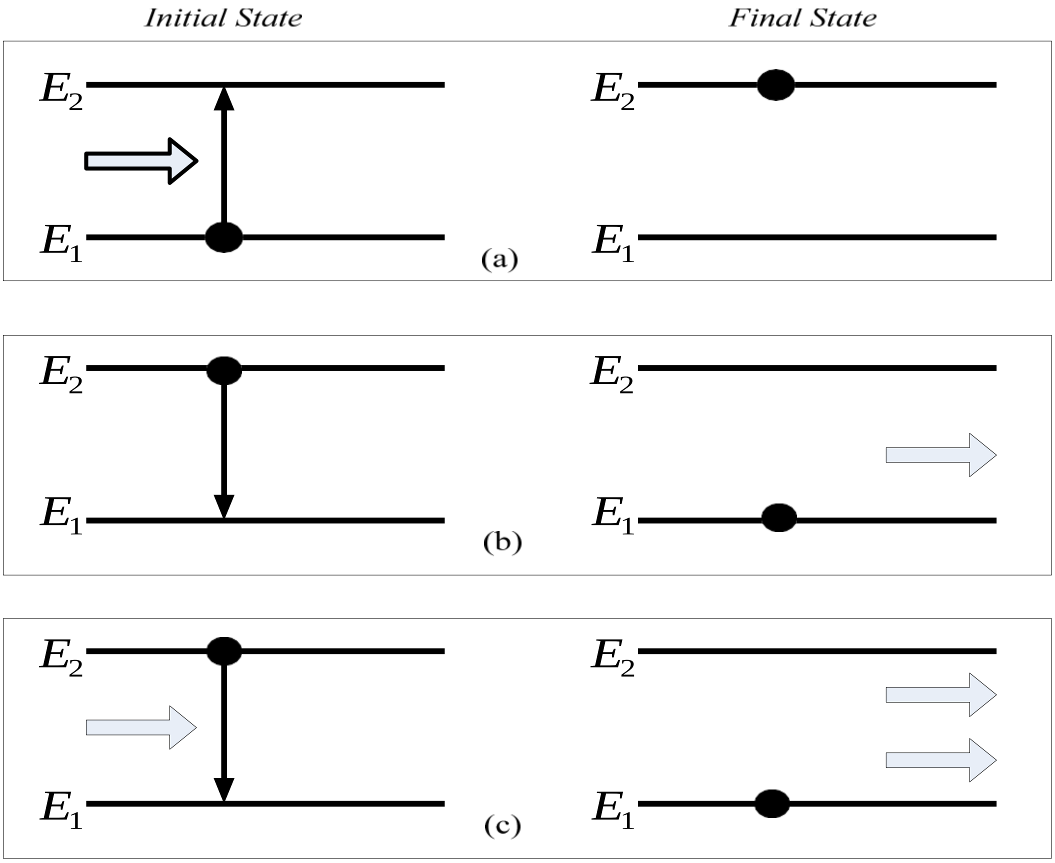


Fig. 16: *Schematic representation of interactions of light with matter*
(a): Absorption (b): Spontaneous emission (c): Stimulated emission

Referring to Figure 16, the amplification energy obtained from an external pump source (optical or electrical) is injected into a section of the fibre that is doped with erbium. This action will excite the erbium ion to transit from energy level E_1 to energy level E_2 through an absorption process as shown in Figure 16(a). The ion will remain in energy level E_2 for a predetermined time and then revert to energy level E_1 through the emission in either of two ways:

1. A spontaneous emission where the excited ion returns to the lower energy level in a random manner as shown in Figure 16(b). Spontaneous emission always involves transition from a higher energy state to a lower energy state. The emitted spontaneous emission eventually becomes the noise that is

generated by the amplifier and is referred to as amplified spontaneous emission (ASE).

2. When a photon having energy equal to the energy difference between E_1 and E_2 interacts with the atoms in E_2, causing them to return to E_1 along with the creation of more photons, as illustrated in Figure 16(c) is called 'stimulated emission'. Photons produced by this process generally possess identical energy to those that caused it and hence, the light associated with them is of the same frequency, phase and polarization.

For the erbium ions, six possible energy levels are available. There are also five possible pumping bands at 520, 620, 800, 980 and 1480nm that can be utilized for optical amplification. Absorption of the pump photons excites the erbium ions to higher energy states. At higher energy levels, the ions may dissipate energy by radiative process thereby releasing photons or converting the energy into heat. In accordance with the 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 erbium doped fibre amplifier. The generally utilized pumping wavelength for the erbium doped fibre amplifier is the 980 and 1480 nm because of the availability and maturity of the laser diodes used for pumping energy at those wavelengths.

We have recently in a study here in BUK, confirmed that 1480 nm pump has better power conversion efficiency as illustrated in Figure 17 than the 980 nm pump. However, on the other hand, the 980 nm pump offers low noise characteristics [33].

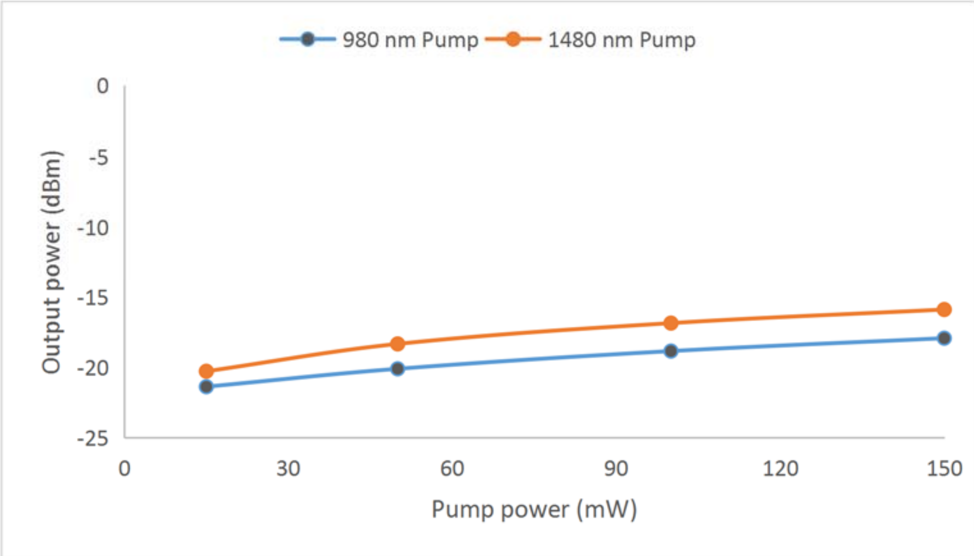


Fig. 17: *Power conversion efficiency between 980 and 1480 nm pumps* [33]

Configuration of EDFA in Optical Fibre

Application of the EDFA in optical fibre transmission system corresponds to three distinct operating regimes; small signal regime for pre-amplifiers, saturation regimes for in-line amplifiers and deep saturation regime for high power amplifiers. The location of the amplifier in a specific transmission system depends on the intended application, as depicted in Figure 18. In this way, the pre-amplifiers are located just before an optical receiver (Rx). This is particular in a situation where the input signal level into the transmission system is extremely low. Such amplifiers are designed to have an extremely low noise figure.

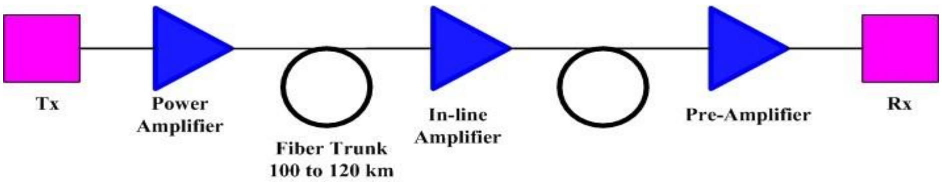


Fig. 18: *Application of EDFA in a standard optical transmission system*

The in-line amplifiers are typically located between the transmitter (Tx) and receiver along the trunk transmission lines. They are placed typically at a distance from 100 km to 120 km to compensate for power attenuation in the transmission system. The in-line amplifiers normally have the characteristics of high gain, high output power and low noise figure. However, power amplifiers are located just after the transmitter, mainly to boost the input signal power from the transmitter so as to provide very high output signal power from the transmitter to support very long haul optical transmission systems.

EDFA Architecture

Basically, there are 3 configurations used in the construction of an erbium doped fibre amplifier, as illustrated in Figure 19.

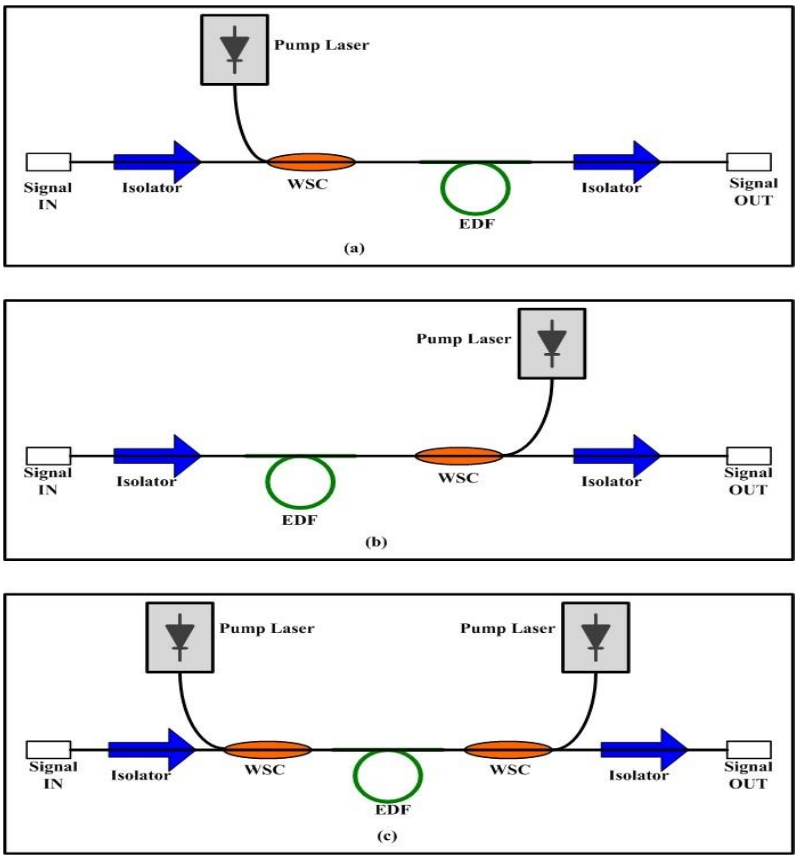


Fig. 19: *Basic configurations of the EDFA a.)Forward pumped b). Backward pumped c.) Bi – directional pumped*

The pump laser used to inject energy for the excitation of the erbium ions is either a 980 nm or 1480 nm laser diode (LD). This action will create population inversion in the erbium doped fibre (EDF) length that is used for optical amplification. Wavelength selective couplers (WSC) are utilized as multiplexers/de-multiplexers for the signal and pump laser lights. Isolators allow for one-way flow of light signals. Isolators effectively block light signals that flow in the opposite direction. They are therefore termed as unidirectional components.

In the forward pumped configuration also known as co-directional pump scheme as illustrated in Figure 19 (a), the pump laser and message signal lights propagate in the same direction along the length of the erbium doped fibre. In the backward pumped configuration also known as counter directional pumping scheme as shown in Figure 19 (b), the pump laser and the message signal lights propagate in the opposite direction. On the other hand, in the bi – directional pumped, also known as dual pumping scheme illustrated in Figure 19 (c), two pump lasers are utilized, one at each of the two EDF lengths. In this scheme, the message signal encounters pump light in both directions. The forward pumped scheme is used where better noise performance in the amplification is required. The back pumped scheme however provides higher gain. The bi–directional scheme however combines the advantages of the two other pumping schemes but its drawback is that it is expensive.

Optical Amplification Band

Fibre attenuation plays an important role in determining the assignment of transmission band in optical fibres. Signals in optical fibres experience losses mainly due to material absorption and signal scattering. The intrinsic attenuation limit in optical fibres is shown in Fig. 3 where there is an absorption peak around 1400 nm owing to strong absorptions of O-H ions. However, with advancement in the technology of fibre manufacture, new fibre types are manufactured to suppress the O-H ions peak. This is represented by a dashed line in Fig. 20. With this breakthrough, data transmission in optical fibres is now possible within 410 nm bandwidth, starting from 1290 nm to 1700 nm. Within this transmission window, bands are allocated as O, E, S, S+, C, L and U as illustrated in Figure 20.

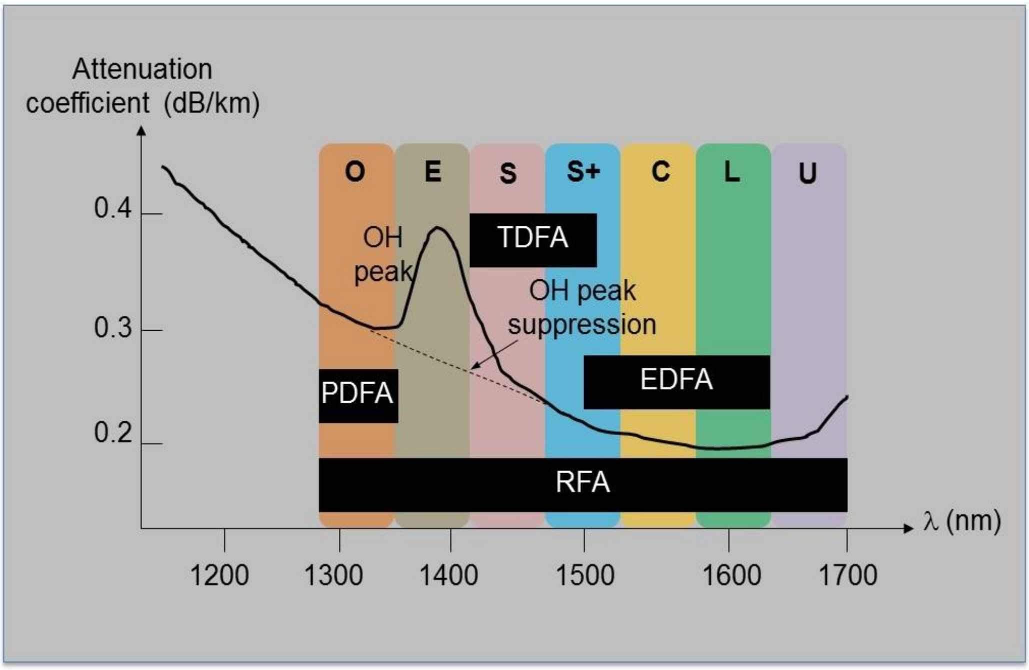


Fig. 20: *Transmission band assignment in optical fibres*

Optical amplifiers are required to correct the problems posed by attenuations. For practical applications, praseodymium doped fibre amplifier (PDFA) covers the O band from 1290 nm to 1320 nm. Thulium doped fibre amplifiers (TDFA) are used to amplify signals in the S and S+ bands that are within the range 1420 nm to 1500 nm. The erbium doped fibre amplifiers are utilized in the bands between 1500 nm to 1620 nm [34, 35] as shown in Fig. 20. Another optical amplifier that can be designed to operate in a wide range within the optical transmission window is the Raman fibre amplifier (RFA). The RFA operates subject to availability of pump lasers at the required wavelength [36]. It can be seen from Fig. 20 that the amplification bandwidth of the EDFA overlapped with the lowest attenuation window of optical fibres, thus the EDFA becomes very popular and the most investigated fibre based optical amplifier. The EDFA together with FRA shape the landscape of optical communications around the globe.

C-B and Optical Amplifiers

Erbium emission spectrum is substantially very high in the C-band transmission window. Thus, acquiring very high gain in the region is much simpler. However, there is a drawback in C-band amplification. The drawback is that there is difference in the emission spectrum along the entire C-band region which is significantly high that generates a 'hump' around 1530 nm as depicted in Fig. 21. This phenomenon causes variation in the gain experienced by signals especially in WDM systems.

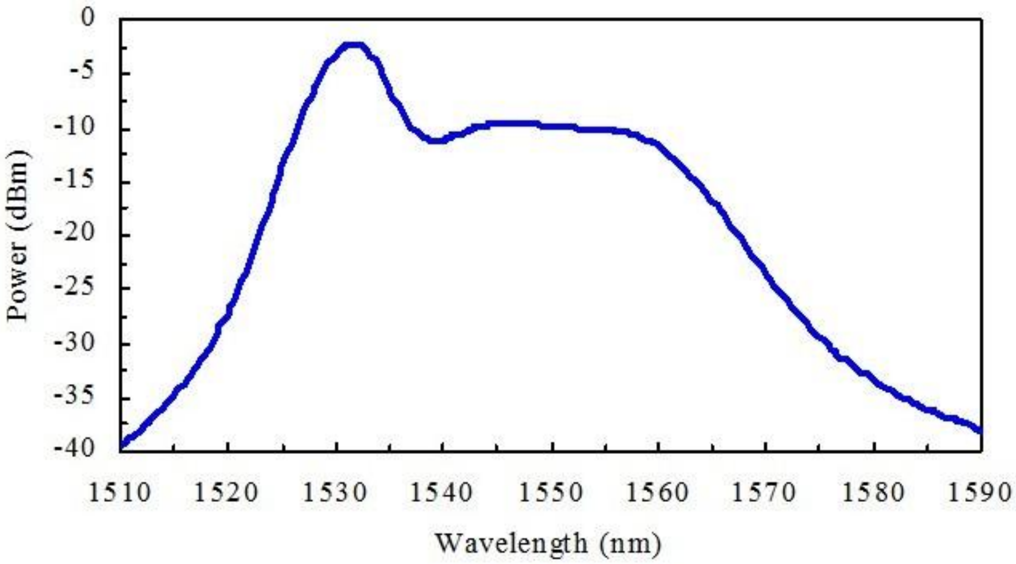


Fig. 21: *Typical gain spectrum of C – Band EDFA*

With the development of high capacity WDM optical communication systems, the gain flattening of EDFA, particularly in the C-band window, has been a research issue in recent years. Here in BUK, we took this challenge. We demonstrated gain flatness of 0.299 dB, average gain of 23dB, noise figure of less than 6 dB and output signal power of about 8mW for 16 channels simultaneous amplification in a single stage EDFA by controlling the fibre length and pump power. The gains are flattened over 12 nm from 1546 nm to 1558 nm as shown in Fig. 22. The results of this study were presented in November 2013 at an international conference on research in science, engineering and technology that was organized by the International Institute of Engineers at Kuala Lumpur, Malaysia [37]. The paper was among the best and with our permission, it was upgraded and published in an international journal of Computing, Communication and Instrumentation Engineering in 2014 [38].

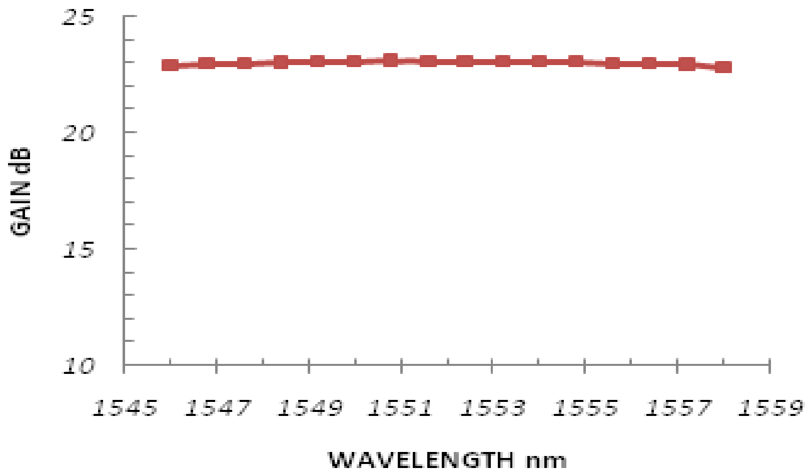


Fig. 22: *Gain flatness of EDFA* [38]

Light Scattering

When a coherent high intensity directional laser beam passes through any homogeneous transmission medium, a light scattering process took place. The light scattering process can broadly be classified under two categories. Firstly, where the fluctuations that induced the light scattering are induced by the presence of the light field itself or secondly where the fluctuations are excited by the thermal or quantum – mechanical effects. The former is called stimulated light scattering whereas the latter is termed spontaneous light scattering. Stimulated light scattering is typically more efficient than spontaneous light scattering. For example if a beam of visible light is passed through 1 cm of liquid water, only one part in 10^5 of the power contained in the beam would be scattered by spontaneous scattering whereas if the beam has sufficiently large intensity, 100% of the beam can be scattered as a result of stimulated scattering process [39]. Light scattering is principally caused by different physical mechanisms that can be grouped; where the light scattering arises from inhomogeneity of the refractive index distribution of the medium of propagation or where the scattering arises from the fluctuation of the polarization response of the molecular system. Stimulated light scattering can also be distinguished from spontaneous light scattering experimentally by looking at the following features [40]:

a. **Threshold of the light scattering**: If the power of the input pump light is lower than a certain threshold, only a weak spontaneous scattering will take place that can only be detected by highly sensitive equipment. On the other hand, if the intensity of the input pump light is higher than a certain threshold, a strong and highly directional scattering signal can be observed. Such a scattering process is said to be stimulated.
b. **Spatial structure of the scattering**: At the point of incident of laser beam, spontaneous light scattering normally takes place in all directions. For most of the stimulated scattering observations however, the scattering process happens in the forward, backward or both directions, depending on experimental conditions.
c. **Mechanism of the scattering**: The basic mechanism of the two types of scattering process differs in the sense that the behaviour of the related process for the stimulated scattering is strongly dependent on the intensity level of the incident coherent light beam. In contrast, the behaviour of the process for spontaneous scattering is rarely dependent on the intensity of the coherent light beam.

Classification of Light Scattering

Light scattering can generally be grouped into two classes; linear and nonlinear scattering. In the linear scattering process which is also termed "Elastic", there is no energy exchange between the optical coherent beam and matter in the propagating medium. An example of elastic scattering is Rayleigh and Mie scattering. In the nonlinear scattering process termed "Inelastic" however, there is exchange of energy between the matter involved and the intense coherent beam. Two important nonlinear optical fibre effects fall in this category, namely the stimulated Raman scattering and the stimulated Brillouin scattering. Both of these two phenomena are related to the vibrational excitation modes of the silica. The major difference between the two phenomena is that optical phonons participate in stimulated Raman scattering whereas acoustic phonons participate in stimulated Brillouin scattering.

Stimulated Brillouin Scattering

Stimulated Brillouin scattering (SBS) is a nonlinear effect that manifest through the generation of backward propagating optical signal when the injected input signal power reaches a certain value called SBS threshold. The backward propagating optical signal, normally termed Brillouin Stokes signal was defined as "the input pump power at which the back scattered power begins to increase rapidly or, equivalently, the pump wave begins to be depleted" [41]. Above SBS threshold value, the power of the input signal rapidly transfers to the Brillouin Stokes signal. The Brillouin Stoke signal is frequency downshifted from the input signal. The value of the downshifted frequency is determined by the material that is used in the fabrication of the optical fibre. For silica based fibre, the downshifted frequency is intrinsically 0.08 nm as shown in Fig. 23.

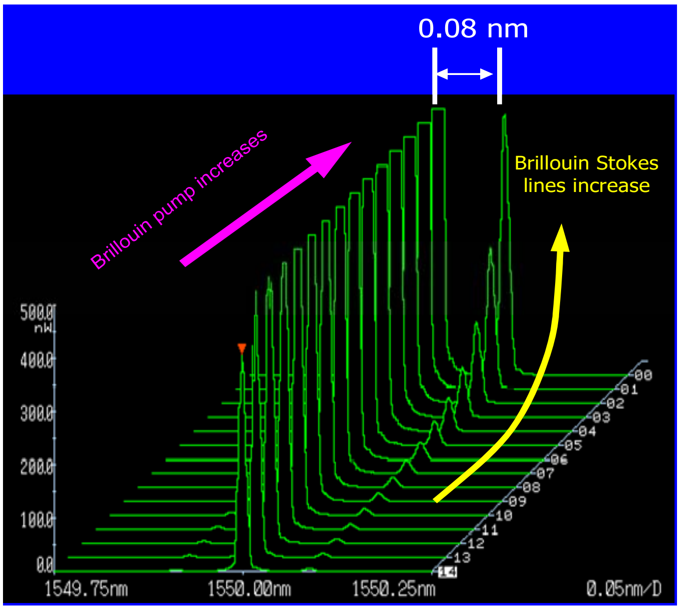


Fig. 23: *Process of SBS in optical fibres showing the growth of Brillouin Stokes Signal with respect to increment of pump power*

Basic concept of SBS

Since the first observation of SBS by Chiao *et al* in a 1964 experiment [42], SBS has widely been studied [43-50]. SBS is principally caused by the thermal acoustic vibrations of the medium in which an intense light is travelling. There are two different mechanisms through which a laser can drive an acoustic wave, electrostriction or optical absorption. Electrostriction is the tendency of materials to become denser in the region of high optical intensity or the tendency of material to become compressed in the presence of electric field [39]. Optical absorption is the inclination of laser to generate heat in the region of high optical intensity within the fibre. The generated heat tends to cause the silica material to expand and as a result, drives an acoustic wave within the optical fibre. Absorption SBS can only occur in a lossy optical medium and thus it is uncommon compared to electrostriction SBS.

Stimulated Brillouin Scattering in Optical Fibres

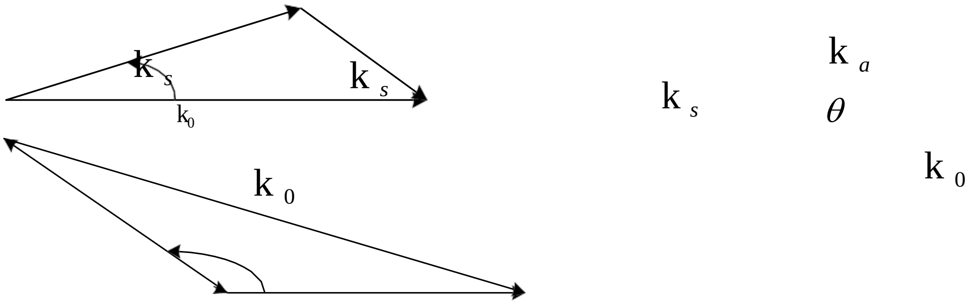
SBS effects in optical fibre was first reported by Ippen and Stolen in 1972 [51]. The SBS effects in optical fibre can be explained classically or quantum theoretically. In the classical description, SBS in optical fibre arises from a resonant interaction between a pump light, a backscattered Brillouin light and an acoustic wave [21]. Through the process of electrostriction (tendency of materials to become compressed in the presence of an electric field), the pump light generates acoustic waves that results in an index grating which co – propagates with the pump wave at acoustic velocity in the fibre and produces the Brillouin scattering light. The Brillouin scattered light propagates backward and its frequency downshifted through the Doppler effects (change in frequency and wavelength of a wave for an observer moving relative to the source of the waves). If the acoustic velocity is termed v_A, the frequency shift v_B is given by the relationship [52]:

$$v_B = (2nv_A)/\lambda_p \tag{3}$$

where λ_p is the pump wavelength and n is the fibre reflective index. For a silica-based optical fibre, the downshifted frequency is typically around 10 GHz. Quantum – mechanically, SBS in optical fibre can be described as a parametric interaction between an input photon, a scattered photon and a phonon inside the fibre. The process can be explained by use of laws of conservation of energy and momentum in two ways: Stokes scattering generation and anti-Stokes scattering generation. In stimulated Brillouin scattering that leads to the generation of Stokes signal, the process can be described as the annihilation of an incident photon and the simultaneous creation of one scattered photon and one induced phonon. In this case, the laws of conservation of energy and momentum require that [40]:

$$\begin{aligned} v_0 &= v_s + v_a \\ \mathrm{k}_0 &= \mathrm{k}_s + \mathrm{k}_a \end{aligned} \tag{4}$$

where v_0, v_s and v_a are the frequencies of the incident photon, scattered photon and induced phonon whereas $\mathrm{k}_0, \mathrm{k}_s$ and k_a are the wave vectors of the incident photon, scattered photon and the induced phonon respectively. The attribute of this scattering process is that partial energy of the input optical wave is transferred to the acoustic wave. The frequency of the Stokes wave is determined by phase – matching conditions as shown in Figure 24.



(a) (b)

Fig. 24: *Phase – matching condition of Brillouin Stokes process for (a) forward scattering (b) backward scattering.*

From (4), we can assume that $\nu_0 \approx \nu_s$ and $k_0 \approx k_s$ since $\nu_a << \nu_0, \nu_s$.

Therefore from Fig. 24 (b), it can be seen that:

$$\frac{1}{2}k_a \approx k_0 \sin\frac{\theta}{2} \tag{5}$$

$k_a = 2\pi/\lambda_a = 2\pi\nu_a/v_a, k_0 = 2\pi n/\lambda_0 = 2\pi n\nu_0/c$; λ_0 and λ_a are the wavelengths of the incident light and the phonon; c/n and v_a are the velocities of the photon and the phonon in the SMF; n is the refractive index of the SMF and θ is the angle between the incident light and the scattered light. Based on (4) and (5), we can obtain:

$$\Delta\nu = \nu_0 - \nu_s = \nu_a = 2\nu_0 \frac{n v_a}{c}\sin\frac{\theta}{2}. \tag{6}$$

From (6), it can be seen that when $\theta = \pi$, the frequency reaches its maximum for the backward scattering light, that is:

$$\otimes v_{max} = v_0 - v_{s\,max} = v_a = 2v_0 \frac{nv_a}{c}. \quad (7)$$

Thus the velocity of the induced phonon can be determined based on (6) and (7). Also, from Fig. 24 it can be seen that for the backward scattering light with $\theta = \pi$, the induced phonon will propagate along the same direction as the incident light, that is, the phase – matching is collinear. In SBS that leads to the generation of anti-Stokes, the process can be described as the annihilation of one incident photon and one existing phonon and the simultaneous creation of one scattered photon. Here, the conservation of energy and momentum requires that [40]:

$$\begin{aligned} v_0 + v_a &= v_{as} \\ \mathrm{k}_0 + \mathrm{k}_a &= \mathrm{k}_{as} \end{aligned} \quad (8)$$

where v_{as} and k_{as} are the frequency and the wave vector of the anti-Stokes. In this case partial energy of the acoustic wave in the fibre is transferred to the scattered light. The frequency shift of the anti-Stokes scattering light is determined by [40];

$$\otimes v = v_{as} - v_0 = v_a = 2v_0 \frac{nv_a}{c} \sin\frac{\theta}{2} \quad (9)$$

If the intensity of the pump wave is so strong that the growth of the induced electrostrictive acoustic wave and the scattered light wave can significantly overcome their losses in the SMF, then stimulated amplification of both waves can be witnessed.

Applications of SBS

Although SBS can be detrimental in coherent optical communications [53], SBS in optical fibre has been useful in a number of applications. It has been used in optical fibre characterization [54, 55], as a means of narrow-bandwidth amplification [56], as a method of frequency shifting [57], microwave generation [58], as a means of distributed strain and temperature measurements [59, 60] and perhaps most interest in SBS has arisen from the use of Brillouin generation in producing fibre lasers [61-63].

Lasers

Laser is an acronym that stands for "Light amplification by stimulated emission of radiation". Lasers produce the best kind of coherent light needed for optical communications [64]. A laser is a device that amplify light signal in as much the same way an electronic amplifier amplifies electrical signal. A laser consists of a gain medium that is normally contained inside an optical cavity. It also consists of a means to supply energy to the gain medium. The gain medium is a material with properties that allow it to amplify a light signal by the process of stimulated emission. The process of supplying the energy to the gain medium is referred to as pumping. The cavity could be linear or a ring. In its simplest form, a linear cavity consists of mirrors arranged in such a way that lights leap back and forth, each time passing through the gain medium, where on each trip, the light signal of specific wavelength is being amplified. The gain medium normally absorbs the pump energy to get its atoms into excited (higher energy) quantum state that is necessary for the laser to work efficiently. In general, the atoms are excited to a level that is two or more levels above the ground state. The excitation of the atoms increases the degree of population inversion. The population inversion is a condition of laser medium where the number of atoms exists in the higher excited energy state than that of the lower ground energy state. If the laser's gain medium is pumped, it will then contain a collection of atoms with some electrons sitting in the excited levels with higher energy levels and lower energy level electrons sitting in the ground, relaxed levels. As the high energy contained electrons relaxed back to the ground state, they release the energy which comes in the form of photons (light energy). The emitted photon normally has specific wavelength that depends on the state of the energy of the electron when the photon is released.

Fibre Lasers

These types of laser employ optical fibre doped with rare-earth elements as the active gain medium. Rare-earth elements such erbium, ytterbium, neodymium, praseodymium and thulium are often used. Fibre nonlinearities such as stimulated Brillouin scattering can also provide gain which can also be exploited for serving as a gain medium for a fibre laser.

Fibre lasers offer many advantages over conventional solid-state lasers for being applicable as a reliable, efficient, compact, low-cost source for many applications such as in radar, sensor, microwave photonics and perhaps most importantly, in optical communication systems. The many advantages of fibre laser include low threshold value, compactness, spectrally clean and can be modulated with little signal distortion. Moreover, fibre – to – fibre compatibility is a distinct advantage particularly in optical communication.

Stimulated Brillouin Scattering has been used in the generation of Brillouin fibre lasers (BFLs) [62]. Owing to their extremely narrow linewidth [65], BFLs are of interest for a number of applications. The key features of BFLs are very high coherence and directional sensitivity of the SBS gain. Because the Brillouin gain is very narrow, BFLs are generally constructed in all-fibre, high-finesse, critically coupled ring resonator arrangement in order to achieve efficient operation [62]. But high-finesse resonator generally results in small output power. Other disadvantages of BFLs include the requirement of cavity matching to the pump signal and the difficulty in incorporating intra-cavity elements because of their associated losses [66].

To overcome the need of critically coupled resonator in the operation of BFLs, Cowle and Stepanov proposed a hybrid Brillouin/Erbium fibre laser [67]. In their reported work, they used erbium-doped fibre amplifier (EDFA) to compensate for the resonator losses while still originating lasing action from the Brillouin gain. This work gave birth to what is now known as Brillouin-erbium fibre laser (BEFL). In BEFL, two gain media are combined, the linear gain from EDFA and the nonlinear gain from stimulated Brillouin scattering process. The EDFA gain allows for large output power generation and contributes to the majority of the output power. The SBS process determine the wavelength of operation of the laser. It also provides additional gain to the Brillouin Stokes signal that is frequency shifted from the injected Brillouin pump signal.

Single Wavelength Brillouin/erbium Fibre Laser

The operation of a single wavelength BEFL in a ring cavity configuration can be understood by referring to the schematic diagram as shown in Figure 25.

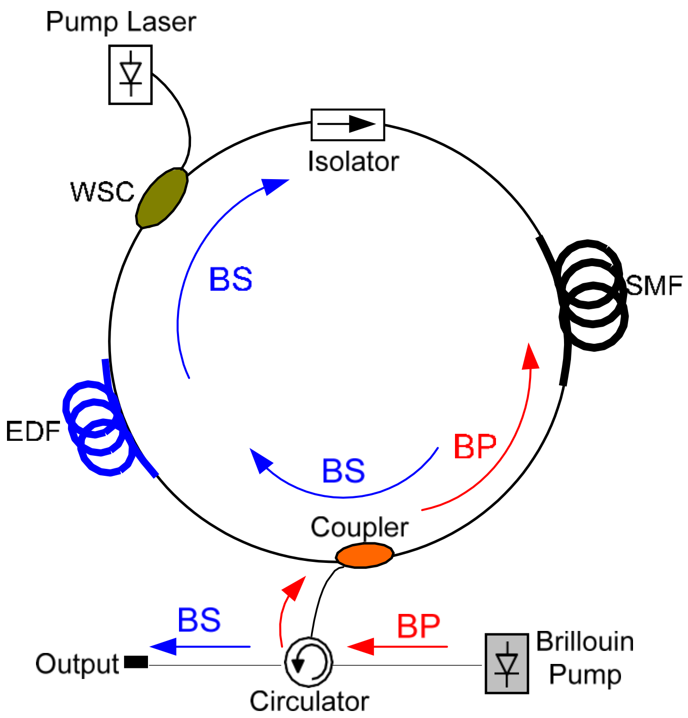


Fig. 25: *Schematic arrangement for a single wavelength BEFL* [68]

When the BP is injected into the SMF, with sufficient power that overcomes the Brillouin threshold of the SMF, Brillouin gain is generated in the SMF and thus Brillouin Stokes signal is created that propagates in the opposite direction to the propagation direction of the BP, at a frequency shifted from the BP frequency. The value of the frequency shift is determined by the material used in fabrication of the SMF. Pumping the EDF will produce gain that can be used to overcome the resonator losses. If the total gain equals the total losses in the cavity, laser action can start at the Stokes shifted wavelength. With no BP injected into the ring cavity and the EDF pumped, self-lasing oscillations will occur in the laser cavity at the maximum gain of the EDF. If the wavelength of the BP is chosen close to where the maximum gain in the EDF is produced, the self-lasing cavity modes can be suppressed from oscillating in the laser cavity. While the Brillouin gain sets the Stokes line wavelength, the EDFA gain contributes to the output power of the Stokes. The BEFL as considered in Fig.e 26 includes an isolator that is used to prevent the BP from entering the EDF and thus prevents an injection locking. Such a BEFL support only a single wavelength operation, because the generated Stokes signal is not resonant by virtue of the direction of the isolator. Experimental results by Cowle *et al* (based on the setup shown in Fig. 25) are depicted in Fig. 26 which shows a fixed BP and variable pump power.

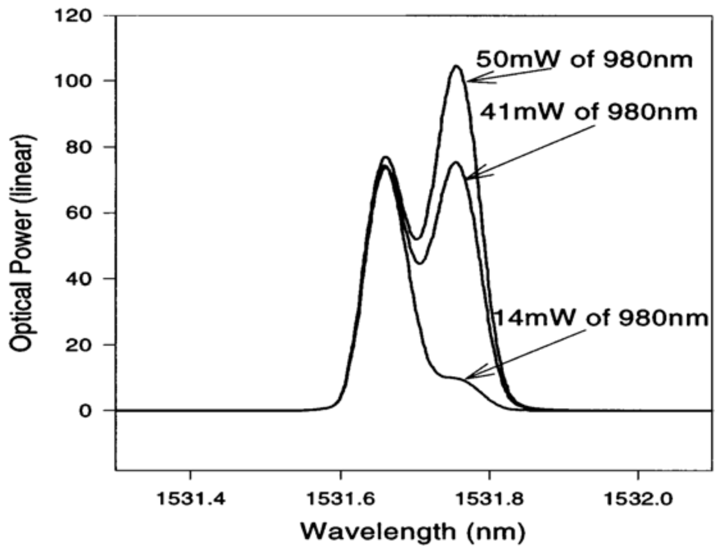


Fig. 26: *Single wavelength BEFL at fixed BP and variable pump power* [67]

Multiple Wavelength Brillouin/erbium Fibre Laser

Multiple wavelengths or multi-wavelength lasers are those lasers that produced multiple laser lines (multiple wavelengths) from a single wavelength light source as shown in Figure 27.

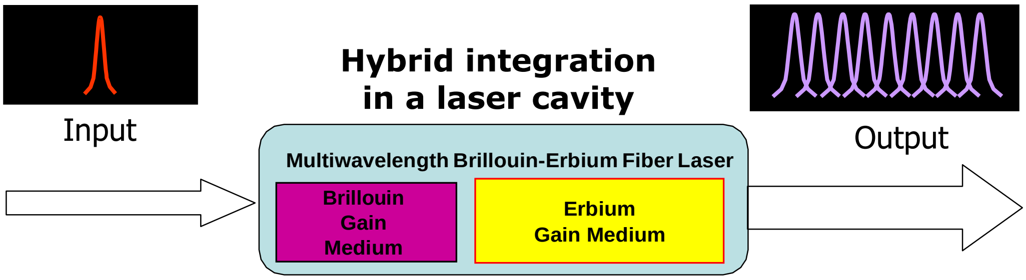


Fig. 27: *Multiple wavelength BEFL*

MWBEFL are attracting much interest because of their several potential applications in optical communication systems, notably as found in dense wavelength division multiplexing (DWDM) systems [69], sensors, such as in laser gyroscopes [70], current monitors [71], and all-optical generation of millimetre wave carriers [72], microwave signal processing [58] and the generation of short optical pulses [73].

Multiple wavelength generation can be achieved in Brillouin/erbium fibre laser by utilizing the output of a single wavelength Brillouin/erbium fibre laser as a Brillouin pump in conjunction with a suitable resonator design.

Multiple wavelengths Brillouin/erbium fibre laser (MWBEFL) has been demonstrated in both ring and linear cavity resonator configuration. In a ring cavity resonator configuration, MWBEFL can be achieved through external or internal cascade techniques. In the external cascade method, MWBEFL are produced by taking the output of BEFL and using it as a Brillouin pump to another BEFL. In such a situation, the two BEFL must be fabricated with identical components. In particular, the optical fibre used in each laser must be the same such that the frequency shift between the two lasers should be identical. The output spectra of the two lasers can then be pairwise-mixed. On the other hand, in the internal cascade technique, the resonator design of the BEFL is modified such that the output is used as a Brillouin pump to support additional Stokes shifted signals. Figure 28 depicts a modified Figure 25 where two optical couplers are inserted, one immediately after the isolator and the other one immediately after the SMF. The two inserted couplers are joined and thus formed the famous reverse – S arrangement. Here, some part of the first Stokes travelling in the clockwise direction is taken and re – injected at the other end of the SMF in the anticlockwise direction. With sufficient power to overcome the threshold power of the SMF, the re – injected signal will create a new second order Stokes line which will be resonant in the same direction as the first Stokes signal. The process will continue until the power of the next Stokes will not be able to overcome the threshold power of the SMF and hence the generation of next higher order Stokes signal will cease.

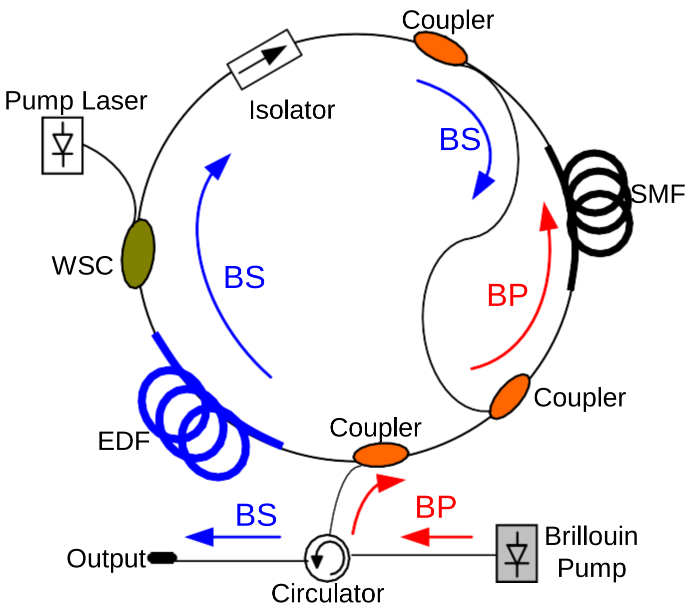


Fig. 28: *Schematic of ring cavity internal cascaded MWBEFL* [74]

The Issues in Multiple Wavelength Brillouin/erbium Fibre Laser

Multiple wavelengths Brillouin/erbium fibre laser is a very good candidate for use in dense wavelength division multiplexing (DWDM) system. However, it has the inherent disadvantage of limited wavelength tunability caused largely by the gain competition imposed by its cavity gain characteristics. Due to homogeneous broadening effects in the erbium-doped fibre [75], oscillating modes within the peak gain of the laser cavity, also known as lasing cavity modes, potential modes, free running cavity modes or self-lasing cavity modes are intrinsically generated and they are always dominant as indicated in Fig. 29.

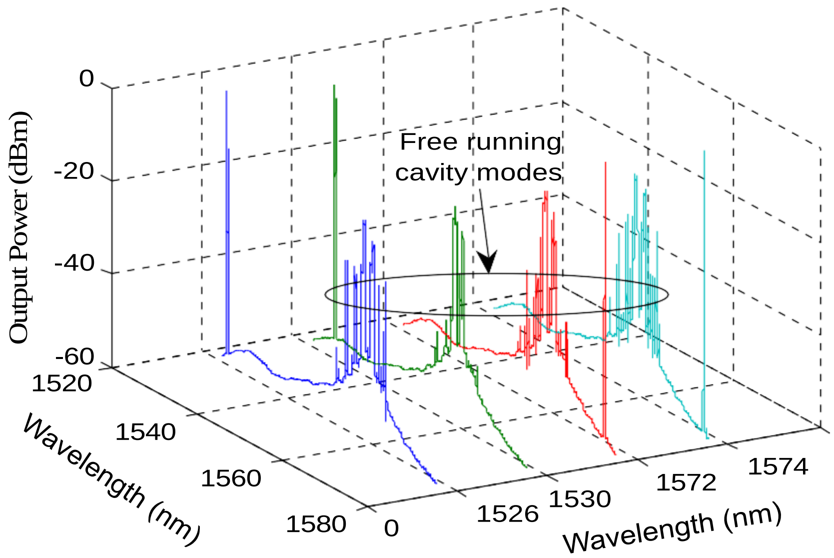


Fig. 29: *Output spectrum of the MWBEFL at BP power of 2 mW and PP of 130 mW with selected BP wavelength of 1526 nm, 1530 nm, 1572 nm and 1574 nm for bi-directional amplifier configuration* [76]

The presence of self-lasing cavity modes however, imposed strong mode competition between the Brillouin Stokes signals and the self-lasing modes within the laser cavity. This effect caused power instability on the multiple Brillouin Stokes signal and also principally limits the wavelength tunability of the Brillouin Stokes lines [77]. The wavelength tunability is defined as the range of Brillouin pump (BP) wavelength which produces the Stokes lines in the absence of self–oscillations cavity modes [78]. Apart from the problem of wavelength tunability in MWBEFL, other notable problems include number of generated output channels, power of the generated individual channel, high threshold power and complexities normally associated with feedback mechanisms [67, 77, 79].

To address the wavelength tunability in MWBEFL, we report experimental demonstration of a MWBEFL that can freely be tuned over the entire C–band window [80]. Tuning range of 39 nm (from 1527 nm to 1566 nm) was experimentally achieved. Our structure, which consists of only 4 optical components in the resonator, is simple, cost effective and devoid of the complexity normally associated with enhancement of feedback mechanism found in the previous MWBEFL studies. The configuration of the proposed setup is as shown in Fig.30. The structure consists of an erbium-doped fibre (EDF) gain block in a ring cavity resonator with four optical components, a circulator, an isolator and two 3-dB optical couplers, designated C1 and C2 in Fig.30. The Brillouin gain media is provided by 11 km long dispersion compensating fibre (DCF).

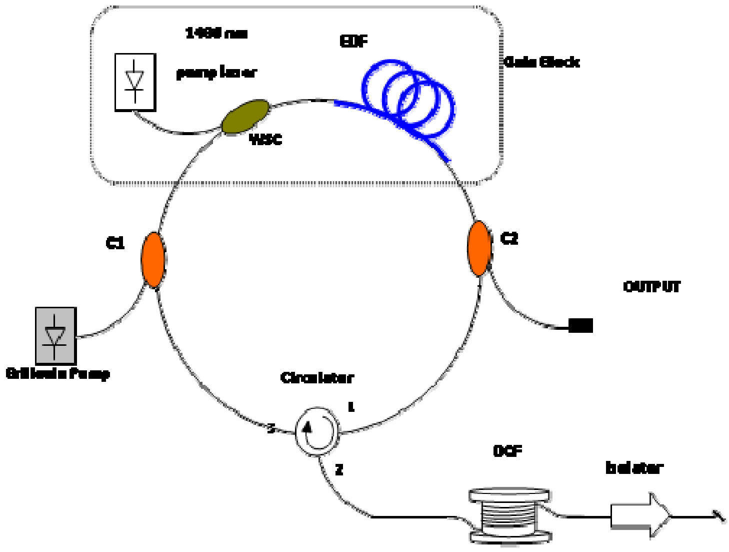


Fig. 30: *Experimental setup of virtual mirror configured MWBEFL* [80]

The main drawback of this laser however, is that at the maximum 1480 nm laser pump power (PP) and BP powers of 130 mW and 2 mW respectively, only four output channels are generated as depicted in Figure 31.

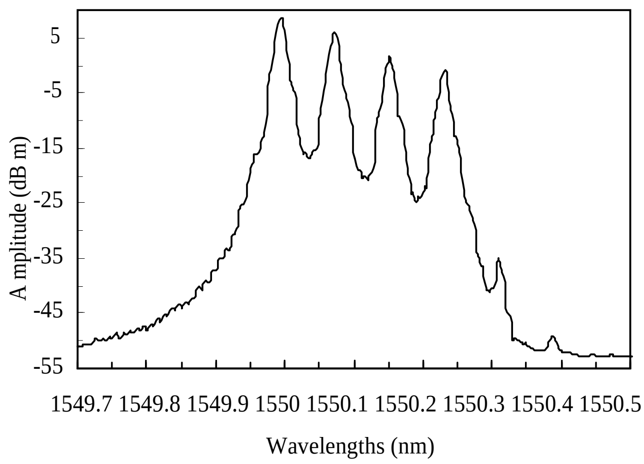


Fig. 31: *Output Spectrum of the MWBEFL at BP power of 2 mW and 1480 nm pump power of 130 mW* [80]

In order to investigate the tunability of the laser, the BP wavelength was tuned from 1525 nm to 1575 nm with a step of 2 nm at maximum BP signal power of 2 mW and the 1480 nm pump signal power of 130. We found out that the 4 generated output channels are tuned over 39 nm, from 1527 nm to 1566 nm as depicted in Fig. 32.

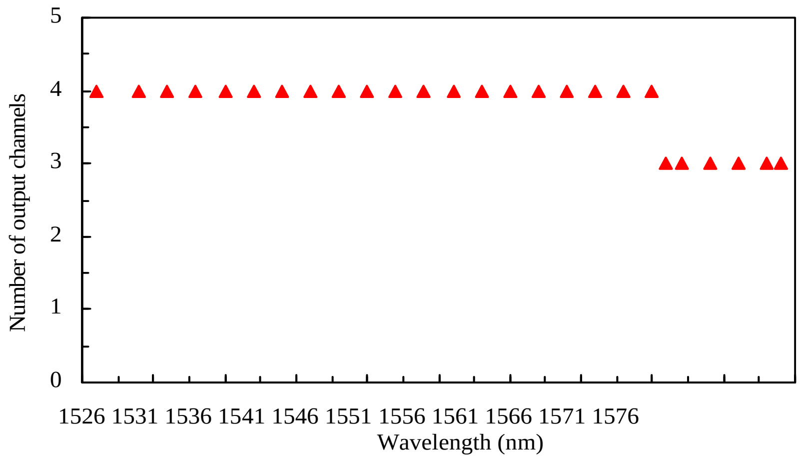


Fig. 32: *Tunable spectra of the generated output channels at 130 mW and 2 mW of the 1480 nm PP and BP powers respectively* [80]

The wavelength tunability otherwise known also as tuning range is only limited by the amplification bandwidth of the erbium gain. This technique utilizes virtual mirror in the laser cavity which provided weak reflectivity that suppresses self-lasing cavity modes from circulating within the cavity, thus the self-lasing modes are eliminated and hence rectifies the tuning range limitations faced by the previous MWBEFL architectures. The output spectrum of the MWBEFL is clean from any self-lasing cavity modes generated from the laser cavity for any BP wavelengths as shown on Figure 33.

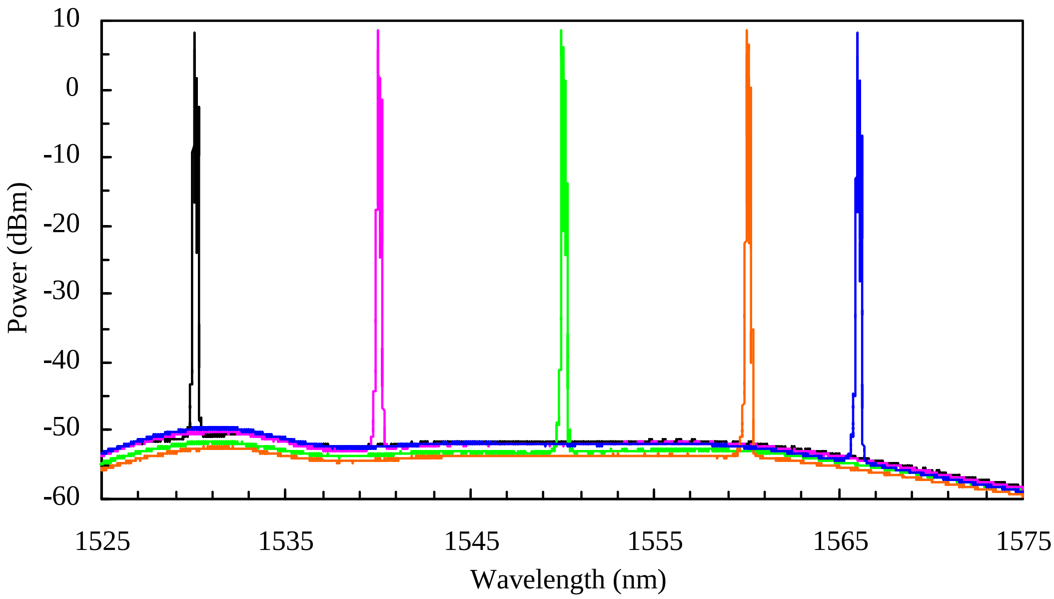


Fig. 32: *Output Spectra of the tunable MWBEFL at 130 mW of 1480 nm pump and 3 dBm of BP powers*

It can clearly be seen from Fig. 32 that the output spectrum is clean from any self-lasing cavity modes generated from the laser cavity for any BP wavelengths.

Although the problem of tunability in the C-band optical window is overcome, the number of the generated channels are low. The generation of multiple wavelengths in Brillouin/erbium fibre laser requires the power of the subsequent Brillouin pump signal to overcome the threshold power of the Brillouin gain media [74]. A reduced threshold value will therefore ensure the generation of a large number of channels [61]. A method to reduce Brillouin threshold is reported through bidirectional propagation of the pump signal in the Brillouin gain media, thereby increasing the Brillouin gain and thus reduce the threshold [81]. Other reported methods of SBS reduction include: employing Stokes noise [82], using fibre loop schemes [83] and most recently by Stokes seeds via acousto-optic effect [84]. We proposed and experimentally investigated a simple structure for stimulated Brillouin scattering threshold reduction through Brillouin pump recycling technique. In a 5km single mode fibre spool, our technique reduced SBS threshold by over 48% (measured at 8.5 mW of input signal against 16.5 mW in the conventional technique under same input signal conditions) as shown in Figure 33. [85]

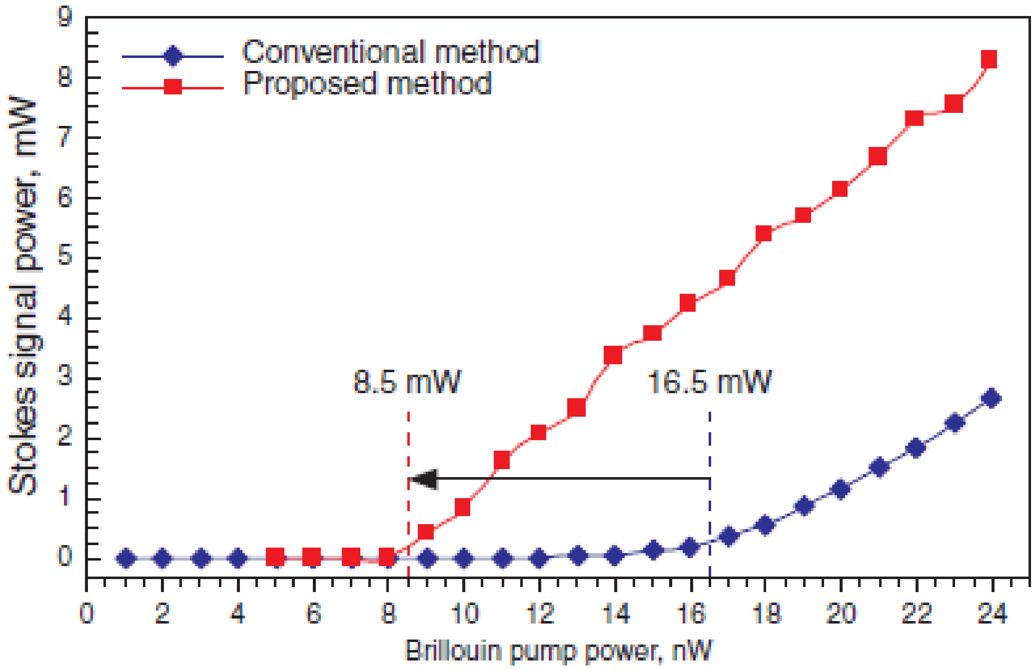


Fig. 33: *Stokes power variations with the input signal power for 5.0 km long SMF* [85]

Having been able to achieve a good result in SBS threshold reduction, the experimental structure was incorporated unto the experimental structure of the virtual mirror setup shown in Fig. 30 with a view to increasing the number of the output channels. Two structural configurations describing uni-directional and bi-directional propagation of Brillouin pump and Brillouin Stokes signals through an erbium-doped fibre gain were proposed and investigated. We compare their basic characteristics in terms of lasing threshold, generation of output channels and the tunability of the generated output channels. We discovered that there is a trade-off between the two fibre laser configurations. While the uni-directional amplifier configuration produces a wider tuning range of 46.8 nm compared to 23 nm as provided by the bidirectional amplifier configuration at Brillouin pump power of 2 mW and pump power of 130 mW, the bidirectional amplifier configuration however produces more output channels [76]. The enhanced experimental structure provides 7 stable that are completely tunable over the entire C-band window as shown in Fig. 34. The evolution of these channels with respect to the pump power of the erbium amplification is shown in Fig. 35.

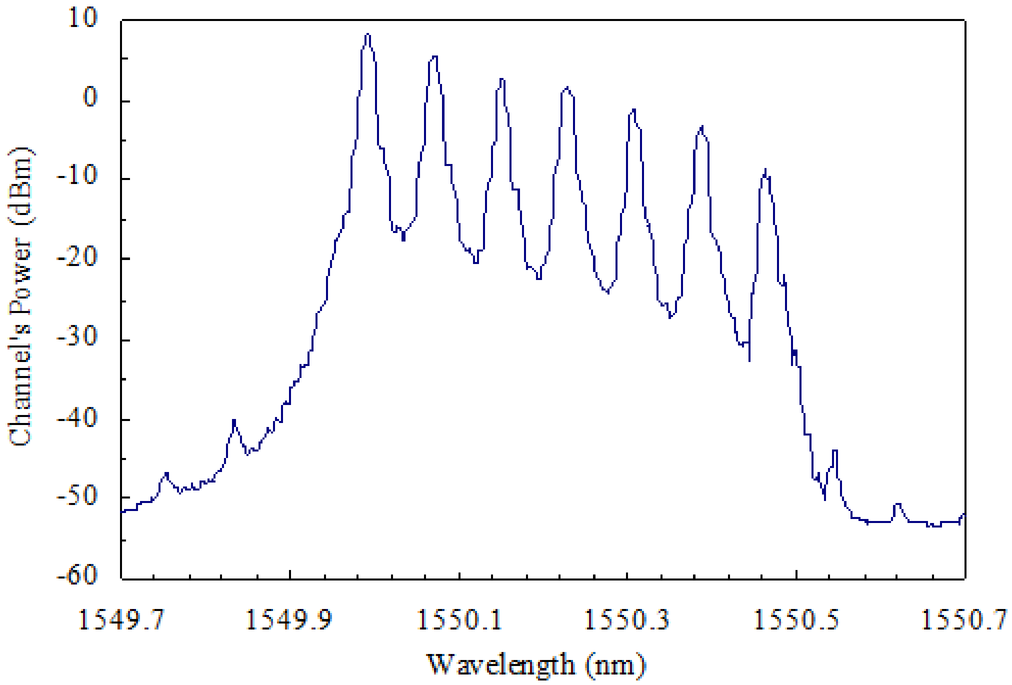


Fig. 34: *Output Spectrum of the enhanced MWBEFL at maximum PP and BP power of 130 mW and 2 mW respectively* [86]

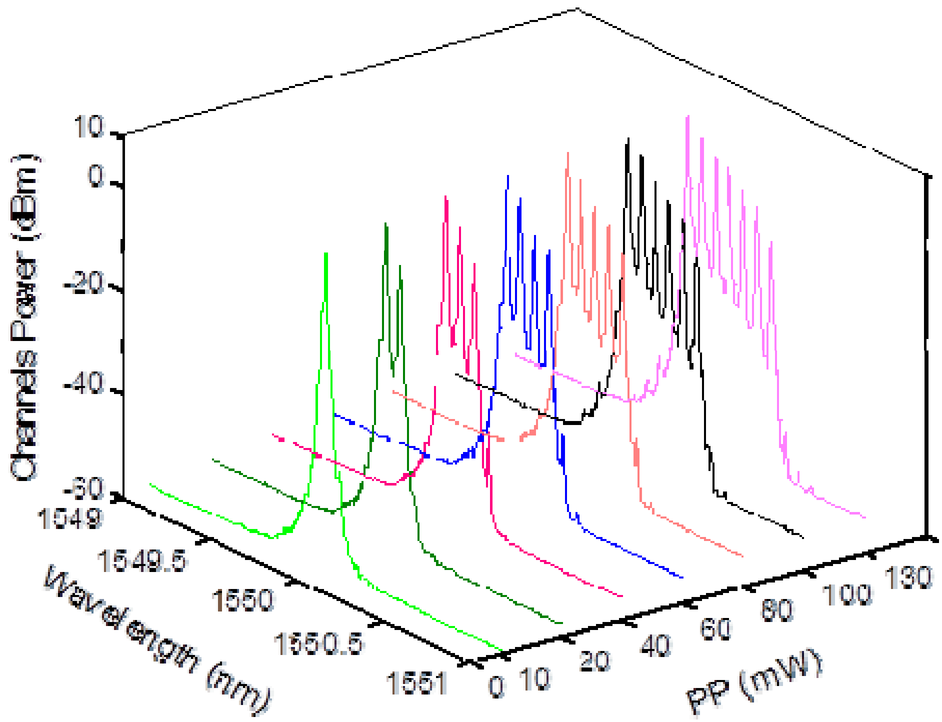


Fig. 35: *Evolution of generated channels at BP power of 2 mW and different values of PP*

We compared the performance of the demonstrated MWBEFL with some prior published work on the same subject. We introduced Figure of merit, defined as the product of the main issues in MWBEFL (number of channels, highest channel power and tuning range) so as to form a basis for comparison with the prior reported works. The result of which is presented in Table 2:

Table 2: *Performance evaluations of the demonstrated MWBEFL*

Reference	No. of Channels	Highest Channel Power (mW)	Tuning Range (nm)	Figure of Merit (mW.nm)
Cowle et al, IEEE *JLWT* vol. 15, pp 1198, 1997.	1	0.1	4.5	**0.45**
Sinivasagam et al, *Elect. Lett.* vol. 34, pp 1751, 1998.	1	8.85	7	**61.95**
Song, et al IEEE *PTL*, vol. 16, pp. 2015, 2004.	12	0.003	14.5	**0.52**
Al-Mansoori, et al OSA *OE*, vol. 13, pp. 3471, 2005.	6	0.044	25.7	**6.78**
Samsuri, el al, OSA *OE*, vol. 16, pp. 16475, 2008	9	3.63	5	**163.35**
Nasir et al, OSA *OE*, vol. 17, pp 12830, 2009	14	0.79	29	**320.74**
Ajiya et al, OSA *OE*, vol.17, pp 5944, 2009	4	7.11	39	**1109.16**
Ajiya et al, ELSAVIER OC, vol.282, pp 4266, 2009 (Uni-directional amplification)	6	0.93	46.8	**261.14**
Ajiya et al, ELSAVIER *OC*, vol.282, pp 4266, 2009 (Bi-directional amplification)	13	1.04	23	**310.96**
Ajiya et al, OSA *JOSA B*, vol.26, pp 1789, 2009	7	6.59	35	**1614.55**

Further Studies on MWBEFL

The spacing between channels in silica-based optical MWBEFL is inherently 10 GHz (0.08 nm) because of the Doppler effects [40]. However practical contribution of MBEFL in a practical optical communication system implementation is limited due to the difficulty of channel multiplexing from the narrow (10 GHz) spacing. Therefore attempts have been made to increase the spacing between channels so that multiplexing and de-multiplexing can be achieved with ease in MBEFL. We demonstrated MWBEFL where the spacing between channels can seamlessly be achieved by changing the values of interferometer delay inserted within the laser cavity. When the time delay of the interferometer was set at 0.1 ns, spacing between channels stood at the usual 0.08 nm. When the time delay was adjusted to 0.01 ns, the spacing between the generated channels stood at 0.8 nm as depicted on Figure 36. The demonstrated laser mitigated the problem associated with fixed channel spaced laser structures. The results of this study were presented in the 5th International Conference on Advances in Engineering and Technology (ICAET 2016) that was held at New Jersey, USA in June 2016 [87]. This paper was also among the best and with our permission, it was upgraded and published in an international journal [88].

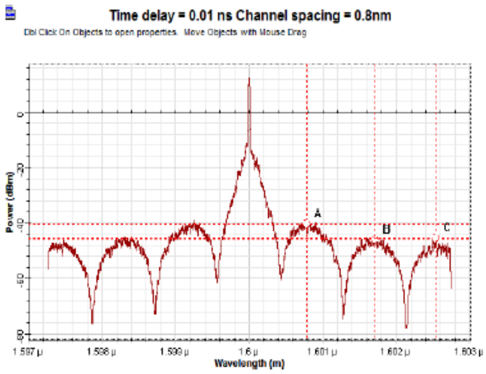


Fig. 36 (a)

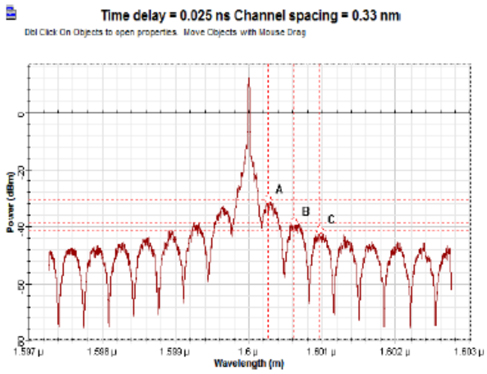


Fig. 36 (b)

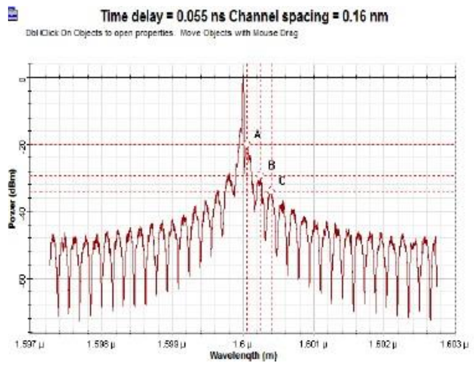


Fig. 36 (c)

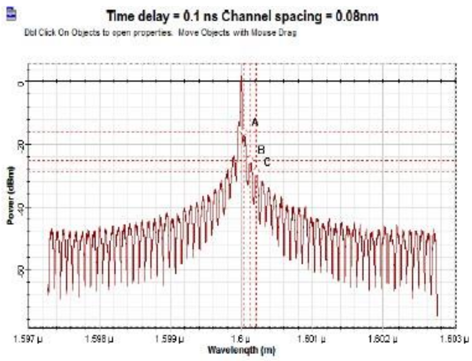


Fig. 36 (d)

Fig. 36: *Output spectrum of wavelength Channel spacing and number of output channel generated at different Time Delay of Interferometer Filter* [88].

In our quest to overcome the difficulty associated with channel multiplexing and de-multiplexing from the narrow single frequency (0.08 nm, approximately 10 GHz spaced) that limits its contribution in achieving practical system implementation, we investigated and demonstrated double frequency shifted lasers (lasers that are spaced by 0.16nm, approximately 20GHz) [89-93].

In an effort to increase the capacity utilization in the optical communication systems, researchers considered the Long wavelength band (L-band) transmission window as an extension of the Conventional band (C-band) window. However, the efficiency of the erbium amplification in the L-band region is very low, thereby giving rise to high lasing threshold in MWBEFL. We studied and reported several aspects of L-band based multiple wavelength lasers [94-97].

Conclusion

The advent of the Internet coupled with advances in technology have transformed the way human beings communicate not only with each other, but with the world around us. Emerging communication technologies nowadays allows machines to use network resources to communicate and share information without the need for human interaction for the purposes of monitoring and control, either of the “machine” itself, or the surrounding environment. This technology known as machine-to-machine (or simply M2M) communications describes the interaction of billions of devices and machines that are connected to the Internet and also to each other. These physical objects integrate computing capabilities that enable them to capture data about the environment around them and share this data with other connected devices, creating an intelligent network of ‘things’ or systems. M2M evolves into the Internet of things, or IoT. The potential interconnection of smart objects and the way we interact with the environment is what the IoT is envisioned to be. The emerging communication technologies continue to push for the need for more communication capacity, both in terms of data rates and global coverage. This translates to the requirement for more bandwidth.

Optical communication systems provide enormous bandwidth, and the optical fibre is the only medium that can meet the modern society's needs for transporting massive amounts of data over long distances. Applications of the optical communications range from global high capacity networks, which constitute the backbone of the internet, the M2M and the IoT to the massively parallel interconnects that provide data connectivity inside data centres and supercomputers.

The race to Petabits per second (10^{15} – quadrillion bits per second) transmission system is very much around us. Researches are actively being pursued to gain this noble achievement. This target is in line with the anticipated unprecedented growth in demand for more bandwidth to support more transparent networks in the very near future. The potential for research in optical communication is immense. Possible targets are in wideband amplifiers with improved gain, better signal quality and flatter gain spectrum. Another research area is in multiple wavelength lasers with high output powers and whose operating wavelength could freely be tunable. Wideband amplifiers and tunable multi-wavelength lasers are two research flavours that formed the bedrock to support ultra-high bit rate transmission systems.

Optical communications is a diverse and rapidly changing field, where experts in photonics, communications, electronics, and signal processing work side by side to meet the ever-increasing demands for higher capacity, lower cost, and lower energy consumption, while adapting the system design to novel services and technologies. It is heartening to note that our local researches here in BUK are contributing to the global body of knowledge in this field with our finding being published in high impact factor journals.

Today, the dynamic worldwide communications revolution continues. Researchers have proven that optical fibre can carry several billions of bits per second. As long as scientists and engineers worldwide continue to invent the technology to send information at a low cost per bit, creative people will find a reason to send proportionally more bits into the optical fibre. In this scenario, it is safe to say that optical communication will continue to provide *seamless global connectivity at the speed of light*.

ACKNOWLEDGEMENTS

MacArthur Foundation

UPM
UNIVERSITI PUTRA MALAYSIA
BERILMU BERBAKTI




























References

[1] Google, "Nigeria Distance," in *http://nigeria.distanceworld.com/distance/1300937-1301061*. vol. 2017, 2017.

[2] "The fastest car ever made: Koenigsegg reaches 284.5MPH in record-breaking run on dead straight Nevada road," in *http://www.dailymail.co.uk/news/article-5054365/Koenigsegg-Agera-RS-world-s-fastest-car.html* London: Dailymail, 2017.

[3] I. Kaminow, T. Li, and A. E. Willner, *Optical fibre telecommunications VB: systems and networks*. San Diego, California, USA: Elsevier, 2010.

[4] H. Barlow and A. Karbowiak, "An investigation of the characteristics of cylindrical surface waves," *Proceedings of the IEE-Part III: Radio and Communication Engineering*, vol. 100, pp. 321-328, 1953.

[5] G. Goubau and F. Schwering, "On the guided propagation of electromagnetic wave beams," *IRE Transactions on Antennas and Propagation*, vol. 9, pp. 248-256, 1961.

[6] C. Eaglesfield, "Optical pipeline: a tentative assessment," *Proceedings of the IEE-Part B: Electronic and Communication Engineering*, vol. 109, pp. 26-32, 1962.

[7] D. Berreman and A. Hutson, "Gas lenses show promise for long distance laser communication," *Bell Lab. Rec*, vol. 42, p. 294, 1964.

[8] W. K. Pratt, *Laser Communication Systems*. Hoboken, New Jersey: Wiley, 1969.

[9] S. E. Miller, "Communication by laser," *Scientific American*, vol. 214, pp. 19-27, 1966.

[10] J. Hecht, *City of light: the story of fibre optics*. New York: Oxford University Press, 2004.

[11] K. C. Kao and G. A. Hockham, "Dielectric-fibre surface waveguide for optical frequencies," in *Proc. Inst. Elect. Eng*, New York, 1966, pp. 1151-1158.

[12] "https://www.nobelprize.org/nobel_prizes/physics/laureates/2009/."

[13] F. Kapron, D. Keck, and R. Maurer, "Radiation losses in glass optical waveguides," *Applied Physics Letters*, vol. 17, pp. 423-425, 1970.

[14] J. B. MacChesney and P. B. O'connor, "Optical fibre fabrication and resulting production," US Patents, 1977.

[15] T. Miya, Y. Terunuma, T. Hosaka, and T. Miyashita, "Ultimate low-loss single-mode fibre at 1.55 µm," *Electronics Letters*, vol. 15, pp. 106-108, 1979.

[16] G. P. Agrawal, *fibre-Optic Communication Systems*, Third ed. New York: John Wiley & Sons, Inc., 2002.

[17] G. P. Agrawal, *fibre - Optic Communication Systems*, 4th ed. Hoboken, New Jessy: John Wiley & Sons, 2010.
[18] G. P. Agrawal, "Optical Communication: Its History and Recent Progress," in *Optics in Our Time*, M. D. Al-Amri, M. M. El-Gomati, and M. S. Zubairy, Eds. Gewerbestrasses, Switzerland: Springer International Publishing AG, 2016, pp. 177 - 199.
[19] M. A. Mahdi, "Optical Transmission Systems and Network," UPM, 2002.
[20] K. Thyagarajan and A. Ghatak, *fibre optic Essentials*. Hoboken, New Jersey.: John Wiley & Sons, Inc., 2007.
[21] G. P. Agrawal, *Nonlinear fibre Optics*, Third ed. New York: Academic Press, 2001.
[22] M. D. Al-Amri, M. El-Gomati, and M. S. Zubairy, *Optics in Our Time*. Gewerbestrasse, Switzerland: Springer International Publishing AG, 2016.
[23] R. J. Mears, L. Reekie, I. Jauncey, and D. N. Payne, "Low-noise erbium-doped fibre amplifier operating at 1.54 µm," *Electronics Letters,* vol. 23, pp. 1026-1028, 1987.
[24] C. J. Koester and E. Snitzer, "Amplification in a fibre laser," *Applied Optics,* vol. 3, pp. 1182-1186, 1964.
[25] C. Millar, I. Miller, B. Ainslie, S. Craig, and J. Armitage, "Low-threshold CW operation of an erbium-doped fibre laser pumped at 807 nm wavelength," *Electronics Letters,* vol. 23, pp. 865-866, 1987.
[26] E. Desurvire, "Analysis of transient gain saturation and recovery in erbium-doped fibre amplifiers," *IEEE Photonics Technology Letters,* vol. 1, pp. 196-199, 1989.
[27] C. R. Giles and E. Desurvire, "Modeling erbium-doped fibre amplifiers," *journal of lightwave technology,* vol. 9, pp. 271-283, 1991.
[28] M. Mahdi, F. M. Adikan, P. Poopalan, S. Selvakennedy, and H. Ahmad, "A novel design of bi-directional silica-based erbium-doped fibre amplifier for broadband WDM transmissions," *Optics Communications,* vol. 187, pp. 389-394, 2001.
[29] Y. Wang, L. Li, and L. Zhao, "Chirped pulse amplification in an all-normal-dispersion erbium-doped fibre amplifier," *Laser Physics,* vol. 27, p. 035102 (5pp), 2017.
[30] J.-B. Trinel, G. Le Cocq, E. R. Andresen, Y. Quiquempois, and L. Bigot, "Latest results and future perspectives on Few-Mode Erbium Doped fibre Amplifiers," *Optical fibre Technology,* vol. 35, pp. 56-63, 2017.
[31] M. Wada, T. Sakamoto, T. Yamamoto, S. Aozasa, S. Nozoe, Y. Sagae, K. Tsujikawa, and K. Nakajima, "Cladding Pumped Randomly Coupled 12-Core

Erbium-Doped fibre Amplifier With Low Mode-Dependent Gain," *journal of lightwave technology,* vol. 36, pp. 1220-1225, 2018.
[32] T. Jose and V. Narayanan, "Effect of gain contouring in erbium-doped fibre amplifiers on bit error rate performance of wavelength-division multiplexing-based radio over fibre links," *Optical Engineering,* vol. 57, p. 036107 (7pp), 2018.
[33] H. I. Khaleel, "Performance Analysis of Erbium Doped fibre Amplifiers at 980 nm and 1480 nm pumping Wavelengths," in *Electrical Engineering*: Bayero University, Kano, 2018.
[34] M. Yamada, A. Mori, K. Kobayashi, H. Ono, T. Kanamori, K. Oikawa, Y. Nishida, and Y. Ohishi, "Gain-flattened tellurite-based EDFA with a flat amplification bandwidth of 76 nm," *IEEE Photonics Technology Letters,* vol. 10, pp. 1244-1246, 1998.
[35] S. Ohara, N. Sugimoto, K. Ochiai, H. Hayashi, Y. Fukasawa, T. Hirose, T. Nagashima, and M. Reyes, "Ultra-wideband amplifiers based on Bi2O3-EDFAs," *Optical fibre Technology,* vol. 10, pp. 283-295, 2004.
[36] L. Saito, P. Taveira, P. Gaarde, K. De Souza, and E. De Souza, "Multi-pump discrete Raman amplifier for CWDM system in the O-band," *Optical fibre Technology,* vol. 14, pp. 294-298, 2008.
[37] M. G. Mustapha, **M. Ajiya**, and D. S. Shuaibu, "Uncluttered Gain Roll Out In Erbium Doped fibre Amplifier," in *International Conference on Research in Science, Engineering and Technology,* Kuala Lumpur, 2013, pp. 5 - 8.
[38] M. G. Mustapha, **M. Ajiya**, and D. S. Shuaibu, "Uncluttered Gain Roll Out In Erbium Doped fibre Amplifier," *International Journal of Computing, Communications & Instrumentation Engineering,* vol. 1, pp. 64 - 67, 2014.
[39] R. W. Boyd, *Nonlinear Optics*, 2 ed. New York: Academic press, 2003.
[40] G. S. He and S. H. Liu, *Physics of Nonlinear Optics*. Singapore: World Scientific, 1999.
[41] D. Cotter, "Observation of stimulated Brillouin scattering in low-loss silica fibre at 1.3*u*m," *Electronics Letters,* vol. 18, pp. 495-496, 1982.
[42] R. Y. Chiao, C. H. Townes, and B. P. Stoicheff, "Stimulated Brillouin scattering and coherent generation of intense hypersonic waves," *Physical Review Letters,* vol. 12, pp. 592-595, 1964.
[43] E. Garmire and C. H. Townes, "Stimulated Brillouin scattering in liquids," *Applied Physics Letters,* vol. 5, p. 84, 1964.
[44] C. L. Tang, "Saturation and spectral characteristics of the Stokes emission in the stimulated Brillouin process," *Journal of Applied Physics,* vol. 37, p. 2945, 1966.

[45] R. G. Smith, "Optical power handling capacity of low loss optical fibres as determined by stimulated Raman and Brillouin scattering," *Applied Optics,* vol. 11, pp. 2489-2494, 1972.

[46] R. G. Harrison, J. S. Uppal, A. Johnstone, and J. V. Moloney, "Evidence of chaotic stimulated Brillouin scattering in optical fibres," *Physical review letters,* vol. 65, pp. 167-170, 1990.

[47] A. L. Gaeta and R. W. Boyd, "Stochastic dynamics of stimulated Brillouin scattering in an optical fibre," *Physical Review A,* vol. 44, pp. 3205-3209, 1991.

[48] R. W. Boyd, K. Rza ewski, and P. Narum, "Noise initiation of stimulated Brillouin scattering," *Physical Review A,* vol. 42, pp. 5514-5521, 1990.

[49] N. A. Brilliant, "Stimulated Brillouin scattering in a dual-clad fibre amplifier," *Journal of the Optical Society of America B,* vol. 19, pp. 2551-2557, 2002.

[50] A. A. A. Bakar, M. H. Al-Mansoori, M. A. Mahdi, M. S. Zainal Abidin, and M. A. Mohd Azau, "fibre break location technique utilizing stimulated Brillouin scattering effects in optical fibre," *Laser Physics Letters,* vol. 6, pp. 59 - 63, 2009.

[51] E. P. Ippen and R. H. Stolen, "Stimulated Brillouin scattering in optical fibres," *Applied Physics Letters,* vol. 21, pp. 539-541, 1972.

[52] G. J. Cowie, D. Yu, and Y. T. Chieng, "Brillouin/erbium fibre lasers," *Lightwave Technology, Journal of,* vol. 15, pp. 1198-1204, 1997.

[53] A. R. Chraplyvy, "Limitations on lightwave communications imposed by optical-fibrenonlinearities," *Lightwave Technology, Journal of,* vol. 8, pp. 1548-1557, 1990.

[54] T. C. Rich and D. A. Pinnow, "Evaluation of fibre optical waveguides using Brillouin spectroscopy," *Applied Optics,* vol. 13, pp. 1376-1378, 1974.

[55] M. Ohashi, N. Shibata, K. Shirakai, N. Center, and J. Ibaraki, "Fibre diameter estimation based on guided acoustic wave Brillouin scattering," *Electronics Letters,* vol. 28, pp. 900-902, 1992.

[56] M. F. Ferreira, J. F. Rocha, and J. L. Pinto, "Analysis of the gain and noise characteristics of fibre Brillouin amplifiers," *Optical and Quantum Electronics,* vol. 26, pp. 35-44, 1994.

[57] K. O. Hill, D. C. Johnson, and B. S. Kawasaki, "Cw generation of multiple Stokes and anti-Stokes Brillouin-shifted frequencies," *Applied Physics Letters,* vol. 29, p. 185, 1976.

[58] D. Culverhouse, K. Kalli, and D. A. Jackson, "Stimulated Brillouin scattering ring resonator laser for SBS gain studies and microwave generation," *Electronics Letters,* vol. 27, pp. 2033-2035, 1991.

[59] M. Tateda, T. Horiguchi, T. Kurashima, and K. Ishihara, "First measurement of strain distribution along field-installedoptical fibres using Brillouin spectroscopy," *Lightwave Technology, Journal of,* vol. 8, pp. 1269-1272, 1990.

[60] T. Kurashima, T. Horiguchi, and M. Tateda, "Distributed-temperature sensing using stimulated Brillouin scattering in optical silica fibres," *Optics Letters,* vol. 15, pp. 1038-1040, 1990.

[61] L. F. Stokes, M. Chodorow, and H. J. Shaw, "All-fibre stimulated Brillouin ring laser with submilliwatt pump threshold," *Optics Letters,* vol. 7, pp. 509-511, 1982.

[62] S. P. Smith, F. Zarinetchi, and S. Ezekiel, "Narrow-linewidth stimulated Brillouin fibre laser and applications," *Optics Letters,* vol. 16, pp. 393-395, 1991.

[63] J. C. Yong, L. Thévenaz, and B. Y. Kim, "Brillouin fibre laser pumped by a DFB laser diode," *Journal of Lightwave Technology,* vol. 21, p. 546, 2003.

[64] H. J. R. Dutton, *Understanding Optical communications*. New Jersey: Prentice-Hall, Inc., 1998.

[65] J. Boschung, L. Thevenaz, and P. A. Robert, "High-accuracy measurement of the linewidth of a Brillouin fibre ring laser," *Electronics Letters,* vol. 30, pp. 1488-1489, 1994.

[66] K. Kalli and D. A. Jackson, "Investigation and applications of all-fibre brillouin ring resonator lasers," *fibre and Integrated Optics,* vol. 14, pp. 303-330, 1995.

[67] G. J. Cowle and D. Y. Stepanov, "Hybrid Brillouin/erbium fibre laser," *Optics Letters,* vol. 21, pp. 1250-1252, 1996.

[68] G. J. Cowle, D. Yu, and Y. T. Chieng, "Brillouin/erbium fibre lasers," *Lightwave Technology, Journal of,* vol. 15, pp. 1198-1204, 1997.

[69] G. Levesque and V. Oliver, *Guide to WDM Technology and Testing*. Canada: Electro-optical Engineering Inc., 2000.

[70] F. Zarinetchi, S. P. Smith, and S. Ezekiel, "Stimulated Brillouin fibre-optic laser gyroscope," *Optics Letters,* vol. 16, pp. 229-231, 1991.

[71] A. Kung, P. A. Nicati, and P. A. Robert, "Reciprocal and quasi-reciprocal Brillouin fibre-optic current sensors," *IEEE Photonics Technology Letters,* vol. 8, pp. 1680-1682, 1996.

[72] T. Schneider, M. Junker, and D. Hannover, "Generation of millimetre-wave signals by stimulated Brillouin scattering for radio over fibre systems," *Electronics Letters,* vol. 40, pp. 1500-1502, 2004.

[73] Y. Shen, X. Zhang, and K. Chen, "All-optical generation of microwave and millimeter wave using a two-frequency Bragg grating-based Brillouin fibre laser," *Journal of Lightwave Technology,* vol. 23, p. 1860, 2005.

[74] G. J. Cowle and D. Y. Stepanov, "Multiple wavelength generation with Brillouin/erbium fibre lasers," *IEEE Photonics Technology Letters,* vol. 8, pp. 1465-1467, 1996.

[75] E. Desurvire, D. Bayart, B. Desthieux, and S. Bigo, *Erbium-Doped fibre Amplifiers: Device and System Developments*. New York: John Wiley and sons, Inc., 2002.

[76] **M. Ajiya**, M. A. Mahdi, M. H. Al-Mansoori, M. Mokhtar, and S. Hitam, "Directivity influence of signals propagation through EDFA gain medium of Brillouin–erbium fibre laser," *Optics Communications,* vol. 282, pp. 4266 - 4270, 2009.

[77] Y. J. Song, L. Zhan, S. Hu, Q. H. Ye, and Y. X. Xia, "Tunable multiwavelength Brillouin-erbium fibre laser with a polarization-maintaining fibre Sagnac loop filter," *IEEE Photonics Technology Letters,* vol. 16, pp. 2015-2017, 2004.

[78] M. H. Al-Mansoori and M. A. Mahdi, "Tunable range enhancement of Brillouin-erbium fibre laser utilizing Brillouin pump preamplification technique," *Optics Express,* vol. 16, pp. 7649-7654, 2008.

[79] N. M. Samsuri, A. K. Zamzuri, M. H. Al-Mansoori, A. Ahmad, and M. A. Mahdi, "Brillouin-Erbium fibre laser with enhanced feedback coupling using common Erbium gain section," *Optics Express,* vol. 16, pp. 16475-16480, 2008.

[80] **M. Ajiya**, M. A. Mahdi, M. H. Al-Mansoori, S. Hitam, and M. Mokhtar, "Seamless Tuning Range based-on Available Gain Bandwidth in Multiwavelength Brillouin fibre Laser " *Optics Express,* vol. 17, pp. 5944 - 5952, 2009.

[81] K. Inoue, "Brillouin threshold in an optical fibre with bidirectional pump lights," *Optics Communications,* vol. 120, pp. 34-38, 1995.

[82] H. S. Kim, S. H. Kim, D. K. Ko, G. Lim, B. H. Cha, and J. Lee, "Threshold reduction of stimulated Brillouin scattering by the enhanced Stokes noise initiation," *Applied Physics Letters,* vol. 74, p. 1358, 1999.

[83] C. Hänisch, A. Heuer, and R. Menzel, "Threshold reduction of stimulated Brillouin scattering (SBS) using fibre loop schemes," *Applied Physics B: Lasers and Optics,* vol. 73, pp. 851-854, 2001.

[84] Y. Zhu, Q. Lu, S. Guo, X. Xu, and X. Cheng, "Threshold reduction of stimulated Brillouin scattering by Stokes seeds via acousto-optic effect," *Optics Communications,* vol. 281, pp. 4523-4525, 2008.

[85] **M. Ajiya**, M. A. Mahdi, M. H. Al-Mansoori, Y. G. Shee, S. Hitam, and M. Mokhtar, "Reduction of stimulated Brillouin scattering threshold through pump recycling technique," *Laser Physics Letters,* vol. 6, pp. 535-538, 2009.

[86] **M. Ajiya**, M. A. Mahdi, M. H. Al-Mansoori, M. Mokhtar, and S. Hitam, "Broadly tunable multiple wavelength Brillouin fibre laser exploiting erbium amplification," *J. Opt. Soc. Am. B,* vol. 26, pp. 1789 - 1794, 2009.

[87] **M. Ajiya**, J. Oladapo, U. Danbatta, and N. A. Hambali, "Seamless Channel Spacing in Multiple Wavelength fibre based Lasers," in *5th International Conference on Advances in Engineering and Technology (ICAET'2016),* New Jersey, USA, 2016, pp. 37 - 41.

[88] **M. Ajiya**, J. Oladapo, U. Danbatta, and N. A. Hambali, "Seamless Channel Spacing in Multiple Wavelength fibre based Lasers," *International Journal of Computing, Communications & Instrumentation Engineering (IJCCIE),* vol. 3, pp. 263 - 266, 2016.

[89] A. Al-Alimi, M. Al-Mansoori, A. Abas, M. Mahdi, F. Adikan, and **M. Ajiya**, "A stabilized tunable dual wavelength erbium-doped fibre laser with equal output power," *Laser Physics*, vol. 19, pp. 1850-1853, 2009.

[90] M. A. Toor, N. A. Hambali, A. Mansoor, **M. Ajiya**, and Z. Yusoff, "Double Brillouin frequency shifted L-band multi-wavelength Brillouin Raman fibre laser utilizing dual laser cavity," *Journal of Optics*, vol. 17, pp. 025502 -1 - 5.

[91] N. A. Hambali, M. Al-Mansoori, **M. Ajiya**, A. A. A. Bakar, S. Hitam, and M. Mahdi, "Multi-wavelength Brillouin-Raman ring-cavity fibre laser with 22-GHz spacing," *Laser Physics,* vol. 21, pp. 1618 - 1624, 2011.

[92] A. Al-Alimi, M. Al-Mansoori, A. Abas, M. Mahdi, and **M. Ajiya**, "Optimization of tunable dual wavelength erbium-doped fibre laser," *Laser Physics Letters,* vol. 6, pp. 727 - 731, 2009.

[93] A. Al-Alimi, M. Al-Mansoori, A. Abas, M. Mahdi, **M. Ajiya**, and F. M. Adikan, "Efficient technique for intracavity loss optimization in a dual-wavelength erbium-doped fibre laser," *Laser Physics,* vol. 20, pp. 2001-2005, 2010.

[94] **M. Ajiya**, J. Oladapo, and N. A. Hambali, "Lasing threshold characteristics of multi-wavelength Brillouin/erbium laser in the L-band region assisted by delay interferometer," *Journal of Nonlinear Optical Physics & Materials,* vol. 25, pp. 1650024-1 - 9, 2016.

[95] N. Ahmad Hambali, M. Ali Toor, Z. Yusoff, and **M. Ajiya**, "L-band multi-wavelength Brillouin/Raman fibre laser utilizing the reverse-S-shaped section," *Journal of Nonlinear Optical Physics & Materials,* vol. 23, pp. 1450026- 1 - 10, 2014.

[96] W. Almusafer, M. Al-Mansoori, M. Jamaludin, F. Abdullah, **M. Ajiya**, and M. Mahdi, "Widely Tunable C+L Bands Multiwavelength BEFL With Double-Brillouin Frequency Shifts," *IEEE Photonics Journal,* vol. 4, pp. 1720-1727, 2012.

[97] **M. Ajiya**, "48 Channels generation in L - Band Brillouin/Erbium fibre Laser," *Nigerian Journal of Engineering,* vol. 18, pp. 47 - 50, 2011.