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Domestic and international development trends of broadband fiber amplifier

Fanxiao Liu[1, 4, †], Xinye Li[2, †] and Haochen Sun[3, †]

[1]School of Information Science and Technology, Fudan University, Shanghai, 200433, China
[2]School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, Hubei, 430074, China
[3]School of Communication Engineering, Shanghai University, Shanghai, 200444, China

[4]20307130166@fudan.edu.cn
†These authors contributed equally.

Abstract. In this era of information explosion, the improvement of communication capacity has become an urgent problem, and the improvement of transmission speed and the reduction of channel spacing are near the limit, so widening the available bandwidth of fiber optic transmission is the most feasible method. The research progress of fiber optic amplifiers is analyzed, and the outlook is presented. Researchers are working to find breakthroughs in C++ band, L++ band, and C+L band, starting with amplifier's materials, structures, and designs. The EDFA targeted C++ and L++ band have been widely studying these years while different types of amplifiers have been invented to simultaneously work on C+L band. Also, as quantum dot is introduced to design innovated fiber amplifier, more new amplifiers need to be invented to achieve better amplification. This paper presents the recent research results of the above-mentioned research directions, and the next goal of researchers is to stabilize all these amplifiers' gain flatness and production implement ability.

Keywords: amplifier, gain, bandwidth, erbium-doped fiber.

1. Introduction

In today's information society, people's demand for communication capacity is increasing day by day, and driven by user demand and social demand, modern fiber optic communication is constantly pursuing for high speed, big capacity and long distance, and the development of broadband fiber amplifiers to broaden the bandwidth is an effective way to expand the capacity of optical communication. In the dense optical wave multiplexing (DWDM) system, the development of broadband fiber amplifiers focus on erbium-doped fiber amplifier (EDFA, Erbium-Doped Fiber Amplifier) [1] and fiber Raman amplifier (FRA, Fiber Raman Amplifier), in recent years, there has been a continuous emergence of new fiber amplifiers, such as bismuth-doped fiber amplifier[2], ytterbium-erbium co-doped fiber amplifier[3], etc., are emerging in recent years.

The low-loss transmission bandwidth of quartz optical fiber can range from 1260 to 1675 nm, with a total of 415 nm. This 415 nm width is generally divided into six bands: O, E, S, C, L, and U. At present, fiber optic communication mainly uses C and L bands, and only a small part of them is used. From the single-fiber capacity = spectral efficiency * spectral bandwidth, the methods to improve capacity can be divided into improving spectral efficiency and broadening the spectral bandwidth. Among them, the spectral efficiency can be achieved by using higher-order spectral shaping scheme or more multi-dimensional multiplexing means, but continuously improve the spectral efficiency will put higher requirements on the signal-to-noise ratio to the receiver, and the research encountered a bottleneck, so the spectrum bandwidth to expand the capacity, comprehensive consideration, by expanding the gain bandwidth of the fiber amplifier to achieve the expansion of transmission capacity is the current fiber optic communication system upgrade The best solution for upgrading fiber optic communication system is to expand the gain bandwidth of fiber optic amplifier.

2. The erbium-doped fiber amplifier (EDFA) for the extended C-band

The Erbium-doped fiber amplifier (EDFA) for the extended C-band is an optical amplifier used to amplify optical signals in the C-band (1530-1565nm) [1]. Its structure mainly consists of Erbium-doped fiber, optical pumping source, optical coupler, and optical signal input/output ports. The working principle of the amplifier is to inject high-power pump light into the Erbium-doped fiber to excite the Erbium ions by stimulated emission, thus achieving amplification of the optical signal.

2.1. Advantages

2.1.1. Higher gain. Compared to other amplifiers, the EDFA for the extended C-band has a higher gain, typically above 10 dB.

2.1.2. Wider bandwidth. The C-band has a larger bandwidth than other bands in optical fiber communication systems, enabling the EDFA for the extended C-band to be used for higher data transmission rates.

2.1.3. Low noise. The noise coefficient of the EDFA for the extended C-band is usually below 5dB, thus improving the signal-to-noise ratio.

2.1.4. Higher reliability. The Erbium-doped fiber is a stable material that provides high-performance reliability.

2.2. Disadvantages

2.2.1. High-power pump light source required. To achieve high gain, the EDFA for the extended C-band requires a high-power pump light source.

2.2.2. Precision optical coupler. High-precision optical couplers are needed to achieve efficient coupling of pump light and optical signals.

2.2.3. Strict temperature and environmental control. Due to the characteristics of optical fibers, the EDFA for the extended C-band requires strict temperature and environmental control to ensure stable performance.

In summary, the EDFA for the extended C-band has the advantages of high gain, low noise, wide bandwidth, and high reliability, but requires a high-power pump light source, precision optical coupler, and strict temperature and environmental control. This amplifier is widely used in long-distance optical fiber communication systems, laser radar, fiber optic sensing, and other fields.

3. The erbium-doped fiber amplifier (EDFA) for the extended L-band

The L-band erbium-doped fiber amplifier (EDFA) is typically pumped with a pump light source. The pump light source usually utilizes a semiconductor laser of either 980nm or 1480nm to deliver energy to the erbium elements within the doped fiber [4]. Within the EDFA, erbium elements absorb the energy from the pump light source, are excited to a high energy state, and are then excited by the external optical field to transition back to a low energy state, emitting energy and generating photons in phase with the input signal, thereby amplifying it.

The L-band EDFA has broad applications in optical communication, including signal amplification, wavelength division multiplexing, and distributed fiber sensing [5].

Compared with traditional optical amplifiers, the L-band EDFA has a wider bandwidth and higher gain, enabling higher data transmission rates and transmission distances [6]. Additionally, since the L-band is in a low-loss window, it is more suitable for long-distance transmission applications. Moreover, the L-band EDFA has good stability and reliability, meeting the demand for highly reliable communication [7].

However, the L-band EDFA also has limitations. First, it has a higher manufacturing cost due to the use of special materials and processes. Second, as the gain bandwidth of the L-band EDFA is wide, it is sensitive to the wavelength and power of the input signal, requiring more precise control and management. Additionally, fiber itself exhibits dispersion and nonlinear effects, which may impact signal transmission quality, necessitating compensation and optimization measures.

4. The fiber amplifier for the C+L-band

As figure 1 shows, compared with the traditional C-band and L-band, C+L-band can realize 192 wavelengths, with a spectral bandwidth close to 9.6THz and nearly 1 times higher transmission capacity. However, for existing fiber-optic amplifiers, there is no type which can operate simultaneously in the C+L band. To manage the problem, the researchers have proposed a variety of solutions, such as attempting new fiber materials, inserting gain equalizers and circulators, introducing a parallel-type fiber amplifier using the single-wavelength pump laser of a particular band, inventing erbium-doped fibers combined the dual-core of both C band and L band, employing bundled Er^{3+}-doped fiber (EDF) [8-12].

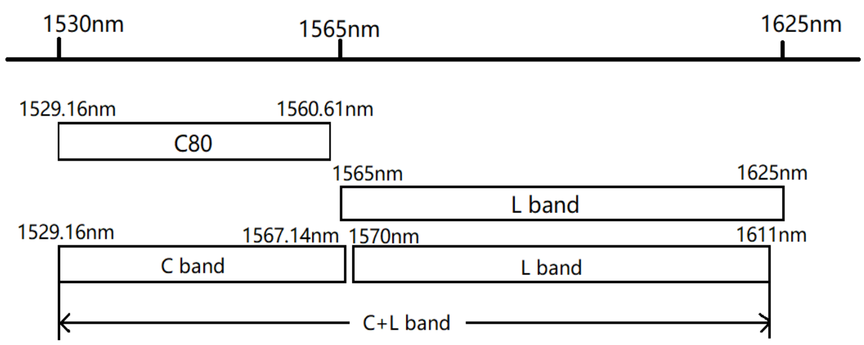

Figure 1. Schematic diagram of C+L-band.

Many researchers hope to achieve better results by improving the structure of the amplifier. In 2004, a new gain-flattened ultra-wideband amplifier structure is proposed and demonstrated, which consists of a combination of two C-band and L-band dual-core erbium-doped fibers with a flat gain of 15 dB in the 105 nm wavelength range from 1515 nm to 1620 nm [11]. The NF varies from 4.5 dB to 4.8 dB over the whole bandwidth. However, the fibers used in the experiment are shorter, the entire gain is appearently subtle, which means in the reality needed longer fiber, there is difficulty to make this measure practical. In 2008, Liaw, Huang and Hsiao introduced a parallel-typed amplifier, dispersion compensating C+L band amplifiers constructed by sharing common laser diodes at 1480 nm. With this type of amplifier, under an input signal of -20 dBm, the gain spectra is more flattened for a gain improvement of 0.4 dB in L-band pump reflector, while NF value ranges from 4.6 dB to 6.5 dB which has less than 0.14 dB polarization dependent gain. The NF is clearly even higher than the above one. In 2012, Makoto YAMADA, Masaharu UNO and Hirotaka ONO proposed a fiber amplifier with a parallel configuration assembled with bundled EDF, but there's no real test to prove it successfully. In 2014, Hai-Yin Hsu, Yi-Lin Yu, Shien-Kuei Liaw, et al. made up for the deficiency of long-distance fiber transmission [13]. They proposed and demonstrated a bridge scheme for a 100 km hybrid C+L-band fiber amplifier that can reduce the gain variation between multiple channels to ±0.2 dB, but nothing mentioned about NF improvement. In 2017, Hang Dong Zhang and Li Zhan proposed a low noise figure C+L-band EDFA with a pre-amplifier to reduce the NF and a fiber brag grating to increase the L-band gain [14]. The experimental results showed the NF reduced about 2 dB and the gain increase to more than 25 dB among the wavelength range of 1525 nm to 1605 nm. In 2021, F. Da Ros and his team applied a ML framework for the optimization of a C+L HA based on EDFAs, and a 12-pump DRA and the gain ripples are decreased from 6.7 dB to 1.9 dB. More researchers need to be done to find a measure for both synthesizing gain and NF [15].

In addition to improving gain, gain flatness and NF, some researchers have also worked to compensate for the dispersion of amplifiers. Hai-Yin Hsu's group designed their fiber amplifier with the characteristics of double-passed dispersion compensator, which optimally compensated all C+L-band channels' chromatic dispersion. This process is usually generated while solving the gain problem.

5. Quantum dot doped fiber amplifier

In the last two years, the gain index of traditional rare earth ion doped fiber amplifiers has been nearly saturated due to the particle energy level structure, fluorescence lifetime and other parameters with certain limitations, so in the face of the increasing pressure of communication, there is the emergence of quantum dot doped fiber amplifiers. Quantum dots, i.e. artificial nanocrystals, are prepared mainly by physical and chemical methods, and because the materials used to make these quantum dots can be artificially controlled, it has certain properties that ordinary rare-earth ions do not have, and because the energy level structure of these quantum dots is non-simple, thus the ability to directly compound radiation fluorescence is stronger, and as the particle size of quantum dots changes, the radiation wavelength changes accordingly, greatly enhancing the available wavelength bandwidth is greatly enhanced [16].

Currently, the following quantum dot doped fiber amplifiers have been realized in the laboratory, one is based on the fusion cone fiber coupled structure of quantum dot fiber amplifier, the technology uses macromolecular polymers to modify the surface groups of PbS quantum dots, the modified PbS quantum dots are coated on the outer surface of the dual single-mode fiber fusion cone coupled structure, and the transient wave excitation quantum dots to generate PL, so as to achieve the signal light The second is a liquid or liquid solid state fiber. The second is a quantum dot fiber amplifier with liquid or liquid solidified core, using UV adhesive as the core substrate, mixing PbSe or PbS colloidal quantum dots and pumping them into the hollow core fiber to form a quantum dot fiber. Third, the glass core substrate of quantum dot fiber amplifier, from the technical performance indicators, stability, maturity and compatibility with the current fiber industry technology, the glass substrate of quantum dot fiber amplifier is the most promising. By high temperature melting method, soda boron aluminosilicate glass is prepared at 1400°C environment, the glass is drawn, the glass filaments are annealed for several hours, and quantum dots are grown-crystallized during the annealing process to prepare into quantum dot optical fiber.

Quantum dot fiber amplifier has a wide bandwidth, low noise and other advantages, in addition to the use of gain medium quantum dots themselves have strong fluorescent radiation, the key is that quantum dots can be manually manipulated, by controlling the particle size and particle size distribution of quantum dots can move and expand the working wavelength region; by controlling the heat treatment conditions can change the particle number density and particle number distribution, so as to reach the excitation threshold and not soon saturated And so on. At present, the quantum dot fiber amplifier has been realized in the laboratory, but has not yet entered industrial production, and it is hoped that it can be realized as soon as possible soon to solve the pressure of large communication [17].

6. Discussion

The EDFAs of C++ band and L++ band, the amplifiers of C+L band and the quantum doped amplifier are all still in the stage of development and research refinement, and understanding their strengths and weaknesses showed in Table 1 is more helpful for targeted research to improve.

Table 1. A table comparing four different pointing amplifiers with their advantages and disadvantages.

	C++ (EDFA)	L++ (EDFA)	C+L	Quantum doped
Advantages	High gain, low noise, wide bandwidth, high reliability	High gain, wide bandwidth, suitable for long-distance transmission, good stability	Wide bandwidth, high gain, high gain flatness	Wide bandwidth, low noise, control of working wavelength region
Disadvantages	Require for a high-power pump light source, precise optical coupler, and strict temperature and environmental control	Higher manufacturing cost, sensitiveness to the wavelength and power of the input signal, exist of dispersion and nonlinear effects	Dispersion among the channels, the requirement of working both on the two bands	Difficulty in manufacturing

7. Conclusion

Based on the above analysis of the emerging optical fiber amplifier, we can find that the current research progress of the optical fiber amplifier still has limitations, one is that in the actual fiber preparation process, due to the material problem will lead to some parameters can not fully achieve the expected simulation effect, which will lead to the actual optical fiber amplifier gain effect is not as expected; second, due to the use of certain technologies Second, the use of certain technologies is still not mature enough, which can lead to the improvement of a certain performance of the amplifier (such as gain bandwidth), affecting other performance indicators (such as noise, etc.), thus losing both. Therefore, the expansion of the gain bandwidth of fiber optic amplifier to enhance the transmission capacity is still the most direct and ideal solution for upgrading fiber optic communication system. Among them, how to expand from C-band, L-band to C++, L++, and even C+L band, as well as quantum dot doped fiber amplifier although there are related research and process development at home and abroad, but still in a rising stage, so how to maximize the gain of these bands, and continue to look for spectral available bandwidth is still the industry needs to focus on the breakthrough direction.

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