OGC 2022
Optoelectronics Global Conference

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***Abstract*—A novelty C+L single-mode fiber (CL fiber for short) which can expand L-band communication is proposed to meet the urgent demand of optical fiber transmission bandwidth for large capacity communication system. The influence of L-band attenuation on the optical signal-to-noise ratio (OSNR) of the system is analyzed and calculated; through the simulation of dense wavelength division multiplexing (DWDM) system, the requirements for fiber attenuation warping degree (FAWD) of CL fiber in 100Gbit/s rate DWDM system are obtained; and the CL fiber and its main attenuation parameters are defined. The results show that, the OSNR of L-band for conventional single-mode fiber will be 2dB-2.5dB worse than traditional C-band on 100km span system, so it is very important to limit the FAWD of L-band; if the L-band transmission can meet the link requirements in relevant standards, it is recommended that the FAWD $\Delta\alpha_{1625}$ of CL fiber is suitable to be controlled below 0.015dB/km, and the fiber attenuation warping degree difference (FAWDD) $\Delta\alpha$ is suitable to be controlled below 0.005dB/km.**

Keywords-CL fiber; C+L band; L-band; Attenuation flatness; Fiber attenuation warping degree; C+L wavelength division multiplexing; Fiber bandwidth; DWDM

I. Introduction

With the gradual maturity, popularization and application of 5G communication technology, Internet users' requirements for network access bandwidth are further improved. According to Cisco estimates, the global fixed access rate and mobile access rate will maintain a compound annual growth rate of 20% and 27% respectively from 2018 to 2023 [1]. The demand of data flow and information consumption for network transmission capacity is increasing rapidly, which makes the existing dense wavelength division multiplexing (DWDM) system show capacity bottleneck.

To continue to improve the transmission capacity of DWDM system, we can only increase the number of optical fiber wavelength division multiplexing channels, improve the transmission rate or spectral efficiency of a single channel, and expand the number of fiber cores in a single fiber [2]. Due to the limitations of optical fiber material properties and optical equipment performance, it is increasingly difficult to simply improve the transmission rate or spectral efficiency of a single channel, and it has approached the Shannon limit; however, the multi-core optical fiber with expanded core number is not mature in terms of manufacturing level and coupling devices. Therefore, increasing the number of optical fiber wavelength division multiplexing channels has become an important and feasible method to greatly expand the transmission capacity of DWDM system. Restricted by the dispersion performance of the optical fiber and the communication light source, it is extremely limited to increase the number of channels by reducing the channel spacing [3], so we have to consider widening the effective band width of the optical fiber to achieve this purpose.

This paper mainly takes single-mode fiber as the main research object, focuses on the problems faced by fiber transmission in L-band, puts forward a novelty CL fiber to expand L-band transmission, determines the feasibility of its application and the requirements for attenuation flatness through system simulation.

II. L-band Transmission Characteristics of SMF

A. Attenuation Difference in the C+L Band

By analyzing the spectral loss (wavelength-attenuation) curve of SMF, it can be seen that its attenuation trend in C-band (1530nm-1565nm) and L-band (1565nm-1625nm) shows an approximate U-shaped state. The attenuation slope of L-band rises rapidly with the increase of wavelength, and the increase of attenuation is greater than the decrease of C-band. This is determined by the infrared absorption and design parameters of optical fiber glass materials, which actually leads to the degradation of L-band transmission performance.

In order to broaden the L-band bandwidth of the existing single-mode optical fiber and realize ultra-wideband (UWB) communication, the optical fiber needs to have the same attenuation level in the L-band as in the C-band while maintaining the low loss of the C-band, and a novelty C+L-band attenuation flat optical fiber (CL fiber) is explored. In order to facilitate large-scale use and replacement, the more appropriate choice is that the fiber still belongs to class G.652 SMF. The spectral loss curves of typical SMF and CL fiber are shown in Figure 1. It can be seen that it has a relatively gentle attenuation increase in the L-band.

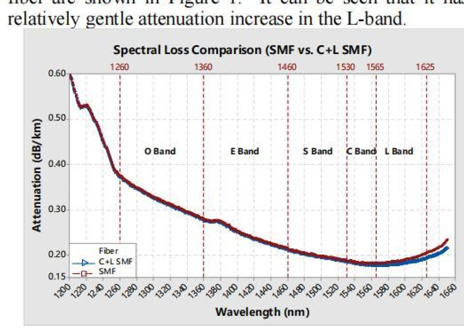


Figure 1. Comparison of spectral loss curves of SMF and CL fiber.

B. L-Band Transmission Performance

According to Shannon's theorem, in the optical transmission channel with random noise, the channel capacity is restricted by OSNR. The higher the OSNR, the greater the transmission capacity of the channel.

$$C = B\log_2(1+S/N) \quad (1)$$

Where, C is the capacity of the channel, B is the channel bandwidth, and S/N is the signal-to-noise ratio. The relevant ITU standard — ITU-T G.692 [5] gives the calculation equation of OSNR:

$$OSNR = P_{out} - L - NF - 10\log N - 10\log(h\nu\Delta\nu_0) \quad (2)$$

Where, P_{out} is the channel output optical power, dBm; L is the span loss between amplifiers, dB; N is the number of spans in the link; NF is the light amplification noise figure; h is Planck constant, (mJ·s); ν is the optical transmission frequency; ν_0 is the reference bandwidth. For general DWDM system with equal optical amplification section, when the optical band width at 1550nm is 0.1nm, OSNR calculation equation [5] can be simplified as:

$$OSNR = 58 + P_{ch} - L - NF - 1\log N \quad (3)$$

Where, P_{ch} is the channel optical power (fiber input power), which is related to the optical end injection power and fiber design parameters. Span loss L is positively correlated with fiber attenuation coefficient α.

Assuming that the channel optical power P_{ch}, optical amplification noise factor NF and optical amplification span number N remain unchanged, the effect of increasing L-band attenuation on OSNR is:

$$OSNR_{L-C} = L_L - L_C = (\alpha_C - \alpha_L)\cdot S = \Delta\alpha_{C-L}\cdot S \quad (4)$$

Where, $OSNR_{L-C}$ represents the signal-to-noise ratio difference between L-band and C-band, L_L and L_C are the link loss of L-band and C-band respectively, α_L and α_C is the optical fiber attenuation coefficient of L-band and C-band respectively, S is the span length, $\Delta\alpha_{C-L}$ is the difference of attenuation coefficient between C-band and L-band.

For conventional SMF, compared with the traditional C-band, the attenuation slope of L-band is steeper, which makes the attenuation at 1625nm greater than that at 1520nm. Assuming that the attenuation difference is 0.01dB/km and the system span is 100km, the $OSNR_{L-C}$ can be calculated from (5):

$$OSNR_{L-C} = \Delta\alpha_{C-L}\cdot S = -0.01\cdot 100 = -1.0(\mathrm{dB}) \quad (5)$$

From (5), it can be seen that, due to the difference in attenuation, the OSNR of single L-band may be about 1dB worse than that of traditional C-band; considering the additional insertion loss introduced by the C/L combiner and splitter in the C+L system, the OSNR in the C+L system will eventually deteriorate by 2dB-2.5dB.

III. Simulation Analysis of the CL Fiber

A. Definition of the CL Fiber

In the wavelength range of C+L, the curve of fiber attenuation coefficient changing with wavelength presents a U-shaped state, and there is a minimum attenuation value and its corresponding minimum attenuation wavelength. To describe the difference of attenuation trend between C-band and L-band, we can evaluate it from the attenuation difference of U-shaped curve on both sides of the minimum attenuation wavelength. Therefore, the optical fiber attenuation warping parameter is added in this paper: within the specified wavelength range, the difference between the attenuation coefficient at a specific wavelength and the minimum attenuation coefficient within the wavelength range when the optical fiber attenuation coefficient presents a U-shaped state with the wavelength, is called fiber attenuation coefficient warping degree (FAWD for short); the absolute value of the arithmetic difference of the FAWD at two different specific wavelengths is called the fiber attenuation warping degree difference (FAWDD for short). Obviously, the smaller FAWD in the C+L band, the better the attenuation flatness; it means that the OSNR of L-band transmission will be close to the level of C-band, so it can be used for the transmission of existing DWDM systems with more than 80 waves like C-band. Therefore, CL fiber can be defined as a single-mode fiber with optimized attenuation performance in C-band and L-band, which can be used to support DWDM systems above 80 waves.

In order to obtain the minimum attenuation value required for calculating the FAWD, it is necessary to test the spectral loss of each optical fiber, and the test scanning time is relatively long, which seriously affects the efficiency of batch obtaining CL fibers. In order to simplify the calculation, it is suggested to define the wavelength at the minimum attenuation of SMF from the statistical point of view and fix it as the minimum attenuation wavelength of the same kind of fiber. For example, the batch statistics of 80 measured CL fiber samples in this paper show that the lowest attenuation wavelength is not in the traditional 1550nm transmission window, but mainly distributed in 1570nm-1580nm, and the average value of the minimum attenuation wavelength is 1576nm, as shown in Figure 2.

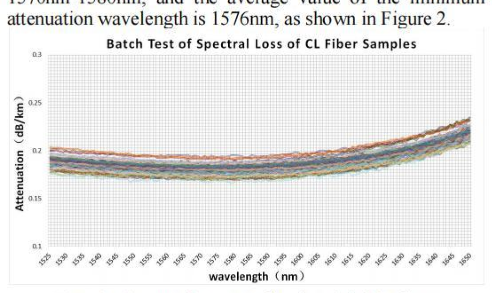


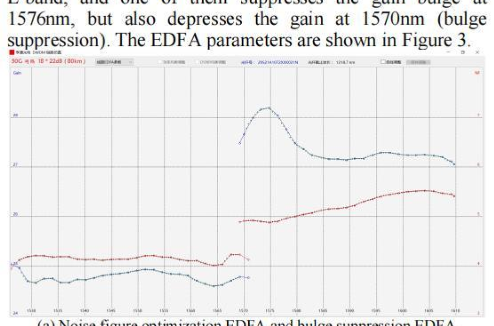
Figure 2. Spectrum loss curve of batch statistical CL fibers.

For this kind of CL fiber, 1576nm can be taken as its minimum attenuation wavelength, and FAWD and FAWDD can be calculated by testing the corresponding window value. Of course, for CL fibers manufactured by different manufacturers, their materials and structures are slightly different, and the minimum attenuation wavelength may not be 1576nm, but this does not affect the judgment of the minimum attenuation wavelength, and this statistical method is still feasible.

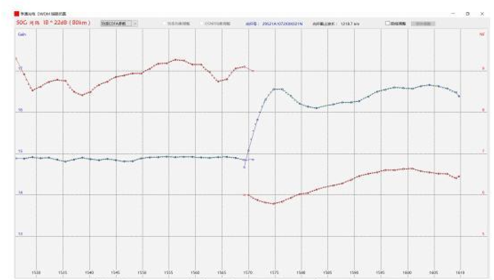
B. System Simulation Analysis

1) Simulations based on the existing EDFA

In the simulation test, two types of EDFA are used for C-band and L-band respectively, and the overall wavelength range is 1525nm-1610nm. Both C-band EDFA can cover all 104 optical channels of C-band (namely, noise figure optimization and flatness optimization); both L-band EDFA can only cover 94 optical channels of short wavelength of the L-band, and one of them suppresses the gain bulge at 1576nm, but also depresses the gain at 1570nm (bulge suppression). The EDFA parameters are shown in Figure 3.



(a) Noise figure optimization EDFA and bulge suppression EDFA

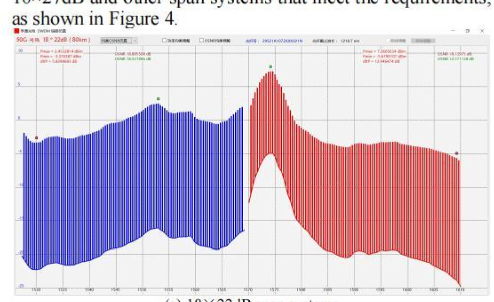


(b) Flatness optimization EDFA and another EDFA

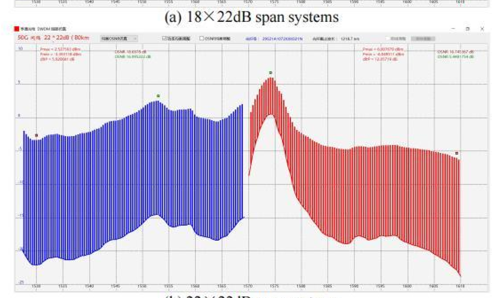
Figure 3. Power parameters of the existing EDFA.

The minimum attenuation wavelength is 1576nm and FAWD at 1610nm ($\Delta\alpha_{1610}$) is 0.0087dB/km of the fiber selected for optical simulation.

Simulation shows that only the C-band noise figure optimized EDFA can meet the requirements of the industry standard YD/T 2485-2013 (2017) [6] after realizing the 18×22dB optical amplification section. The 22×22dB span system built with this EDFA can barely meet the requirements of the industry standard YD/T 3070-2016 (2017) [7] (there is no 22 span in the link standard, refer to the 20 span type), but cannot build 26×22dB, 12×27dB, 10×27dB and other span systems that meet the requirements, as shown in Figure 4.



(a) 18×22dB span systems



(b) 22×22dB span systems

Figure 4. Performance on C-band noise optimized EDFA.

C-band gain flattening optimized EDFA cannot meet any link type requirements recommended in the industry standard YD/T 2485-2013 (2017) [5] due to its high noise figure. For L-band bulge suppression EDFA, only the shortest link type of 10×22dB can meet the requirements of industry standard YD/T 2485-2013 (2017) [7] for C-band, as shown in Figure 5.

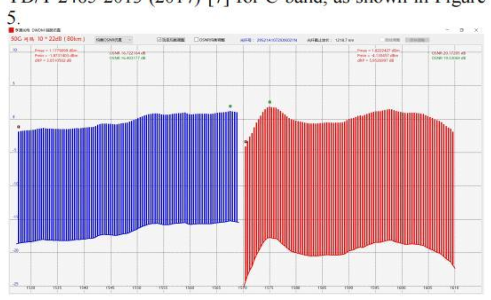


Figure 5. Performance in 10×22dB span system on L-band bulge suppression EDFA.

2) Simulation based on the optimized EDFA

Assuming that after continuous technological development, the technical level of L-band EDFA can also reach today's C-band level, we will transfer the gain curve of C-band EDFA to L-band for simulation. It can be found that on the 14×22dB span, the system can meet the requirements of 18.5dB received OSNR and 6dB maximum channel power difference specified in relevant industry standards, as shown in Figure 6. At the same time, it can be seen that the FAWD of the fiber at the long wavelength has a great impact on the flatness of the optical channel.

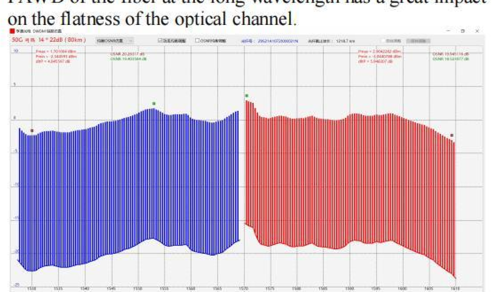


Figure 6. Performance in 14×22dB span system on L-band optimized EDFA, $\Delta\alpha_{1610} = 0.0087$dB/km.

When the $\Delta\alpha_{1610}$ is adjusted from 0.0087dB/km to 0.010dB/km, the simulation result shows that for the 14×22dB system, the received OSNR and the maximum channel received optical power difference are somewhat deficient in line with the requirements of the industry standard, as shown in Figure 7.

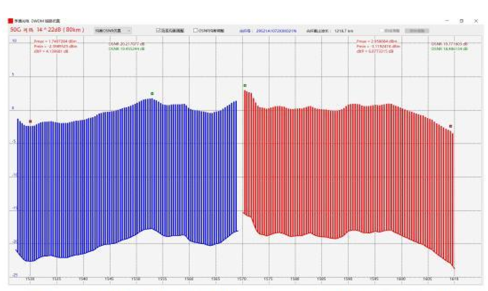
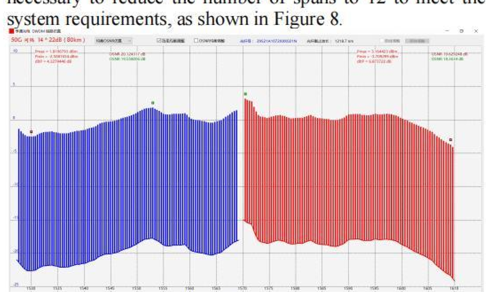
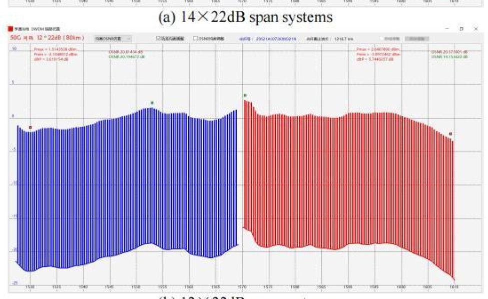


Figure 7. Performance in 14×22dB span system (L-band optimized EDFA, $\Delta\alpha_{1610} = 0.010$dB/km).

Continue to improve the $\Delta\alpha_{1610}$ to 0.012dB/km. It can be found that the performance of the wavelength division system is degraded more seriously in terms of both the received OSNR and the channel flatness. At this time, it is necessary to reduce the number of spans to 12 to meet the system requirements, as shown in Figure 8.



(a) 14×22dB span systems



(b) 12×22dB span systems

Figure 8. Performance on L-band optimized EDFA, $\Delta\alpha_{1610} =$ 0.012dB/km.

3) Simulation results

Because the fiber can only meet the requirements of receiving OSNR of 18.5dB and maximum channel power difference of 6dB on the shortest link specified in the industry standard, when the $\Delta\alpha_{1610}$ is 0.012dB/km. Therefore, it is better to limit the $\Delta\alpha_{1610}$ less than 0.012dB/km, when selecting the optical fiber used to open the wavelength division system in the C+L band. If it is extended to 1625nm wavelength, the $\Delta\alpha_{1625}$ is suitable to be limited to less than 0.015dB/km.

C. Attenuation Recommendations for CL Fiber

For the optical fiber itself, it is appropriate to specify the maximum FAWD of C-band and L-band to fully meet the C+L band extended transmission. As the novelty CL fiber will support the maximum 240 wave multiplexing in the future, the FAWD will not be limited to the wavelength range covered by the above system simulation. It is recommended to add two FAWD values in the C+L band, which are $\Delta\alpha_{1520}$ and $\Delta\alpha_{1625}$; at the same time, the absolute value $\Delta\alpha$ is specified. Referring to the above simulation results and the wavelength attenuation characteristics of SMF, it is suggested that the attenuation parameters of the novelty CL fiber is shown in Table 1.

TABLE I. Attenuation Recommendations for CL Fiber

Parameters	Units	Recommended Values
Attenuation @1550nm	dB/km	≤0.20
Attenuation @1625nm	dB/km	≤0.25
$\Delta\alpha_{1520}$	dB/km	≤0.010
$\Delta\alpha_{1625}$	dB/km	≤0.015
$\Delta\alpha$ (Absolute Value)	dB/km	≤0.005

In order to obtain CL fibers that meet the above requirements, it is necessary to analyze the relevant parameters that may affect the FAWD of SMF. It is expected that stable CL fibers can be obtained quickly and in batches through the selection of certain conditions or the adjustment and control of some parameters, which will be carried out in the future work.

IV. Conclusion

C+L single mode fiber in L band is defined, simulated and analyzed. The OSNR in the L-band system alone will be significantly worse than the traditional C-band system, which makes the attenuation warping and attenuation warping difference of the CL fiber should be controlled at a reasonable level to meet the requirements of the signal to noise ratio and power difference of the 100Gbit/s wave division multiplexing system.

Acknowledgment

This work was supported by National Key Research and Development Program (No. 2021-YFB2900700), Suzhou Major Innovation Team Program (ZXT2019001).

Thanks to F. Lei, senior engineer, who provided the independently developed simulation software.

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