Available Online: 2 July 2026 DOI: 10.54254/2977-3903/2026.34890

Research on resource allocation methods for nonlinear noise suppression in 5G communications

Yicheng Huang**, *Lintai He, Jiasen Wang, Ankang Chu

Xizang University, Lhasa, China

*Corresponding Author. Email: 2627613948@qq.com

Abstract. In modern communications, optical fiber communication has become an indispensable means of information transmission. With the rapid development of cloud computing, the Internet, short-video platforms, artificial intelligence, and related technologies, the demand for higher transmission rates and broader bandwidth in optical fiber communication systems has continued to grow. As fiber transmission rates increase, the constraints imposed by nonlinear effects on the development of optical fiber communications have become increasingly significant. One typical nonlinear effect is Four-Wave Mixing (FWM), which has a substantial impact on high-power and high-speed optical communication systems. This paper introduces three types of nonlinear effect noise, namely Rayleigh scattering, stimulated Brillouin scattering, and four-wave mixing. Particular emphasis is placed on the four-wave mixing effect. To suppress FWM, a method combining thin-film filters with three effective channel allocation schemes is proposed, including non-uniform channel spacing, enlarged channel intervals, and increased guard bandwidth. The proposed approach contributes to the suppression of four-wave mixing noise in high-speed optical communication systems and significantly improves system reliability and stability, especially in transmission lines operating under heavy traffic loads, such as Dense Wavelength Division Multiplexing (DWDM) systems.

Keywords: optical fiber communication, nonlinear effects, four-wave mixing, channel allocation

1. Introduction

Optical fiber communication is an important communication technology that uses optical waves as information carriers and optical fibers as the transmission medium. Research on optical fiber communication in China began in 1972 at the Wuhan Research Institute under the leadership of the academician Zhao and his team. Over the past five decades, the development of optical fiber communication has advanced dramatically, and more than 90% of global data transmission is now carried through optical fiber networks [1]. The major advantages of optical fiber communication include large transmission capacity, long repeater spacing, strong confidentiality, high environmental adaptability, as well as small size and light weight. Owing to these advantages, optical fiber communication rapidly replaced traditional electrical communication methods and greatly alleviated the growing global demand for communication capacity. During this half-century of rapid development, the transmission capacity of a single optical communication link increased from 8 Mb/s to 96 × 100 Gb/s, representing a growth of approximately 1.2 million times. Typical transmission distances expanded from 10 km to 3,000 km, an increase of 300 times. Electrical cross-connect capacity rose from 64 Mbit to 64 Tbit, improving by a factor of one million, while the cost of optical devices (optical modules) decreased from 20,000 RMB to 100 RMB, a reduction of 200 times [1]. It can be said that modern communication networks operate on the "information highway" provided by optical fiber communication; without optical fiber communication, today's Internet would not exist.

At present, optical fiber communication is developing rapidly in China. However, scholars such as Shaohua Yu argue that over the past decade, the growth rate of Internet traffic demand has far exceeded the increase in optical transmission capacity. Consequently, improving optical fiber channel rates, system capacity, and transmission distance has become an urgent task [1]. Currently, emerging technologies such as hollow-core optical fiber are leading the next stage of optical fiber communication development. A representative example is the "hollow-core optical fiber" recently introduced by YOFC. Compared with conventional solid-core optical fibers, this technology increases optical signal transmission speed by approximately 47% and reduces transmission latency by about 30%, setting multiple world records in the field of optical communication transmission. Furthermore, the company's ultra-low-loss hollow-core optical fiber has achieved an exceptionally low attenuation coefficient of 0.05 dB/km, demonstrating substantial performance improvements over traditional solid-core optical fibers [2]. Optical fiber communication has developed not only in commercial applications but also in household scenarios. At present, China's three major telecommunications operators are vigorously promoting Fiber to the Room (FTTR) technology, which can significantly enhance the connection stability of smart home devices and provide new networking solutions for large residential spaces.

Although optical fiber communication has made tremendous contributions across various fields, it is not without limitations. Shi pointed out that in the practical deployment of optical fiber communication systems, optical fiber nonlinear effects can easily induce signal distortion and significantly increase the bit error rate, thereby becoming a key bottleneck restricting the transmission performance and communication quality of high-capacity long-haul optical transmission systems [3]. Common nonlinear effects such as self-phase modulation and cross-phase modulation can also generate additional noise during signal transmission, further increasing the bit error rate [4]. Huang likewise argued that the damage caused by nonlinear effects to signal transmission is seriously hindering the development of optical fiber communication [5]. Today, nonlinear effects have become the central barrier to achieving ultra-high-speed, ultra-long-distance, and ultra-large-capacity optical fiber communications. Unlike linear impairments, the damage caused by nonlinear effects cannot be completely eliminated and can only be mitigated through compromises such as reduced transmission performance, increased system complexity, and higher implementation costs. Therefore, nonlinear effects can be regarded as one of the most critical challenges in the development of optical fiber communication systems.

2. 5G optical communication architecture and nonlinear noise analysis

2.1. Applications of optical fiber in 5G communications

As shown in Figure 1, the current mainstream 5G optical communication architecture adopts the CU/DU separation scheme. During signal transmission, the communication process is generally divided into three segments in the industry: fronthaul, middlehaul, and backhaul [6].

Fronthaul: At the mobile terminal, signals are transmitted wirelessly through the air interface to a nearby Active Antenna Unit (AAU). After receiving the high-frequency analog radio-frequency signals from the mobile device, the AAU performs preliminary signal processing and then transmits the signals to its corresponding Distributed Unit (DU) through optical fiber. Middlehaul: After the DU receives the signals transmitted from the AAU, it performs further signal processing. In simple terms, the DU decapsulates the data, removes redundant baseband sampling information, restores the data into standard transmission data blocks, and checks whether the data have been corrupted. If corruption is detected, the DU immediately requests retransmission from the mobile terminal. Finally, the DU reconstructs complete data packets and forwards them to the Centralized Unit (CU). Backhaul: After receiving the signals, the CU likewise decapsulates the data packets sent from the DU and performs core PDCP-layer processing on the data stream to verify whether the data have been intercepted, tampered with, or forged. Subsequently, SDAP-layer processing is carried out to assign priority labels to the data, ensuring that critical information is transmitted preferentially. Finally, legitimate data are packaged and uploaded to the 5G core network. The above description refers to uplink data transmission; the downlink transmission process is similar and will therefore not be discussed in detail here.

Throughout these transmission processes, optical fiber plays an indispensable role. However, as mentioned in the introduction, various nonlinear noises inevitably arise during signal propagation. These noises increase the bit error rate during 5G communication and significantly interfere with the development of optical communication technologies.

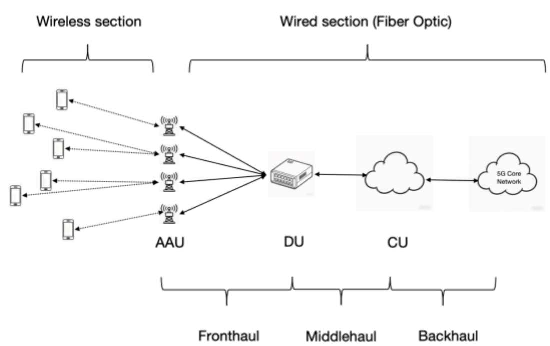

Figure 1. End-to-end transmission architecture of the 5G access network

2.2. Analysis of nonlinear noise

2.2.1. Rayleigh scattering noise

The primary component of optical fiber is silicon dioxide, commonly known as glass. Because glass is inherently inhomogeneous, the density distribution throughout the optical fiber is not completely uniform. When light propagates through the fiber, variations in internal density cause the light to scatter in different directions. As a result, unwanted noise is generated, and repeated reflections occur between the fiber core and the cladding. This process leads to attenuation of the incident optical power and constitutes the origin of Rayleigh scattering. The equivalent noise optical power generated by Rayleigh scattering can be expressed as follows:

$$P_{RN} = \alpha_R \cdot P_{in} \cdot L_{eff} \cdot S \tag{1}$$

where P_{RN} denotes the Rayleigh scattering noise power, α_R is the Rayleigh scattering loss coefficient, P_{in} is the launched optical power, L_{eff} is the effective interaction length, and S is the backscattering coefficient.

2.2.2. Stimulated brillouin scattering

When the incident optical power exceeds a certain threshold, Stimulated Brillouin Scattering (SBS) occurs. SBS is a type of stimulated scattering effect. As the optical field intensity increases to a sufficient level, the optical wave inside the fiber interacts with acoustic phonons in the optical fiber medium [7]. Part of the incident optical energy is transferred to backward-propagating Stokes light, while acoustic phonons are simultaneously generated. This process causes signal power loss, channel interference, and even damage to optical transmitter modules, thereby limiting the launched optical power of a single optical channel. The equations governing the generation of Stokes light during stimulated Brillouin scattering are given as follows:

$$\frac{dP_p(z)}{dz} = -g_B \frac{P_p(z)P_s(z)}{A_{eff}} - \alpha P_p(z) \tag{2}$$

$$\frac{dP_s(z)}{dz} = g_B \frac{P_p(z)P_s(z)}{A_{eff}} - \alpha P_s(z) \tag{3}$$

where $P_p(z)$ is the pump light power, $P_s(z)$ is the Stokes light power, g_B is the Brillouin peak gain coefficient, A_{eff} is the effective mode-field area of the optical field, and α is the optical fiber attenuation coefficient. In silica optical fibers, the typical value of g_B is $5 \times 10^{-11}\, m/W$.

The acoustic phonon power generated during stimulated Brillouin scattering can be expressed as:

$$P_a = \frac{A_{eff}v}{2\rho_0} \langle |\rho_{ss}|^2 \rangle \tag{4}$$

where P_a is the average acoustic phonon power, A_{eff} is again the effective mode-field area, v is the acoustic velocity in the medium, ρ_0 is the static average density of the medium, and $\langle |\rho_{ss}|^2 \rangle$ represents the ensemble average of the squared density fluctuation amplitude.

2.2.3. Four-Wave Mixing (FWM)

When multiple optical signals with different frequencies propagate simultaneously within an optical fiber, nonlinear polarization interactions occur among them. This phenomenon is known as Four-Wave Mixing (FWM) [8]. Four-wave mixing satisfies both the energy conservation condition and the phase-matching condition, thereby generating new frequency-mixing products. The following equation describes the frequency of a newly generated mixing product caused by four-wave mixing, where ω_4 represents one of the newly generated frequencies. Figure 2 presents a schematic illustration of this phenomenon. The arrow lengths represent the signal power levels, with longer arrows corresponding to higher signal power. Black arrows denote communication channels, while red arrows represent four-wave mixing products. The same notation is used in Figures 4, 5, 6, and 7 and will therefore not be repeated.

$$\omega_{ijk} = \omega_i + \omega_j - \omega_k \tag{5}$$

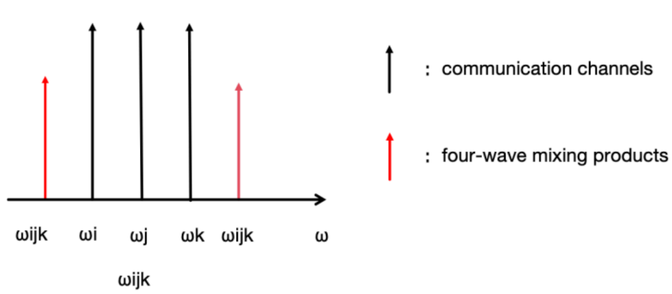

Figure 2. Schematic diagram of four-wave mixing channels

The intensity of the frequency-mixing products generated by four-wave mixing is given below for subsequent analysis:

$$P_{FWM} \approx \eta\gamma^2 L_{eff}^2 P_i P_j P_k e^{-\alpha L} \tag{6}$$

where

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha} \tag{7}$$

$$\eta = \frac{\alpha^2}{\alpha^2+\Delta\beta^2}\left[1 + \frac{4e^{-\alpha L}}{(1-e^{-\alpha L})^2} sin^2\left(\frac{\Delta\beta L}{2}\right)\right] \tag{8}$$

$$\Delta\beta \approx -\frac{2\pi\lambda^2}{c} D(\Delta f_{ik})(\Delta f_{jk}) \tag{9}$$

In the above equations, $P_i P_j P_k$ represent the optical powers of the three waves participating in the four-wave mixing process; γ is the nonlinear coefficient of the optical fiber; α is the fiber attenuation coefficient; L is the fiber length; L_{eff} is the effective fiber length; and $\Delta\beta$ denotes the phase mismatch parameter.

3. Scheme design

3.1. Suppressing four-wave mixing through thin-film interference filters

A Thin-Film Interference Filter (TFF) is an optical filter that utilizes the optical interference effects of multilayer dielectric films to selectively transmit light at specific wavelengths. This optical device allows desired optical signals to pass while blocking unwanted wavelengths. When nonlinear effects occur, TFFs can be employed to block or significantly attenuate newly generated optical frequencies produced by nonlinear interactions [9]. Figure 3 illustrates the use of a thin-film interference filter to remove newly generated frequency-mixing products caused by four-wave mixing during optical fiber transmission.

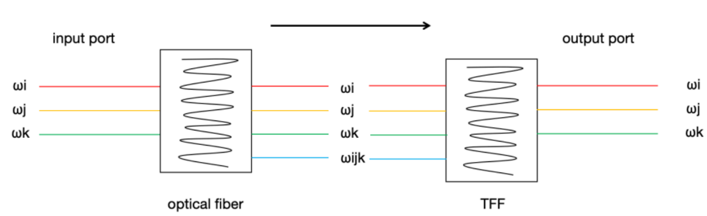

Figure 3. Schematic diagram of TFF-based filtering and removal of FWM products in optical fiber transmission

However, TFFs are not universally effective. A straightforward derivation from the four-wave mixing equations shows that when the frequency spacing between transmitted optical signals is equal, the newly generated frequency-mixing products may overlap with the wavelengths of the original communication channels. Under such circumstances, TFFs cannot effectively suppress nonlinear effects simply by blocking specific optical frequencies. Therefore, it is necessary to preconfigure the transmission wavelengths such that newly generated frequencies produced during four-wave mixing do not coincide with the original communication channels, thereby facilitating subsequent filtering.

3.2. Channel allocation schemes for suppressing four-wave mixing

To suppress four-wave mixing, it is first necessary to understand two key characteristics of FWM. First, when communication channels are arranged at equal intervals, the newly generated frequency-mixing products also appear at equal intervals and may overlap with the communication channels, as shown in Figure 2. Second, increasing the spacing between communication channels significantly reduces the intensity of the generated mixing products. Based on these two characteristics, several methods for reducing FWM can be proposed.

3.2.1. Non-uniform channel spacing

As discussed in Scheme Design 1, when communication channels are arranged with non-uniform spacing, frequency-mixing products generated outside the communication frequency bands can be removed using various optical filters. Achieving this effect requires advance planning of channel allocation. For example, in a system with three communication channels, if the originally equal channel spacing X_0 is adjusted such that the first interval remains X_0 while the second interval becomes $2X_0$, all first-order four-wave mixing products can be shifted away from the communication channels. Figure 4 demonstrates how this approach forces all possible frequency-mixing products to fall outside the communication frequency bands.

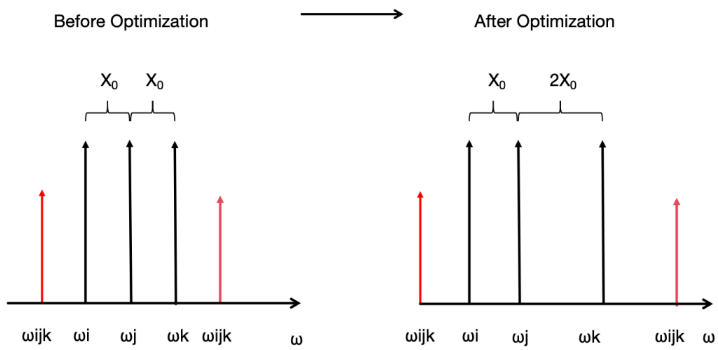

Figure 4. Avoiding FWM products falling into communication channels through non-uniform channel allocation

The main advantage of this method is that automated channel allocation can be achieved algorithmically. Compared with simply enlarging all channel spacings under the same available spectrum resources, this approach is more spectrum-efficient. However, its design complexity is relatively high and increases exponentially with the number of communication channels. Adding new channels may also disrupt the previously optimized allocation structure. Consequently, this method is particularly suitable for communication systems in which channel configurations are relatively fixed, can be preplanned in advance, are highly sensitive to four-wave mixing, and cannot tolerate excessive spectrum waste.

3.2.2. Increasing the spacing between communication channels

When the spacing between communication channels is enlarged, the phase-matching conditions for four-wave mixing generally deteriorate, leading to a corresponding reduction in the intensity of the generated mixing products. From Equations (6), (7), (8), and (9), it can be approximately inferred that: $\Delta\beta \propto (\Delta f)^2$. Thus, whenever the channel spacing doubles, the corresponding phase mismatch parameter $\Delta\beta$ becomes approximately four times larger. Therefore, the following relationship can be obtained:

$$\frac{P'_{FWM}}{P_{FWM}} = \frac{\eta(4\Delta\beta)}{\eta(\Delta\beta)} \tag{10}$$

where P_{FWM} is the power of the four-wave mixing product before increasing the channel spacing, and P'_{FWM} is the corresponding power after increasing the spacing.

When $\Delta\beta$ is much larger than α, it can further be approximated that: $\eta \propto \frac{1}{\Delta\beta^2}$. Since $\Delta\beta \propto (\Delta f)^2$, it follows that: $P_{FWM} \propto \frac{1}{(\Delta f)^4}$. Under this condition, if the spacing between communication channels doubles, the intensity of the four-wave mixing products can be approximately reduced to: $\frac{P'_{FWM}}{P_{FWM}} = (\frac{1}{2})^4 = \frac{1}{16}$. That is, the FWM product intensity decreases to approximately one-sixteenth of its original value, as illustrated in Figure 5.

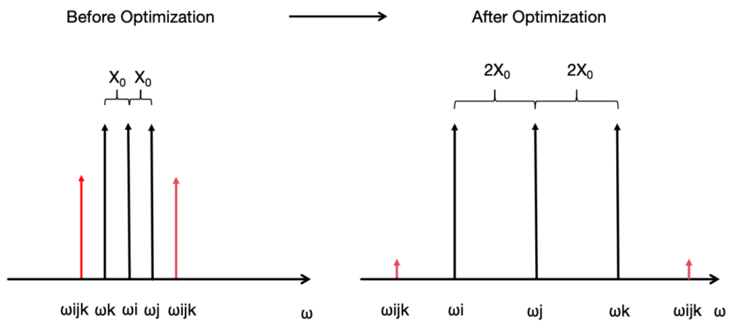

Figure 5. Reduction of FWM intensity by increasing channel spacing

The advantages of this method include simplicity, low equipment requirements, minimal design risk, and low maintenance cost. In addition, it can significantly suppress the intensity of four-wave mixing products. However, its main drawback is inefficient spectrum utilization and reduced communication capacity. Therefore, this method is more suitable for communication systems with relatively abundant available spectrum resources and a limited number of communication channels.

3.2.3. Increasing guard bandwidth

Increasing the guard bandwidth introduces sufficient spacing between adjacent communication channels. In this case, four-wave mixing products can be made to fall as much as possible within the guard bands, thereby reducing the probability that they overlap with communication channels. Assume that $\omega_i > \omega_j > \omega_k$. Let the guard bandwidth on the lower-frequency side of the communication channels be denoted as Δ_1, and the guard bandwidth on the higher-frequency side be denoted as Δ_2. According to Equation (2)-(5), the following relationships can be obtained:

$$\Delta_1 = |\omega_k + \omega_j - \omega_i| \tag{11}$$

$$\Delta_2 = |\omega_i + \omega_j - \omega_k| \tag{12}$$

In practical applications, however, the guard bandwidth cannot be configured strictly according to the above equations. The expressions only guarantee normal system operation under ideal conditions. In reality, system precision limitations require the guard bandwidth to be enlarged appropriately. For example, using a guard bandwidth of $2\Delta_1$ can significantly reduce the precision requirements for system instruments, as shown in Figure 6.

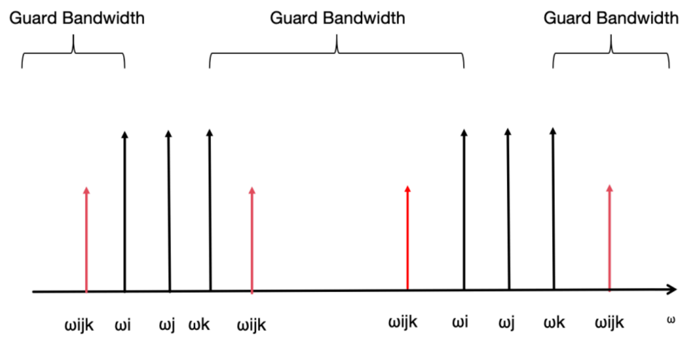

Figure 6. Reducing the probability of FWM products falling into communication channels by increasing guard bandwidth

The advantages of this method are its high flexibility and its ability to protect a small number of high-priority communication channels. It is particularly useful for flexible-grid systems and can also mitigate sideband collision problems. However, if a four-wave mixing product directly overlaps with a communication channel, increasing the guard bandwidth alone has only a limited effect on reducing interference while simultaneously sacrificing available spectral resources. This method is therefore suitable for systems that require focused protection of a few sensitive channels, dense channel boundary protection, or support for heterogeneous service bandwidths.

3.2.4. Practical engineering solutions

In practical applications, a single method is rarely used independently to suppress the power of four-wave mixing products. Figure 7 illustrates a practical engineering solution in which non-uniform channel spacing is combined with increased guard bandwidth.

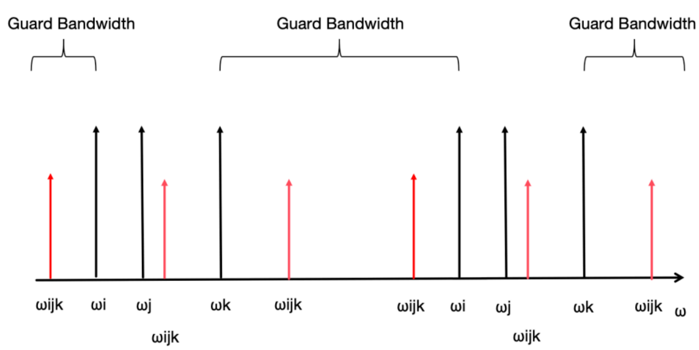

Figure 7. Practical engineering solution combining non-uniform channel allocation and increased guard bandwidth to reduce FWM effects

Through such combined solutions, four-wave mixing products can be handled in a more effective and "clean" manner. In practical engineering, integrating multiple channel allocation schemes also allows the advantages of different methods to complement one another. For example, the above scheme alleviates the increased design complexity associated with adding channels under non-uniform spacing while simultaneously reducing the spectrum waste caused by enlarging guard bandwidths.

4. Feasibility analysis

In the previous sections, two methods for suppressing four-wave mixing were proposed: thin-film interference filtering and channel allocation optimization. The following section analyzes the differences among the channel allocation schemes.

Table 1. Comparison of advantages and disadvantages of different channel allocation schemes

Scheme	Implementation Method	Advantages	Disadvantages
Non-uniform channel spacing	Avoids FWM products falling into communication channels through non-uniform allocation of communication channels	1. Automated channel allocation can be achieved algorithmically 2. More spectrum-efficient than simply enlarging channel spacing	1. Design complexity is relatively high 2. Adding new communication channels after optimization may destroy the original optimal structure
Enlarged channel spacing	Reduces phase matching and suppresses FWM intensity by increasing the spacing between communication channels	1. Simple design with low equipment requirements 2. Directly reduces FWM intensity	Causes severe spectrum waste and low communication capacity when many channels are used
Increased guard bandwidth	Expands guard bands so that FWM products fall as much as possible within the guard bandwidth	1. Flexible and easy to implement, capable of protecting a small number of high-priority channels 2. Helps mitigate sideband collision problems	Cannot effectively reduce the bit error rate when FWM products directly overlap with communication channels

As shown in Table 1, each channel allocation scheme possesses its own advantages and disadvantages, and their applicable scenarios are not identical. Although the non-uniform channel spacing scheme is relatively complex and costly to design, it provides superior performance. It enables more thorough post-filtering of four-wave mixing products and is therefore more suitable for systems that are extremely sensitive to four-wave mixing, such as Dense Wavelength Division Multiplexing (DWDM) systems. Increasing the spacing between communication channels is comparatively simple in design, low in cost, and easy to implement. However, its performance is relatively moderate because it cannot completely separate four-wave mixing products from communication channels. This method is therefore more suitable for systems with fewer communication channels and relatively abundant spectral resources. Although increasing guard bandwidth alone may not always reduce the bit error rate effectively, it features low implementation cost, high flexibility, and relatively good practical performance. Consequently, it is the most frequently adopted channel allocation scheme in practical engineering applications. This approach is particularly suitable for systems in which service bandwidths differ, a small number of high-priority channels require protection, or dense channel boundaries need isolation.

Thin-film interference filters, on the other hand, are primarily used after appropriate channel allocation schemes have been implemented, serving to filter out four-wave mixing products that fall outside the communication channels.

5. Conclusion

This paper combines thin-film interference filters with channel allocation strategies and proposes three channel allocation schemes for suppressing four-wave mixing: non-uniform channel spacing, enlarged channel spacing, and increased guard bandwidth. These methods effectively reduce the interference caused by four-wave mixing in high-speed optical communication systems. At the same time, a practical engineering solution that integrates multiple channel allocation methods is proposed to further enhance the suppression effect on four-wave mixing. By combining different schemes, the disadvantages of a single method—such as excessive spectrum waste or high design complexity—can be mitigated, while enabling "cleaner" filtering of four-wave mixing products and significantly improving the system's noise resistance capability. For scenarios with heavy transmission loads and strict bit error rate requirements, the combination of non-uniform channel spacing and thin-film interference filters can substantially reduce four-wave mixing interference. In systems where channel resources are relatively abundant, increasing channel spacing or enlarging guard bandwidth can improve system stability at relatively low cost. These methods do not require replacement of existing optical fiber hardware and can be implemented solely through wavelength planning and optical filtering devices, demonstrating strong engineering practicality. They provide a feasible technical approach for improving both the reliability and spectrum utilization efficiency of high-speed optical communication systems.

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