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The application of optical fiber in network communication

Jingyao Li

Academy of Physics and Photonics, South China University of Technology, Guangzhou 510055, China

phstudentljy@mail.scut.edu.cn

Abstract. In recent years, optical fiber communication has gained widespread use in daily life due to its robust communication and transmission capabilities, strong confidentiality, anti-interference properties, and the availability of convenient and accessible materials. This technology has made remarkable strides in network communication and integrated device design, among other areas. This article will commence by discussing the fundamental structure of optical fibers and illustrating the propagation of optical signals within them. It will then analyze the benefits, such as higher transmission rates, wider frequency bands, and the low loss characteristics of optical fibers. Subsequently, the article will enumerate two of the most commonly utilized Optical Fiber Communication (OFC) technologies: Wavelength Division Multiplexing (WDM) technology and optical amplifier technology. It will summarize their principles and strengths. Finally, the article will showcase the practical applications of optical fiber communication, particularly focusing on its role in 5G mobile communication, military operations, and radio and television communication.

Keywords: optical fiber, wavelength division multiplexing, network communication.

1. Introduction

Optical fiber communication, also known as optical fiber communication technology, is a kind of modern information technology which was born at the end of the 20th century and has been developed rapidly since then. It is based on optical fiber to achieve high-speed and efficient communication. Fiber is a kind of pure glass fiber that can be wound, it is made of glass or plastic, and can be divided into many types, such as infrared fiber, quartz fiber, etc..... Figure 1 shows the basic structure of the optical fiber. Generally speaking, it consists of three parts from the inside to the outside: the core layer, the cladding layer and the coating. Among them, the core layer and cladding together constitute a concentric glass cylinder. The refractive index of the cladding layer n_2 and the refractive index of the core layer n_1 satisfy the following formula: $n_2 = n_1(1 - \Delta)$ (Δ represents the difference between the relative refractive index of the core layer and the cladding layer, and its value is generally between 0.2% and 1% for single-mode fiber or 1% to 3% for multi-mode fiber).

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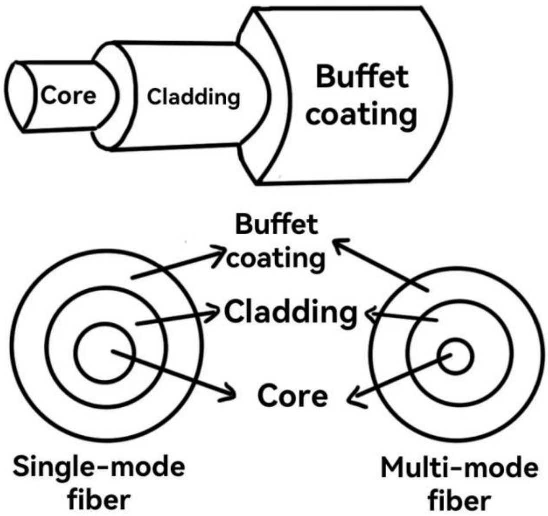

Figure 1. The basic structure of optical fiber [1].

As shown in Figure 2, optical fiber adopts the principle of total reflection of light to achieve the propagation of optical signals: when a beam of light waves incident from the end face of the fiber at a small angle, they will be partially or completely reflected on the interface of the core layer and the cladding layer to the interface on the other side, and then reflect again. Light signals rely on such a repetitive reflection process to propagate forward.

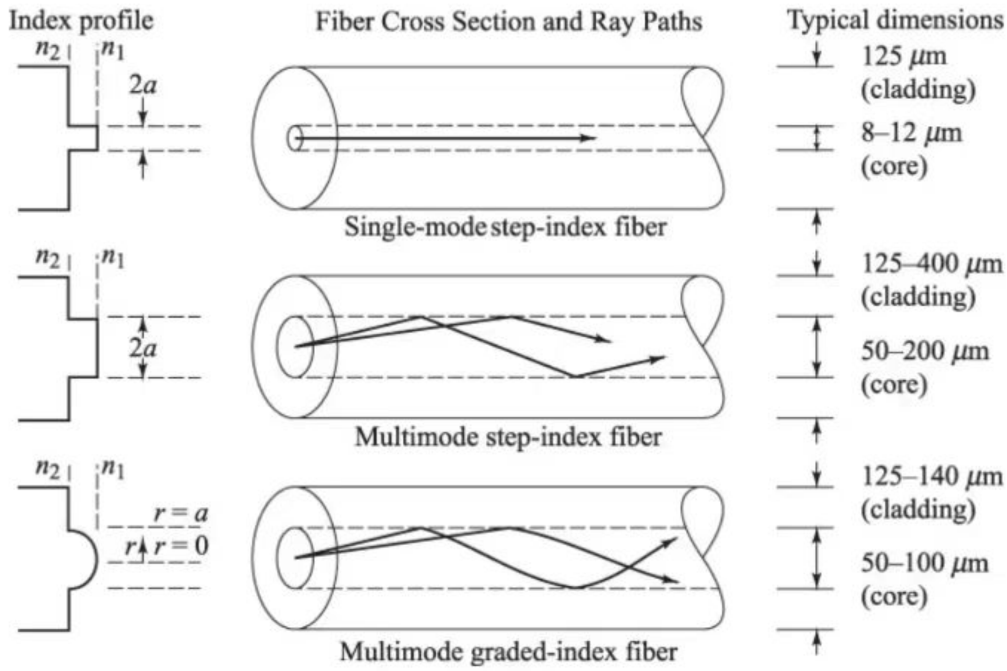

Figure 2. The schematic diagram of the propagation of the optical signal inside the optical fiber.

The coating layer, located at the outermost part of the fiber, is designed to protect the fiber, increases its toughness, so that it will not be easily damaged and corroded by external factors, and thus ensure that the optical fiber can achieve safe and reliable long-distance transmission.

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2. Advantages and disadvantages of optical fiber

As one of the most commonly used materials nowadays, optical fiber has the following advantages:

2.1. High transmission rate and a wide frequency band

The transmission capacity of the optical fiber is related to the width of the frequency band, the higher the carrier frequency, the larger the bandwidth of the transmitted signal, and the larger the transmission capacity. Currently available bandwidth is up to 50,000GHz. Although the bandwidth will be affected by the loss of optical fiber on different frequency components of light, the value can reach up to 30000GHz even in the lowest loss zone. In the VHF band, the bandwidth is only about 250MHz, so the value of optical fiber communication is about 200,000 times higher than VHF band! Thanks to this apparent advantage of optical fiber in bandwidth, it has been used in the transmission of multi-channel telecommunications since the early stages of its development [2].

2.2. Strong anti-interference ability

Optical fiber is mainly made of quartz, which has excellent insulation characteristics [3]. It does not conduct electricity and only transmits light, so the optical signal transmitted in the optical fiber will not be affected by electromagnetic interference and industrial interference and can be transmitted without loss. In addition, the light material itself also has good absorption, enabling full reflection of light. In this way, the transmission process of optical fiber also has good security. Signals are not easy to leak or to be stolen, so OFC is also favored in secure communication.

2.3. Low loss

In a system consisting of coaxial cables, the cable with the lowest loss will lose 40dB of signal per kilometer when transmitting a signal whose bandwidth is 800MHz. By contrast, when the optical fiber transmits lights with the wavelength of 1.55um, the loss per kilometer is only 0.2dB, only one hundred millionth of the coaxial cable. Consequently, light signals can be transmitted much farther in an optical fiber, which, in general, can reach tens of thousands of meters. In addition, the loss of optical fiber transmission is uniformly distributed in the cable channel and will not be fluctuated by external factors such as environment and temperature. All these make the expenses of constructing relay stations, equalizer greatly much lower, which is quite economic and environmentally-friendly.

Of course, it is undeniable that there are still some disadvantages in optical fiber communication:

2.4. High expenses of construction

The cost of building optical fiber communication network equipment is still relatively high. Compared with traditional copper wire communication, considerable optical fibers and related precision optical devices are the raw materials to conduct optical fiber transmission, and some economically underdeveloped countries are not able to afford this equipment, which makes it difficult to thoroughly popularize optical fiber communication technology in these places.

2.5. Apt to endure destruction

Secondly, some optical cables are exposed on the surface or in the air, and might be easily endure physical damage by construction, mining activities or various natural disasters, so they need regular maintenance and repair. The maintenance of optical cable also needs lots of money, which will eventually increase the economic burden of operators and even the government, to some degree.

3. Some OFC technologies and their advantages

3.1. WDM technology

WDM technology, also known as wavelength division multiplexing technology, can use multiple lasers to send several laser beams of different wavelengths on a single fiber at the same time, thus greatly improving the transmission capacity of the fiber. The realization of this principle mainly relies on light source devices, optical amplifiers, wave synthesizers and wave separators. In essence, the synthesizer and the separator belong to two different kinds of optical filters, which are generally placed at both ends of the optical fiber to multiplexed and demultiplexed different optical path signals respectively, and the multiplexed optical path signals are directly amplified by optical amplifiers, thus solving the ultra-long distance transmission problem of WDM system [4].

The popularity of WDM technology is due to the following advantages:

3.1.1. Large transmission capacity. WDM technology can conduct the propagation of multiple optical signals on a single optical fiber, so its transmission capacity is much higher than that of TDM technology. Generally speaking, in the WDM system, the multiplexed optical path rate ranges mostly from 2.5Gbit/s to 10Gbit/s, and the number of multiplexed optical path can be 4, 8, 16, and even more, so the transmission capacity of the whole system can be kept at about 300 to 400Gbit/s [5].

3.1.2. It saves optical fiber resources and construction costs. In a WDM system, no matter how many SDH subsystems exists, the entire multiplexing system only needs one pair of fibers to achieve bidirectional fiber transmission, while in a traditional single-wavelength system, one SDH system needs one pair of fibers. As the number of SDH systems grows larger, WDM systems can undoubtedly save a lot of fiber resources, and greatly reduce the cost and space required to construct optical fiber.

*3.1.3. Convenient and flexible networking. T*here are many potential applications of WDM technology, and the most prominent one is the formation of all-optical networks. In an all-optical network, through the adjustment of optical signals on the optical path, various services can be linked up and down or cross-connected, which helps to break the bottleneck of electronic devices in E/O conversion. The combination of WDM system and OADM can also form a variety of networks, including but not limited to long-distance trunk networks and multiple-access local area networks, providing them with a higher degree of transparency, flexibility and convenience to qualify the needs of broadband transmission networks.

3.2. Optical amplifier technology

Optical amplifier is a kind of active devices which directly amplifies optical signals without photoelectric conversion, and the most commonly used ones include erbium-doped fiber amplifiers and Raman fiber amplifiers.

Erbium-doped fiber amplifier mainly relies on the stimulated emission of the amplifier gain medium to achieve light amplification: when the external light source is stimulated, the erbium ion in the ground state will absorb the energy of the light and transforms to the stimulated state, and then the erbium ion will radiate energy to the surrounding ions, which will be transferred to other photons in the fiber, making them also transferred to the stimulated state. The process continues until the energy of the photon reaches the level required for amplification.

Although the structure of Raman fiber amplifier is similar to that of erbium-doped fiber amplifier, the basic principle of its light amplification is Raman scattering [6]. Raman scattering is a type of light scattering caused by specific vibrations of molecules or crystals. When light travels through a molecule or crystal in a medium, there is interaction between the photons, so that the vibration energy of a part of the atom or molecule is converted into the energy of the scattered light.

In general, the optical amplifier has the following advantages: First, it has a very significant amplification effect on the signal. In ordinary optical amplifiers, the input weak light signal is amplified to a higher power level to improve its transmission distance and transmission quality, which can effectively reduce the signal attenuation problem in long-distance fiber transmission and optical communication systems. Besides, it has high rate of response. Optical amplifiers amplify input optical signals in nanoseconds, which makes them widely used in optical sensing, high-speed communications, and other applications where signal processing speed is strictly demanded. Moreover, it is highly adjustable. For some optical amplifiers, the gain is adjustable, so the strength of the output signal can be accurately and flexibly adjusted according to requirements, making them accessible to a wide variety of systems.

4. Applications in network communication

4.1. 5G mobile communication

5G mobile communication, that is, the fifth-generation mobile communication development technology, is a new generation of broadband mobile communication technology with high speed, low delay and wide connection range. Its realization depends on the development of optical arc communication. Fundamentally speaking, optical arc communication belongs to all-optical nonlinear communication. The optical fiber itself has a sort of nonlinear characteristics, which leads to the compression effect of the optical signal pulse. Meanwhile, the internal group velocity dispersion can cause the optical pulse broadening. In the anomalous dispersion region, the compression and broadening of the pulse can neutralize each other, and the light pulse can form an optical arc, just like a single and isolated particle, maintaining a stable state in the transmission of the fiber, so as to achieve long-distance and large-capacity communication to meet the needs of 5G communication.

At present, with the support of optical fiber communication technology, 5G mobile communication has been tightly connected with people’s daily life. During people's work or study and life, it is often necessary to hold online meetings. However, the traditional network might lack stability, which leads to the embarrassing situation of frequent delay, which has negative effects on these meetings. The emergence of 5G mobile communication has improved the fluency and clarity of the conference [7]. In addition, 5G communication can also guarantee the reliability and speed of data transmission and improve the efficiency of information processing, so it can be used in various forms of network services such as the Internet of Things and smart homes.

4.2. Military operations and communications

In military operations, the situation of the battlefield is closely related to the quality of communication technology. If combat troops cannot receive instructions timely and accurately, they might misjudge the enemy's position and surrounding environment, resulting in serious consequences. In modern military wars, optical fiber communication is often used for tactical exchange and communication. Firstly, in the transmission process of signals, optical fiber communication has stronger pertinence and confidentiality, which is not easy to be monitored by the enemy; Secondly, the signal in optical fiber communication has strong anti-interference ability. It can not only safely conduct signal transmission, but also ensure the smooth progress of tactical communication in different battlefield environments; Thirdly, the size of the signal is smaller and more flexible, so when building the headquarters, it can go beyond the restrictions of time and space, thus reducing the cost of building routines of optical fibers.

In addition to communication between troops, optical fiber communication has also been instrumental in the manufacture of military equipment. For example, in the army operation, the principle of optical fiber guidance can be applied to produce missiles with long launching distance and high precision, and accurately hit the target through real-time tracking of the target’s image. The application of optical fiber communication technology in fighter aircraft can connect all parts of the aircraft with optical fiber lines, which can not only ensure the flexibility of the aircraft and the stability of the equipment on board, but also maintain the contact with the command center on the ground. Therefore, troops can accurately receive signals sent by the command center, without being affected by radio frequency and electromagnetic interference, and can reduce unnecessary trouble for the battle [8].

4.3. Radio and television communications

The application of optical fiber communication in broadcasting and television transmission is mainly divided into two categories: compressed transmission mode and uncompressed transmission mode [9]. In the compressed transmission method, the signal is compressed by the compression device before transmission, so that the light wave signal is compressed to reduce the space occupied by a single. Hence, more signals can be transmitted in a single channel at the same time. The uncompressed transmission mode aims to ensure the integrity of the transmitted signal in terms of format and content.

Based on the advantages of strong timeliness and low latency of optical fiber communication itself, broadcast and television optical fiber network can be organically combined with 5G communication technology to build a low-cost, high speed and stable information transmission channel, and promote the development of other emerging technologies, such as high-definition 4K TV technology and VR technology, to provide more high-quality programs and bring better viewing experience to the audience [10]. In addition, in the future, with the continuous improvement and development of optical fiber communication technology, "smart TV" and "smart broadcast" are no longer merely a fantasy, and the audience will no longer just passively receive the information but can quickly and selectively watch TV programs according to their own preferences and get the information they want.

5. Conclusion

As one of the fastest-growing and most eye-catching means of communication in modern times, optical fiber communication technology has brought much convenience to network communication and other aspects of people's daily life. It is believed that in the future, with the rapid improvement of optical fiber communication technology itself and its deepening combination with other fields, people are bound to develop more high-end, advanced, intelligent and environmental-friendly products. For example, with the combination of digital twins and traditional optical fiber communication technology, we are able to predict the environmental state and its transforming tendency, both inside and outside the optical network, more precisely, so as to allocate and deploy resources more timely. Furthermore, The in-depth development of all-optical network will make OFC technology more energy-saving, thus promoting the coordinated development of human and nature. In short, the advancement of OFC indeed plays an indispensable role in leading to a more efficient life.

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