Why are erbium doped fiber amplifiers used in fiber optic communications?

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Significant advances in the fabrication of optical fibers over the past decades have allowed them to replace coaxial copper cables as the transmission medium of choice for telecommunication and computer networking. The erbium-doped fiber amplifier outperforms every other amplifier in its class and is by far the most versatile amplifier for amplifying fiber optic communication signals. In this report, we will look at the properties of optical fibers and the erbium-doped fiber amplifier and explain why it has become the amplifier of choice in fiber optic communications.

I. FIBER OPTICS

A. Optical Fibers

An optical fiber is like a wire, but carries light signals instead of electrical signals. Physically, it is a cylindrical dielectric waveguide, usually made of silica glass or plastic due to their low loss properties. Light is guided through a central core cable, which has a small diameter compared to the cladding in which it is embedded. The cladding has a slightly lower refractive index. This allows light to undergo total internal reflection provided it is incident on the core-cladding boundary at an angle greater than the critical angle. Light at greater angles will lose some power into the cladding every time they get reflected and won't be guided. This allows certain light to travel from one end of the cable to the other, and allows for a flexible cable. This effect can be exploited to create different types of optical fiber, namely single-mode and multi-mode fibers[**?**].

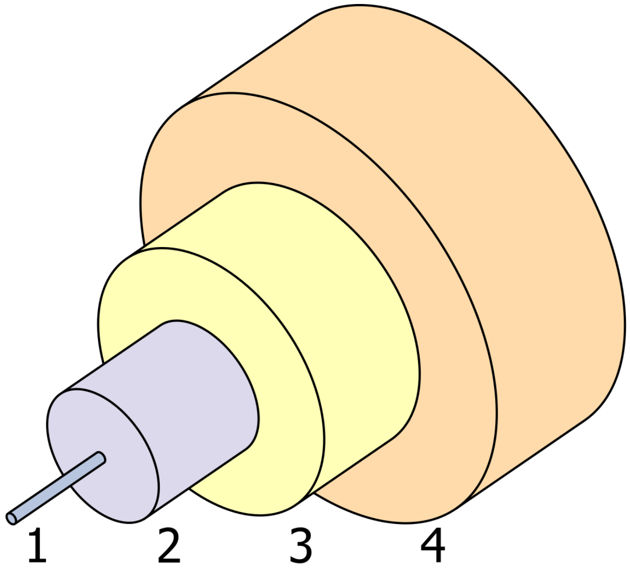

FIG. 1. Schematic of the internal structure of a typical single-mode optical fiber. 1. Central core. 2. Cladding. 3. Buffer encapsulates the inner core for mechanical isolation and to protection from physical damage. 4. Jacket for extra protection and fiber identification. (Source: Wikimedia Commons)

Single-mode fibers can only guide a single spatial mode, which generally has a Gaussian profile. This mode is similar in profile to the TEM_{00} mode, and is called the LP_{01} mode, or $l = 0, m = 0$ linearly polarized mode. Such fibers are made by having a tiny core, on the order of a few μm, and by having a cladding refractive index that is just slightly lower than that of the core. Multi-mode fibers on the the other hand, have a larger core, and a large index of refraction difference between the core and the cladding, which allows for the propagation of many more modes.

Typical losses in an optical fiber can be as low as 0.2 dB/km, which is close to the theoretical limit[**?**]. Recent advances in optical fibers have acheived gross transmission throughputs of 255 Tbit/s over a 1 km multi-mode fiber[**?**].

Interestingly, it's been demonstrated that an unpigmented human hair can act as an optical fiber. Hair color was found to be by far the most important factor in determining the attenuation properties of humain hair. Brown hair does not transmit light but grey hair does[**?**].

B. Fiber Optic Communications

Optical fibers are extensively used in communications and computer networking, where they significantly outperform electrical wiring in all regards, especially in terms of attenuation, and data bandwidth. As a result, they have made high volume trans-continental communications possible, and much of the internet backbone's infrastructure utilizes fiber optics[**?**].

Fiber optic communication systems tend to only use single-mode fibers. The different modes propagating in a multi-mode fiber may have different group velocities, which would distort the signal and have a massive effect over larger distances. This is called modal dispersion, as opposed to the more common chromatic dispersion. While single-mode fiber signals can go over 100 km without any need for amplification or processing, multi-mode signals require processing every few kilometers[**?**].

Multi-mode fibers are still useful for communications over shorter distances such as in local area networks, and between buildings. They also have many uses in photonics, where they can be used to send high power beams where a high mode area is required, or if your beam quality is poor.

The fiber itself is electrically non-conductive so it's immune to electromagnetic radiation and would not pick up any electromagnetic signals by acting as an antenna. This also means you don't have to worry about ground loops distorting the signal or about lightning striking the cable. Fiber optics can even be used alongside electrical wiring without any interference.

Optical fibers have plenty of other applications besides being a communication medium. They can be doped and act as a gain medium, allowing you to build fiber lasers and fiber amplifiers. They can be used as sensors, and for transporting light from one place to another, acting as the electrical wire analogue for light signals.

C. Doped Fiber Amplifiers

Optical fibers can act as a gain medium if doped, usually with rare earth ions such as Er^{3+}, Nd^{3+}, or Yb^{3+}. You can use such a fiber to build a fiber amplifier then, which would just be a device that amplifies an optical or light signal directly, without having to convert it to an electrical signal first. Such amplifiers are called doped fiber amplifiers, and can actually amplify light without an optical cavity[?].

II. ERBIUM-DOPED FIBER AMPLIFIERS

The most common example of a doped fiber amplifier is the Erbium-doped fiber amplifier (EDFA). The core of a silica fiber is doped with Er^{3+} ions, which can be efficiently pumped at 980 nm or 1.4 μm, and exhibits gain in the 1.5 μm region. The 1.5 μm region is an extensively used transmission region. This is where optical fibers experience minimum transmission loss, and as a result, is the most commonly used region when working with them. The fact that EDFA's can efficiently amplify signals in this region has been responsible for its popularity. Advances and improvements over the past few decades have only made the EDFA a better amplifier for these signals, and today it is unmatched for amplifying fiber optic telecommunication signals[?].

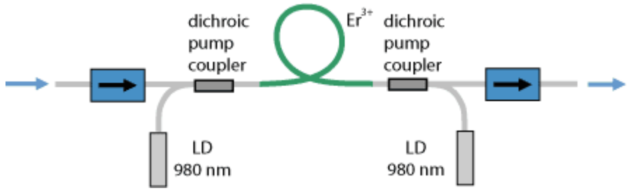

FIG. 2. Simple bidirectionally pumped EDFA setup. The Er^{3+} doped fiber is pumped by 980 nm laser diodes. The pump is coupled with the signal light via dichroic fiber couplers. Faraday isolators are placed on both sides to prevent signal back-reflection, which may damage the amplifier. (Source:[?])

The doped fiber is pumped with a laser, typically a laser diode, which is just a semiconductor laser in which the gain medium is a p-n junction, like in a light emitting diode. The fiber can be pumped through only one end, or through both ends which would require two laser diodes. Both are commonly used. The pump frequency is usually picked to be 980 nm to excite the Er^{3+} ions to the ${}^4I_{11/2}$ state, or around 1.4 μm, exciting them to the ${}^4I_{13/2}$ state. The EDFA acts as a quasi-three level laser, and eventually in either case, stimulated emission back to the ${}^4I_{15/2}$ state would cause the emission of a 1.5 μm photon. This wavelength coincides with the wavelength of the light signal we want to amplify, which would usually be 1.5 μm to make use of the optical fiber's minimum loss. The EDFA is a quasi-three level laser because the ${}^4I_{15/2}$ state is close enough to the ground state that it is partially occupied at thermal equilibrium[?].

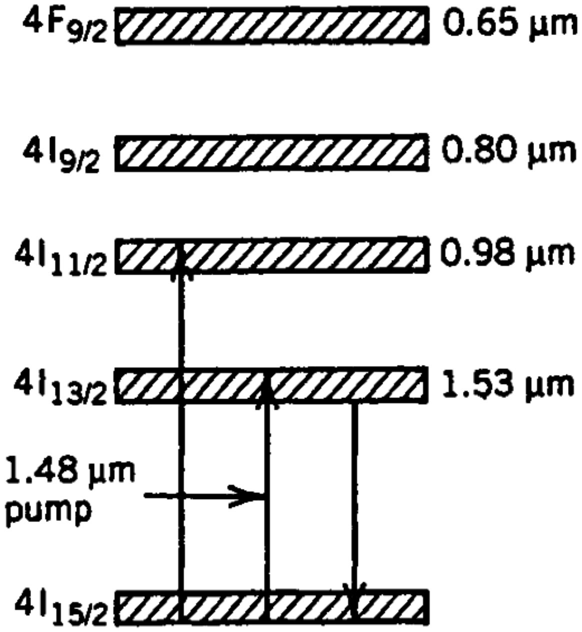

FIG. 3. Energy diagram of Er^{3+} ions in silica fibers. (Source: [?])

A. Gain Spectrum

The electronic transitions of isolated ions are well defined, but the Er^{3+} ions are embedded in the fiber, and so their energy levels are broadened, allowing for a variety of possible photon emissions around the 1.5 μm region. This broadening is homogeneous and slightly inhomogeneous. The homogeneous broadening causes all the ions to experience the same broadening, and is due to interactions with phonons in the fiber itself. The inhomogeneous broadening causes individual ions to experience different broadening, and is due to their location and surroundings being different, exposing each ion to different local electric fields which would shift the energy levels of each ion differently due to the Stark effect[**?**].

This broadening gives the EDFA a rather wide amplification window, which is the range of wavelengths over which signals may be amplified. This is another great feature of the EDFA, as it allows multiple widely used transmission bands to be amplified. Namely the conventional band or C-band (1530-1565 nm) and the long band or L-band (1565-1625 nm). The C-band is even named the conventional band since that's exactly the region of optimal EDFA operation[**?**].

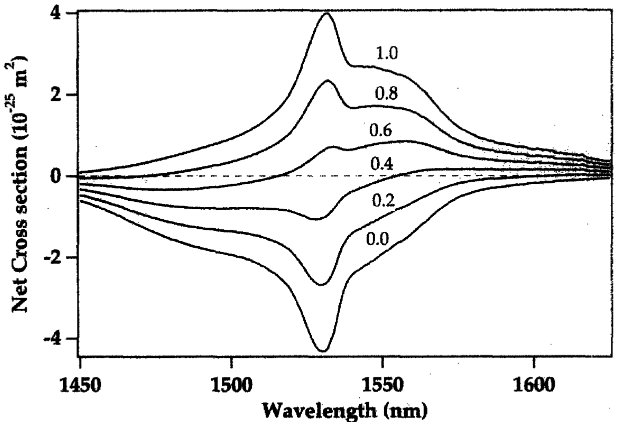

FIG. 4. Net cross section (absorption minus the emission cross section) of Er^{3+} in the 1.5μm region, for different excitation levels of the Er^{3+} population. The net cross section is proportional to the gain, so this would look exactly like the gain spectrum of Er^{3+}. (Source: [**?**])

The wide amplification window also allows the possibility of amplifying signals with multiple wavelengths mixed in, or wavelength division multiplexing (WDM). This is when signals of slightly different wavelengths are combined, transmitted together, then separated. So really it's the same as regular frequency division multiplexing but uniformly spaced wavelengths do not correspond to uniformly spaced frequencies due to the inverse relationship between wavelength and frequency. WDM significantly boosts the transmission capacities of optical fibers and is responsible for the huge improvements seen over the past couple of decades in internet speeds[**?**].

The gain spectrum of the EDFA can be made flatter over the entire region by using either modified optical fibers or by placing differently doped EDFAs in series such that their total gain spectrum is flat. The allows almost uniform gain across a wider region of wavelengths and allows the EDFA to uniformly amplify WDM signals. This makes the EDFA even more useful because it can then efficiently amplify multichannel signals, allowing for higher data bandwidth while keeping the low loss benefits of using a single-mode fiber[**?**].

B. Properties

While standard telecom fibers, i.e. mostly silica fiber, experience their minimum loss in the 1.5 μm region, they still have nonzero chromatic dispersion in this region. They exhbit zero chromatic dispersion in the 1.3 μm region, which is where early optical fiber communication systems operated. However, with the dominance of the EDFA, operation in the 1.5 μm region became more desirable but the sometimes significant dispersion was an issue. This is until dispersion-shifted fibers were developed, which moved the zero chromatic dispersion wavelength into the 1.5 μm region by modifying the refractive index profile of the core. While not a property of EDFA's, it did contribute to their wide use. You can't shift the region of minimum loss into the 1.3 μm but you can shift the region of zero chromatic dispersion into the 1.5 μm region so the EDFA wins.

Other dispersion modifications are possible and sometimes sought after. Zero chromatic dispersion is actually not a good thing for transmitting WDM signals, as four-wave mixing effects can cause distortions due to different channels adding in phase without the dispersion. Having some chromatic dispersion is good here as it stops different channels from staying in phase, but you want to control the amount of dispersion. Cables with non-zero dispersion in the 1.5 μm region, and zero dispersion elsewhere have been developed, and allow you to avoid such distortions. Apparently you can also avoid this problem by using non-uniform channel spacing when transmitting WDM signals[**?**].

Another reason that EDFA's are an excellent choice for amplifying WDM signals is that they have very small cross talk between respective channels, causing minimal distortion even over longer distances. This is due to their relatively long gain saturation recovery time[**?**]. The cross talk is actually negligible for frequencies higher than several kHz, and so, even dense WDM signal amplification is possible over long distances.

The high gain of the EDFA combined with the low attenuation of optical fibers allow them to transmit signals over long distances without frequent need for amplification. This allows EDFA's to be used for undersea and trans-continental telecommunication. They have been deployed on the ocean floor to span cable distances of over 10,000 km, with a repeater spacing of 240 km[**?**].

C. Other Applications

EDFA's can, of course, be used in any application where high gain is required. Any time you have a long fiber or a system with huge losses, you can put an EDFA before the input. Or if you're splitting a signal into many fibers, like in the case of transmitting a consumer TV signal. I suppose this is an advantage of any amplifier but the EDFA is so versatile it can be used in virtually any telecommunication system.

The low noise figure of EDFAs allow them to be cascaded, which can provide even higher gains. In particular, early attempts at long distance coherent multichannel optical transmission relied on cascaded amplifiers, and they are still useful[**?**].

III. CONCLUSION

Optical fibers have become the medium of choice for telecommunication and computer networking. An amplifier capable of efficiently amplifying signals in optical fibers was of course highly desired, and the EDFA proved to be the best amplifier to do this. As a result, it has seen a lot of development, and now vastly outperforms every other amplifier in its class, leading it to become the amplifier of choice for fiber optic communications.

EDFA's can efficiently amplify light in the 1.5 μm region, which is an especially important region in telecommunications where optical fibers exhibit minimum loss and so it became a widely used transmission window. EDFA's have a broad usable gain bandwidth, which allows the efficient amplification of various widely used transmission windows in telecommunications. With some design tuning, EDFA's can efficiently amplify WDM signals and transmit them over long distances in single-mode fibers. This has led to huge advances in data transmission throughput over the past couple of decades. EDFA's also exhibit negligible cross talk between respective channels, making long distance WDM signal transmission a reality. Optical fibers that shift the zero chromatic dispersion into the 1.5 μm region exist, and allows EDFA's to efficiently amplify signals with both minimal loss and minimal chromatic dispersion. EDFA's have high gain and coupled with the low loss characteristics of fiber optics, can be used to transmit signals over very large distances, with a relatively large repeater spacing.

The improvements in consumer internet speeds we've seen in the past decade can be attributed to our ability to transmit large amounts of data efficiently to anywhere in the world via fiber optics, and every time you send or receive something from the internet, that signal probably went through a few EDFA's along the way.

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