Research Progress and Development Trends of L Band Fiber Lasers

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Abstract. Fiber lasers have developed rapidly in recent years and play an important role in many fields. The L band refers to a wavelength range in fiber optic communications, usually between 1570 nanometers and 1625 nanometers. At present, research on L-band fiber lasers mainly focuses on improving their output power, enhancing spectral purity, and reducing costs. In this article, the author discusses the research progress and development trends based on the development of fiber lasers in the 1570 nm to 1650 nm band at home and abroad. Through investigation and research, it can be concluded that after 30 years of rapid development of single-frequency fiber lasers, the average power is hundreds of watts, the peak power is several kilowatts, the laser line width is 100 Hz, the intensity noise is close to the quantum noise limit, and the wavelength tuning range is tens of nanometers. Despite great progress, there are still some deficiencies in basic research and applied technology that need more development.

Keywords: Fiber lasers; L band development; nanometers.

1. Introduction

Over the past fifty years, fiber laser technology has advanced. Over the past 20 years, fiber laser technology has developed quickly thanks to the quick advancement of diode laser technology, sophisticated fiber production technology, and novel pumping methods. Due to their inherent benefits and appealing characteristics, fiber lasers have found extensive application across multiple fields[1]. The benefits of single-frequency fiber lasers are all-fiber structure, high conversion efficiency, good coherence, low noise, and compact line width. They find applications in high-precision spectrum measurement, laser weaponry, laser radar, coherent optical communications, space laser communications, and gravitational wave detection, among other fields. With so many potential applications, the field has emerged as a laser research hotspot. After thirty years of development, single-frequency fiber lasers have advanced significantly in both basic research and application technology since Ball et al. of the United Technology Research Center in the United States achieved single-frequency laser output in Er3+-doped silica fiber in 1991 using a short linear cavity. Nonetheless, there are still certain scientific and technological issues that require immediate attention. Numerous domestic units have studied single-frequency fiber lasers, each with unique properties. For instance, research on 1.0μm and 1.5μm DBR single-frequency fiber lasers is primarily conducted at Beijing University of Technology. Studies on the use of DFB-type single-frequency semiconductor lasers as seed sources for 2.0μm single-frequency fiber laser power amplification are also being conducted at the Chinese Academy of Sciences. Optics Shanghai Research on pulsed single-frequency fiber lasers and ring-cavity single-frequency fiber lasers has been done by the Institute of Precision Machinery and Tianjin University, respectively.

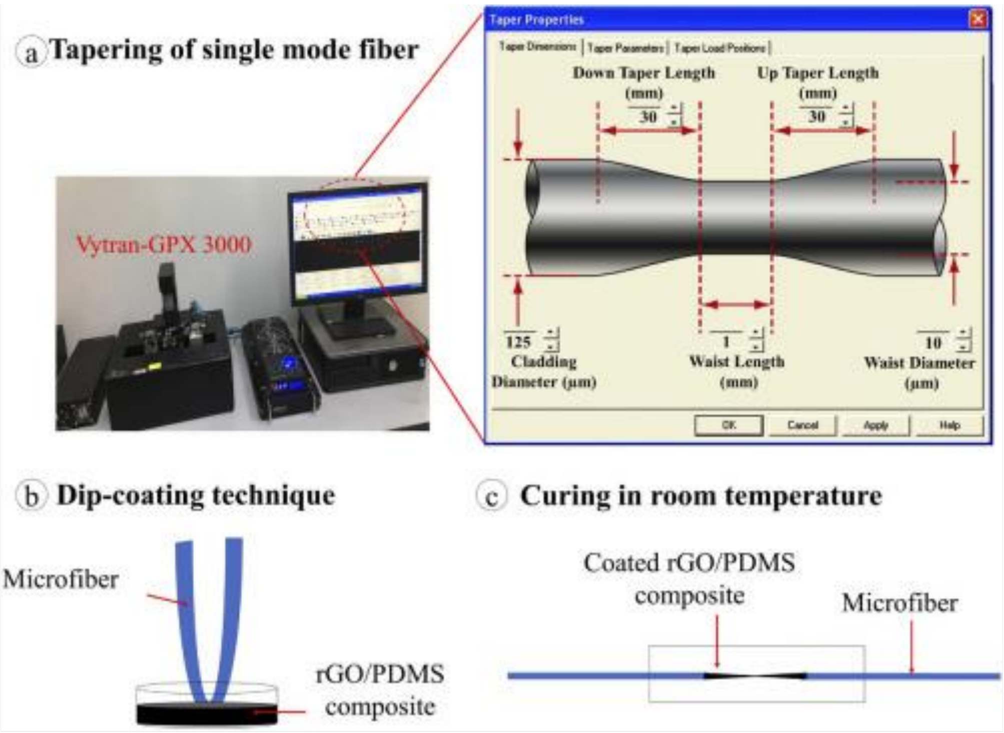
Through the investigation of domestic and foreign research on L-band fiber lasers. The author found that the development directions at home and abroad were different, which can be briefly understood in this article. This article will discuss the current development of fiber lasers at home and abroad, and provide suggestions and prospects for the future development of L-band fiber lasers and existing problems.

2. L band Passively Mode-locked Erbium-doped Fiber Laser

L band femtosecond fiber laser based on a reduced graphene oxide polymer composite saturable absorber. Presenting an L band passively mode-locked erbium-doped fiber laser with a pulse train of 5.68 MHz that emits at a wavelength of 1599.43 nm. Used to create the microfibre-reduced graphene oxide composite, which exhibited the behavior of a saturable absorber. They were observed during operation. It was several times lower than the majority of the earlier evaluations in the same class of graphene-saturable absorbers and wavelength bands. Pulse had a maximum average output power of 6.75 mW and a duration of 568 fs. The straightforward fabrication method's superiority made it easier to produce in large quantities for use in the ultrafast photonics sectors.

The in-situ wet chemical and dip-coating techniques were used to create the microfibre-reduced graphene oxide composite, which exhibits the behavior of a saturable absorber. At a mode-locking threshold of 40 mW, a single-pulse solution was observed during operation. This is several times lower than the majority of the earlier evaluations in the same class of graphene-saturable absorbers and wavelength bands. The pulse had a maximum average output power of 6.75 mW and a duration of 568 fs. Furthermore, this straightforward fabrication method's superiority makes it easier to produce in large quantities for use in the ultrafast photonics sectors[2].

The fabrication plan uses dip-coating (see Fig. 1), microfibre tapering, and in-situ wet chemicals for material preparations. This started with the dispersion of 0.8 mg of granules in 10 ml of IPA using an ultrasonic probe (Hielscher UP200s) for one hour. The homogenous rGO solution was supplemented with 1.0 g of polymer (PDMS) following sonication. This was heated to 80°C for 16 hours while being constantly stirred at about 200 rpm to guarantee that all of the solvent had evaporated. This stage is essential for the rGO/PDMS combination to solidify. After adding 0.1 g of curing agent, the liquid was agitated for ten minutes. The mixture was degassed in the vacuum oven (CONSTANCE VC-6050) for thirty minutes to eliminate any bubbles[2].



Down Taper Length (mm) 30
Up Taper Length (mm) 30
125 Cladding Diameter (µm)
1 Waist Length (mm)
10 Waist Diameter (µm)

Fig 1. Deposition processes (a) tapering of single-mode fiber, (b) dip-coating of rGO/PDMS composite on the microfiber and (c) sample curing at room temperature[2]

A single-mode fiber (SMF-28) was decoated (3 cm length) to prepare it for microfiber tapering. The fiber was then placed into stage holders of a glass processing workstation (Vytran GPX-3000). With a waist diameter of 10 µm, a waist length of 1 mm, and a taper transition of 30 mm, the taper properties are displayed in Fig. 1(a). With a tapering loss of less than 0.3 dB, these choices allowed for adiabaticity while maintaining a significant evanescence interaction length. The integrated software allows for exact adjustment of the heat source to produce the desired microfibre diameter. Following the tapering procedure, as shown in Fig. 1(b), the microfiber was coated for 20 seconds using a dipping method with the completed rGO/PDMS composite. Next, as illustrated in Fig. 1(c), the microfiber was adhered to a sample holder with a slot using epoxy glue. To harden and stabilize the composite, this stand was placed in a dry cabinet and left there for a whole day[2].

3. Method through Numerical Simulations

It has not yet been possible to use fiber lasers to generate mode-locked pulses and continuous wave (CW) lasers simultaneously. The concept may find use in several specialized photonics and optical communications applications. Consequently, using numerical simulations, a novel technique for training mode-locked pulses and producing CW lasers simultaneously was developed. It involved connecting two cascaded cavities of tunable Erbium-doped fibers (EDFs) in the C+L-band (1555–1625 nm) via a fiber Bragg grating (FBG). An active mode-locked fiber laser is realized using an MZM positioned within the second cavity and controlled by Gaussian pulses at a repetition rate of 2 MHz. This MZM produces a train of pulses with a full-width at half maximum (FWHM) of around 38 ns. The suggested design is tailored for the Er3+ doping concentration and EDF length[3].

Numerous applications in optics and photonics can benefit from the cascaded C+L-band tunable Erbium-doped Fiber laser design that has been proposed. As was previously indicated, one specific use of the suggested design in microwave photonics is the creation of UWB and mm-wave signals entirely optically. As shown in Fig 2, UWB and mm-wave signals are produced using two specialized semiconductor lasers tuned at different wavelengths, one of which is data-modulated and the other CW. Wang and associates[3].

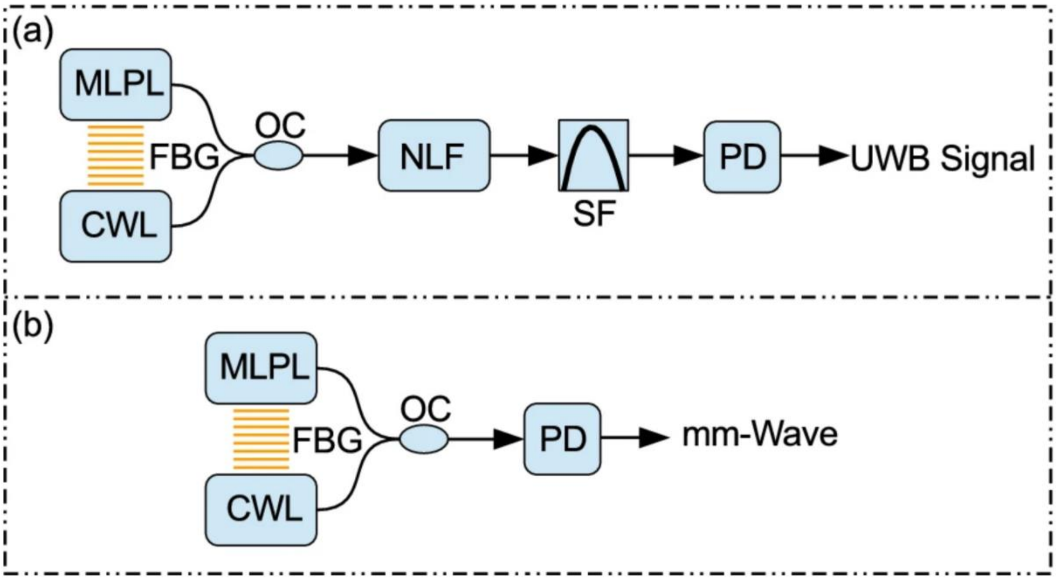


Fig 2. Application of the proposed design [3]

Make two co-doped silica fibers (BELDFs) of Bi/Er/La. The gain-spectrum bandwidth of the gain >17 dB is up to 58 nm (1565-1623 nm) based on a dual-pump system, and the fluorescence-spectrum bandwidth of the intensity >−35 dBm approaches 75 nm (1548-1623 nm) with the high-concentration doped BELDF. Subsequently, a two-stage triple-pump amplification is examined, allowing the L-band gain bandwidth to be increased to 1625 nm with a gain of more than 16 dB and to 58 nm (1562-1620 nm) with a gain of more than 25 dB. The results show that using the homemade BELDF has a lot of potential applications for optical amplifiers, fiber sensors, fiber lasers, and other devices. It can also be a useful solution to the transmission capacity bottleneck of silica optical fiber communication systems in the future[4].

4. Results and Discussion

This letter describes two types of Bi/Er/La co-doped silica fibers (BELDFs) and how they were developed in order to create an extended L-band amplifier with a dual-stage, bi-directional pump configuration. Research is done on the amplification performances using a wide bandwidth and high gain.By integrating atomic layer deposition (ALD) technology with the modified chemical vapor deposition (MCVD) method, two types of BELDFs are produced. A fiber cross-sectional elemental composition test is performed on two constructed BELDFs using an electron probe micro-analyzer (EPMA-8050G, SHIMADZU, Japan). As shown in Fig 3, elements Bi, Er, La, Al, Ge, O, Si, and P are present in both BELDFs. In BELDF-1, the atomic percentages of Bi, Er, and La are 0.004, 0.015, and 0.007, respectively; in BELDF-2, they are 0.007, 0.028, and 0.015[4].

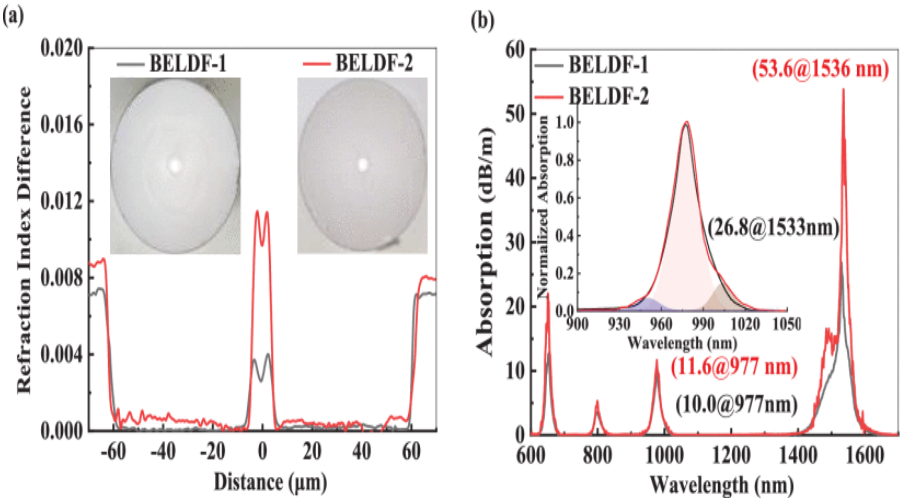


Fig 3. Fiber properties of two BELDFs. (a) Refraction index distribution and cross-section (insert). (b) Attenuation spectra [4]

L-band lasers are widely employed in modern optical telecommunication systems because they may increase the transmission capacity. Fiber lasers are more advantageous in practical applications than bulk laser systems due to their small size, affordability, robustness, and efficient heat dissipation. Moreover, silica fibers have very little L band loss. Researchers' interest in L-band fiber lasers has increased recently because of their practical advantages. In long-distance optical fiber transmission systems, there is an increasing need for communication capacity due to the quick development of computer networks and other innovative data transfer services. A popular topic in the field of optical communications is how to further increase communication capacity using the current optical fiber transmission system to fulfill this growing demand [5].

An enhanced stacking-drawing technique was employed to effectively create a nested tube-type hollow-core anti-resonant fiber (NestedHC-ARF) with ultra-low loss in the communication C+L band, thereby reducing the transmission loss of the hollow-core anti-resonant fiber in the communication band even further. The average transmission loss in the 1545–1660 nm spectral band is 0.38 dB/km, and the fiber preparation length is 720 nm. Simultaneously, the fiber high-order mode suppression ratio is 38.9dB, and the fiber LP11 mode loss reaches as high as 2.96dB/m. The created NestedHC-ARF is projected to be deployed as a new generation of transmission optical cable in optical fiber communication systems because of its very high fiber mode purity and ultra-low transmission loss, which is on par with that of solid-core single-mode fiber, according to the measurement results. The Nested HC-ARF structural model, which is seen in Fig 4(a), was created using the theoretical analysis mentioned above. The optical fiber has the following dimensions: its outer diameter is 250 μm, its core diameter is 40 μm, the inner and outer nested capillaries have sizes of 22 μm and 42 μm, respectively, and the quartz wall thickness is 1.1 μm. The second-order light guide passband of the NestedHC-ARF design has a central wavelength of around 1550 nm. The transmission loss of the NestedHC-ARF design was quantitatively analyzed using the finite element modeling program

COMSOL Multiphysics. The transmission loss spectrum of the design model, which was calculated by simulation, is displayed in Fig 4(b). Optical fiber has a low-loss transmission wavelength of 1200 nm to more than 1700 nm. In the 1290–1700 nm wavelength region, optical fiber loss is less than 0.3 dB/km[5].

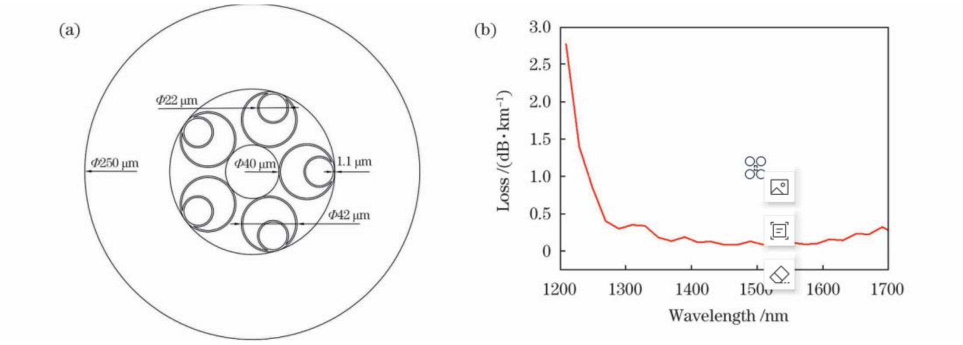


Fig 4. Designed Nested HC-ARF model a Structural diagram b simulated loss spectrum[5]

Er3+-doped or Er3+/Yb3+ co-doped gain fibers serve as the foundation for single-frequency lasers that mostly operate in the 1.5μm band (C-band: 1530~1565nm) and a portion of the L-band (1565~1625nm). Since its wavelength falls within the C window of optical fiber communication, the 1.5 μm band single-frequency fiber laser is highly valuable in coherent optical communication, high-resolution sensing, optical frequency domain reflectometry, lidar, and other related fields. Its narrow linewidth and low noise characteristics further enhance its utility. Furthermore, high-resolution molecular spectroscopy, lidar, high-performance pump sources for Tm3+-doped lasers, and nonlinear frequency conversion can all benefit from the employment of eye-safe L-band single-frequency fiber lasers[6].

In 2017, squareg et al. announced a 1.6μm single-frequency fiber laser employing Er3+/Yb3+ co-doped phosphate with a length of 1.6cm. This was achieved at a wavelength of around 1.6. A DBR short cavity was created using the optical fiber. A 1603nm linearly polarized single-frequency laser output with a power of 20mW and a line width of 1.9kHz was achieved by improving the Bragg grating settings and gain fiber length. At 5 MHz/Hz, its relative intensity noise was less than -140 dB. / Hz. Fig 5 displays the diagram of the experimental gadget. This research group's Yang et al. amplified a 1.6 μm single-frequency fiber laser seed source in 2018 using the MOPA structure. A large mode field area Er3+/ with a length of 4 m and a core diameter of 25 μm was employed in the primary amplification stage. A continuous single-frequency laser output at 1603 nm with a power of 15 W, a line width of 4.5 kHz, and a polarization extinction ratio better than 23dB was achieved using Yb3+ co-doped polarization-maintaining double-clad fiber[6].

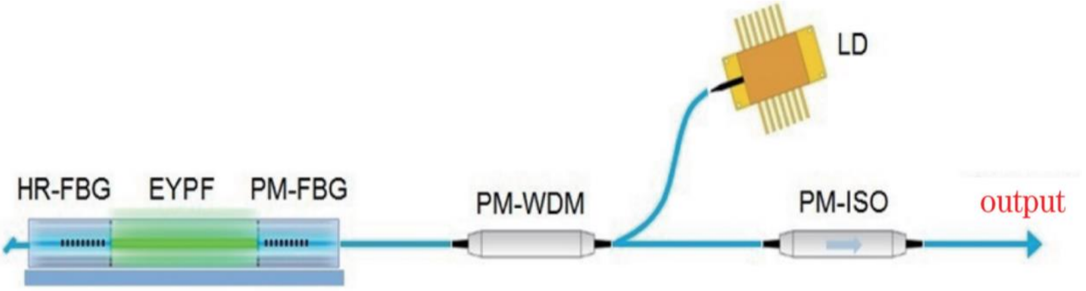


Fig 5. Structural diagram of 1.6μm linearly polarized DBR single-frequency fiber laser[6]

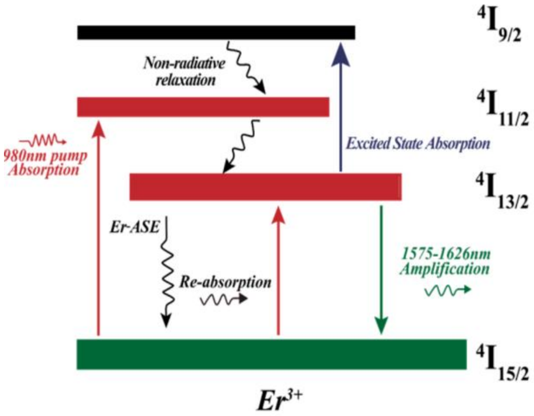


Fig 6. Energy level diagram of Er3+[7]

Erbium-doped fiber amplification (EDFA) has opened a new era in large-capacity optical fiber communications and greatly increased the data transmission capacity of optical fiber communication systems. It has also encouraged the application and development of dense wavelength division multiplexing technology.

Domestic BELDF has enormous potential application prospects in optical amplifiers, fiber sensors, lasers, etc., and can become an effective solution to the transmission capacity bottleneck of quartz fiber communication systems in the future through domestic and international research on L-band fiber lasers. was possible to obtain an extremely low transmission loss in the C + L band of 0.38dB/km and a 38.9dB suppression ratio for the fiber's high-order mode. series of hollow-core anti-resonant optical fibers with outstanding light-guiding properties, the 0.38dB/km ultra-low loss NestedHC-ARF in the C+L band, is crucial for advancing the independent controllability of key technologies for high-quality hollow-core optical fibers made in the country. As shown in Fig 6, Er3+/Yb3+ co-doped phosphate fiber of 1.6 cm in length is used in the 1.6μm single-frequency fiber laser to create a DBR short cavity. The Bragg grating settings and gain fiber length were optimized to yield a 1603nm line with a power of 20mW and a line width of 1.9kHz. At a frequency of 5 MHz, the relative intensity noise of the polarized single-frequency laser output is less than -140dB/Hz. If you follow the “checklist” your paper will conform to the requirements of the publisher and facilitate a problem-free publication process.

5. Conclusion

After 30 years of rapid development, single-frequency fiber lasers achieve outputs with average power of hundreds of watts, peak power of several kilowatts, laser linewidth of hundreds of Hz, intensity noise close to the quantum noise limit, and wavelength tuning range of tens of nanometers. In-depth research and development is presently being done on single-frequency fiber lasers with an eye toward high power/high energy, ultra-narrow linewidth, ultra-low noise, unique wavebands, and tunable wavelengths. Notwithstanding significant advancements, fundamental research and application technology continue to face challenges. There are a few issues. The output power needs to be further improved. There are relatively few reports on pulsed single-frequency lasers with high peak power/high pulse energy, and their technical research needs to be further promoted.

New rare earth ion-doped optical fiber materials need to be further explored. The advancement of single-frequency fiber laser technology will significantly raise its scientific and practical value while supporting state-of-the-art research, national economic growth, and national security requirements.

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