Principle of Free-electron Laser and Applications in Medical Research and Lithography

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Abstract. In recent years, as a breakthrough light source technology, free-electron laser (FEL) has the unique advantage of producing coherent radiation with high brightness, high energy, good directivity and excellent monochromaticity. With this in mind, this study will systematical discuss the historical development of FEL technology, from Einstein's laser theory to Dr. Maiman's first commercial laser, as well as the birth and evolution of FEL. To be specific, the basic principles and construction of FEL technology will be discussed in detail, including key components such as electron sources, electron accelerators, and oscillators. The application of free electron laser (FEL) technology in medicine and lithography will also be demonstrated in this paper. According to the analysis, the current limitations of the state-of-art facilities as well as the future development trends and improvements for FEL system will be clarified based on the evaluations. Overall, these results shed light on guiding further exploration of FEL techniques.

Keywords: Free-electron lasers, medicine, lithography.

1. Introduction

In retrospect, the exploration of light is endless. Every time there is a new understanding and utilization of light, it will promote the progress of human society and science. Laser is a milestone invention in human history. The emergence of coherent light sources with high brightness, high energy, good directionality and good monochromaticity has been provided for human science. Tracing back the development of lasers, the first theoretical cornerstone is the theory of stimulated emission and spontaneous emission proposed by Albert Einstein in 1916, that is, photons can excite atoms to emit the same photons. Russian physicist Valentin a. Fabrikant pointed out that under certain conditions, stimulated radiation may produce amplified light. Later, Charles H. Townes proposed a newer concept. He proposed that in the resonant cavity, the stimulated radiation of microwaves would oscillate, thereby producing coherent output. Then Townes and his students used excited ammonia molecules to oscillate in the resonant cavity at Columbia University, thus obtaining the first maser. Light amplification by stimulated emission of radiation is known as "laser" and was first used by Gould in 1957 [1]. In 1960, 44 years after Einstein proposed the theory, Dr. Theodore Harold Maiman produced the first commercial laser, the ruby laser, thus turning stimulated emission from theory into practice [2]. Since the first ruby laser, it inspired many researchers to manufacture lasers, which made the laser technology develop rapidly. After the 1960s, many types of lasers emerged, such as Carbon dioxide laser, sapphire laser, Semiconductor lasers and, in this article, free-electron laser (FEL).

In fact, long before the advent of the ruby laser, someone had proposed the idea of using electron stimulated Compton scattering to generate coherent electromagnetic radiation. Subsequently, Motz et al. proposed to use alternating periodic magnetic fields to make electrons generate spontaneous radiation. However, due to the rapid development of conventional lasers at that time, the development of coherent radiation of free electrons was relatively slow. This situation was not until 1971 when J. Madey of Stanford University first proposed the theory of using free electrons to pass through an undulator with a periodic magnetic field to generate laser light, which is the famous Madey theory. In 1977, Madey et al. successfully made free electrons generate laser light in oscillation mode, and created the free electron laser. After that, FEL began to attract the attention of researchers and the international scientific and technological community. Free-electron lasers with low and high gains theories were also proposed one after another, and free-electron lasers were also developed in the

direction of short-wavelength and high-gain. At the end of the 20th century, when traditional lasers were stuck in a bottleneck, UCLA researchers realized the verification of the SASE mode, which also proved high-gain theory [3]. Therefore, free-electron lasers began to develop rapidly, and in addition to the SASE mode, various high-gain operating modes began to be continuously proposed and tested. In the 21st century, researchers realized soft X-ray free-electron laser devices. In 2009, G. Stupakov et al. proposed a new mode EEHG, that is, echo-type harmonic generation FEL. This mode can greatly increase the conversion rate and achieve a shorter wavelength FEL.

FELs have unique properties that differ from conventional lasers. Unlike conventional lasers, FELs use free electrons to generate coherent, high-power radiation, and synchronization of electron beam with a fluctuating magnetic field facilitates radiation emission. This mechanism leads to the amplification of self-luminescence and the generation of strongly coherent light. the capacity to regulate the accelerated electrons' energy provides tunability not found in other laser systems. This property enables FELs to span a broad wavelength range, making them ideal tools for a variety of applications. Compared with traditional lasers, FEL has the advantages of shorter wavelength, monochromaticity, better coherence, shorter pulse length and higher brightness [4].

Advances in FEL technology have led to countless applications in different fields. This article focuses on the application of FEL in the fields of medicine and lithography. In recent years, FEL has received extensive attention for its outstanding contributions in medical research and diagnosis. It can play an important role in generating high-resolution imaging and spectroscopic data [5], which enhances our understanding of biological structures and processes. Furthermore, its coherence and tunability make FELs a tool for probing molecular dynamics and elucidating complex biochemical interactions. In lithography, FELs have transformed semiconductor manufacturing, especially in extreme ultraviolet (EUV) and next-generation light sources [6]. The shift to smaller feature sizes in semiconductor chips requires the development of light sources with shorter wavelengths. FELs, especially high-power EUV sources operating at 13.5nm, have enabled the production of finer features and increased chip densities, contributing to the advancement of modern electronics. This article aims to introduce the history, current situation, basic principles and structure of FEL, summarize and generalize applications of FEL in the fields of medicine and lithography, and analyze its limitations and future research prospects.

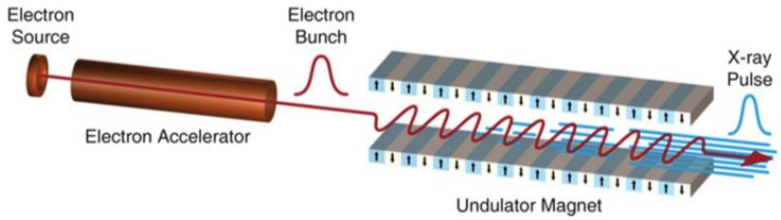


Figure 1. The structure of FEL

2. Basic Descriptions of FEL

Free electron lasers use free electrons as working substances to produce strong coherent radiation with adjustable wavelength. It is different from the traditional laser generation principle. The general laser generation principle is to stimulate the working substance in the excited state to radiate through the pump source to produce laser light with the same frequency, phase and direction. Compared with the bound electrons in traditional lasers, FEL uses high-speed electrons to interact with an external magnetic field, converts the kinetic energy of electrons into photons, and amplifies the light through the interaction between electrons and photons to obtain laser light [7]. Since the electrons are free to move, it is named as free electron laser. Because high-speed electrons need to move in a periodic magnetic field, the composition of a FEL requires an electron source, an electron accelerator and an undulator. The electron source is used to provide free electrons, and the electron accelerator accelerates free electrons to a high-speed, high-energy state. The undulator is used to provide a periodic magnetic field, and the structure of the FEL is shown in Fig. 1. Compared with traditional

lasers, FEL has a shorter output laser wavelength, better monochromaticity and coherence, and FEL also has wavelength tunable and higher peak brightness output characteristics [8]. FELs differ from other tubes in that the wavelengths range from the infrared to the x-ray band. The specific principle of FEL will be introduced in next section.

3. Principle

The principle of free electron laser is actually to convert the kinetic energy of free electrons into light energy. In free electron laser, the first step to generate laser is to generate synchrotron radiation light source, which involves speeding up electrons to create electron beams that are almost as fast as light, after which an undulator is created by passing magnets longitudinally (seen from Fig. 2). The polarity of these magnets is horizontal and alternates periodically. The Lorentz force causes the electron beam to swing and deflect laterally as it travels through the magnetic field; also, because the magnetic field's polarity alternates, the electron beam's walking path takes the shape of a sinusoidal curve., which means that the acceleration of the electrons has changed, so that the electrons lose kinetic energy, and the lost kinetic energy is released in the form of photons. This is the synchrotron radiation. These lights are single Colored light has no high directionality and is not very coherent. This is because the random distribution of electrons makes the time and position of the photons released different.

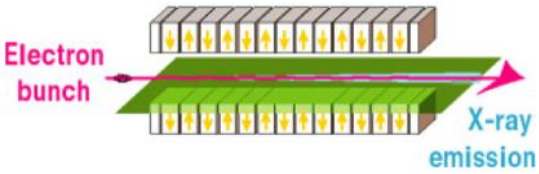


Figure 2. Electron beams pass the magnetic field

In order to turn the synchrotron radiation into a laser with good monochromaticity and coherence, the simplest method is to place mirrors parallel to each other at the two longitudinal ends of the undulator to form a resonant cavity, and the light converted by the electron power continues to optically resonate the cavity is reflected back and forth and interacts with the new free electron beam in the undulator, and then generates resonance, which makes the spontaneous emission continuously amplified. When the intensity is large enough to a certain extent, it is sufficient to cause the longitudinal current of the sinusoidally moving electron beam to interact with the longitudinal electric field of the beam. Based on force of mass dynamics, energy of the electrons increases in some positions, and decreases in others. Finally, the light wave modulates the distribution of the electron beam so that there is a little concentration within the wavelength of each light wave, and the lateral part of the sinusoidal path of the electron beam begins to be concentrated at these points. As a result, the time and position of the photons released by the original random distribution begin to change in the same phase, the emitted photons become coherent, which leads to further concentration of the horizontal part of the electron path, and so on. And finally, most of the electrons also release photons in the same phase, achieving coherence and high directionality, that is, producing lasers, and this method is actually a low-gain FEL with an output wavelength [9]:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \tag{1}$$

Where λ is the output laser wavelength, λ_u is the undulator period, γ is the relative Lorentz factor, and K is the dimensionless undulator strength parameter. The interaction of the beam-radiating system results in an exponential increase in radiation strength with distance from the undulator for sufficiently brilliant electron beams and sufficiently long undulators. This high-gain free-electron laser can magnify both the input seed signal and the spontaneous fluctuating radiation produced by electron shot noise without the need for an optical cavity. Therefore, in the X-ray wavelength range where mirrors and coherent input sources are challenging to achieve, high-gain free-electron lasers

can create powerful coherent radiation. When the beam loses enough energy to break up the resonance condition, exponential gain finally comes to an end. Maximum saturation levels are reached for both radiation intensity and electron beam microbunching, where the radiation power is [10]:

$$P(s) \sim e^{s/L_g} \tag{2}$$

Where Lg is the gain length and it is related to the Pierce constant [10]:

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho} \tag{3}$$

It can be used to characterize some characteristics of FEL, such as at saturation, the relative FEL bandwidth is near to ρ, and the saturation power is roughly ρ times the electron beam power. Since the basic principle of FEL is different from that of traditional laser, free electron laser has more advantages in more fields. In next two sections, this article will describe the application and development of free electron laser in the fields of medicine and lithography.

4. Application in Medical

A new era of opportunities for medical research has begun thanks to FELs, with unique properties enabling scientists and clinicians to explore previously unknown territories. Using the coherent, intense radiation produced by FELs, researchers have harnessed their potential for a variety of medical applications, leading to transformative results. There is no DNA damage, genotoxicity or mutagenic effect on the embryonic stem cell genome from the FELs' terahertz band radiation, so it can be used to study the non-thermal effect of various organisms and their different levels of structure and function organization, such as from the cell structure of Escherichia coli to human stem cells, from DNA and RNA to protein macromolecules [11], as shown in the Fig. 3.

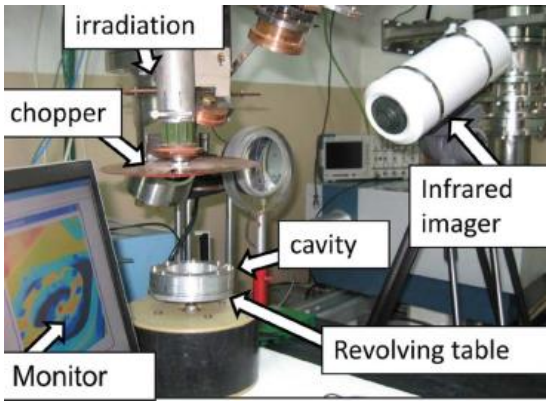


Figure 3. Biological experimental apparatus with FEL

X-rays produced by FEL have been shown to help reveal the complex structures of biomolecules. In X-ray crystallography, FELs allow researchers to visualize proteins and other macromolecules in their native state, eliminating the need for crystallization. This breakthrough provides insights into the dynamic properties of biomolecules, revealing functional mechanisms and aiding drug design. In a study, the use of FELs on regenerable non-crystalline bioparticles (acanthamoeba polyphagous mimivirus. Perform three-dimensional imaging. With sizes ranging from 30 to 300nm, there are numerous significant renewable biological things. Within the 100-200nm range, there are three significant disease-causing viruses: HIV, influenza, and herpes [12]. If one can further understand the three-dimensional structure of these viruses, it will have a huge effect on the treatment of related diseases. FELs have shown great potential in diagnosis and therapy. The high resolution and contrast provided by the x-rays produced by FELs aid in early disease detection, enabling the identification of subtle structural changes associated with various diseases [13]. This could significantly improve diagnostic accuracy, allow for earlier intervention and improve patient outcomes. In cancer therapy,

FELs offer promise for targeted therapy. Their ability to deliver precise doses of radiation to tumors while sparing healthy tissue could revolutionize radiation therapy.

5. Application in Lithography

Lithography, the cornerstone of modern semiconductor fabrication, has undergone a paradigm shift because of the integration of FELs. The unique capabilities of FELs have pushed lithography to new heights, enabling the production of smaller and more complex semiconductor devices with unprecedented precision and efficiency. In the last 50 years, transistors have become smaller and smaller, which has led to rapid development of electronics, and many areas of life have been affected by this, such as higher performance electronic devices, more practical tools, and these rely on lithography. In lithography, light is used to transfer a pattern from a mask to a chemical photoresist that is light-sensitive and is applied to the surface of a semiconductor wafer. Lithography typically uses excimer lasers with wavelengths in the deep ultraviolet (193nm) and sizes up to 30nm. However, continuing to reduce the size requires more complex processes, which will make the speed of technology iteration slow and make the cost higher. Therefore, the move to shorter wavelength sources has been a long-term goal, and it has long been expected that the next step will be EUV sources operating at 13.5nm [14]. At present, the power achieved by LPP is not high(~100W). Gradually, FEL with high power and a larger wavelength range began to be considered as a light source for lithography techniques. Additionally, it will offer a smooth path for future conversion to shorter wavelengths. Therefore, in the field of lithography, FEL has potential, for example the JLab IR Upgrade FEL achieves continuous >10kW operation at 1.6μm with >1% efficiency in the oscillator FEL configuration [15].

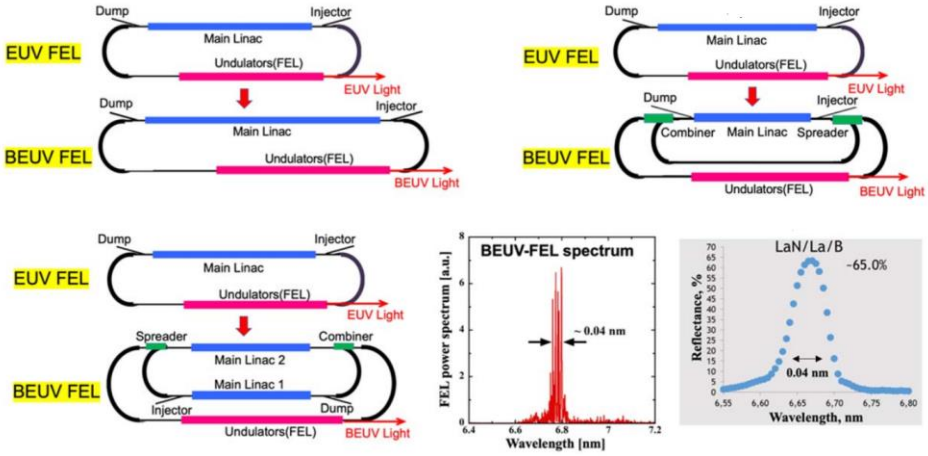


Figure 4. Possible solutions for EUV FEL

Another important development for finer patterning is the so-called "extreme EUV", where EUV-FEL can be upgraded to BEUV-FEL for the development of lithography systems based on shorter wavelengths such as 6.75 nm wavelength or shorter. Furthermore, it enables variable control of the polarization of FEL light [16]. Although under BEUV, the fluctuating system length required for FEL increases proportionally with E. BEUV-FEL power can be equivalent to EUV. Fig. 4 shows one possible scenario for upgrading from EUV-FEL sources to BeUV-FEL sources. The issue has an easy fix. Based on the single-loop design, the beam's energy is boosted while its wavelength is halved compared to the EUV. Since the saturation length of the FEL is proportional to the beam energy, the cross-sectional length of the undulator is also increased [16].

6. Limitations and Prospects

While free-electron lasers (FELs) have demonstrated remarkable capabilities, they are not without limitations. One of the main challenges is the complexity and cost associated with FEL systems. The

complex interplay between electron dynamics, magnetic fields, and beam synchronization requires complex engineering and precise control. This complexity translates into higher operating costs, limiting the accessibility of FEL technology to only a few research institutions and industries with significant resources. Another limitation is achieving consistent and stable FEL operation. Factors such as electron beam quality, undulator design, and synchronization accuracy all affect laser reliability. Variations in these parameters can lead to fluctuations in output intensity and wavelength, hindering their practical application in some situations. Additionally, FEL systems require advanced and specialized infrastructure, making their installation and maintenance challenging.

Despite current limitations, the future of free-electron lasers (FELs) holds great promise. As researchers continue to push the boundaries of accelerator technology and beam control, several avenues for progress have become apparent. Advances in accelerator technology may lead to the development of more compact and efficient FEL systems. Less energy demand could make free-electron laser technology more accessible, allowing a wider range of researchers and industry to take advantage of their capabilities. In addition, enhanced electron beam quality and synchronization techniques can address stability issues, leading to more reliable FEL operation. In terms of applications, FELs have the potential to reshape various fields of science and industry. In medical research, FEL-generated x-rays could revolutionize diagnosis and treatment by providing greater clarity and precision. The study of ultrafast kinetics could lead to breakthroughs in drug discovery and materials science. In addition, the integration of fele-driven lithography can continue to drive semiconductor miniaturization, leading to the development of more powerful and energy-efficient electronics. Collaboration between researchers, institutions and industry will play a key role in realizing the full potential of FELs. Interdisciplinary efforts can provide innovative solutions to existing challenges, leading to improvements and widespread adoption of FEL technologies.

7. Conclusion

In conclusion, free-electron lasers (FELs) epitomize the development of laser technology with remarkable versatility and impact. Their applications go beyond the traditional realm of lasers, transforming medical research and lithography. Changing medical research by providing advanced imaging capabilities, revealing ultrafast dynamics, and contributing to diagnostics and therapeutics; Complex semiconductor devices become possible. This integration not only maintains the pace of technological advancement, but also expands the horizons of what is possible with modern electronics. As FEL technology continues to evolve, its impact on the semiconductor industry will shape the future of computing and innovation. The ability of FELs to produce coherent, high-intensity, and tunable light has pushed them to the forefront of scientific advancement. As FEL technology continues to mature and evolve, its potential to reshape research, technology and innovation remains limitless. This study highlights the profound impact of FELs on modern science and highlights their role as catalysts for future progress. Although free-electron lasers (FELs) currently face limitations in complexity, cost, and operational stability, their future prospects are promising. Advances in accelerator technology, beam control, and collaborative research have the potential to address current challenges and expand the accessibility and applications of FELs. As FEL technology develops, it can catalyze transformations across multiple domains, enhancing scientific discovery, technological innovation, and industrial capabilities. From current limitations to future potential, the journey of electronic experimentation exemplifies the dynamic nature of scientific progress and the resilience of human ingenuity.

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