1

From Photoacoustic Effect to Laser-generated Ultrasound Technology

Ultrasound is a mechanical wave characterized by a frequency beyond the upper threshold of human hearing (20 kHz) and wavelengths typically falling within the millimeter to micrometer range. Methods for generating ultrasonic waves primarily include the piezoelectric method and the magnetostrictive method. The piezoelectric method represents the most widely adopted mainstream technology, operating on the principle of the inverse piezoelectric effect exhibited by piezoelectric crystals such as piezoelectric ceramics and quartz [1]. When subjected to a high-frequency alternating electric field, the crystal lattice of the piezoelectric material undergoes periodic deformation, thereby inducing mechanical vibrations. These vibrations are subsequently transmitted into the propagation medium via a coupling layer to form ultrasonic waves. Conversely, the magnetostrictive method relies on the periodic volumetric changes of ferromagnetic materials—including nickel alloys and ferrites—under an applied alternating magnetic field to excite mechanical vibrations [2].

Despite the established advantages of both piezoelectric and magnetostrictive approaches in ultrasound generation, devices based on electric or magnetic actuation generally exhibit limitations such as narrow operating frequency bands and susceptibility to electromagnetic interference. In recent years, laser-generated ultrasound (LGUS) devices, which operate on the photoacoustic effect, have gained increasing attention due to their unique advantages [3, 4]. As a novel approach for ultrasound generation, LGUS is governed by the fundamental principle of mutual conversion between light energy and acoustic energy. The key operational sequence comprises the absorption of light energy, followed by localized thermoelastic expansion, which ultimately leads to the emission of ultrasonic waves [5].

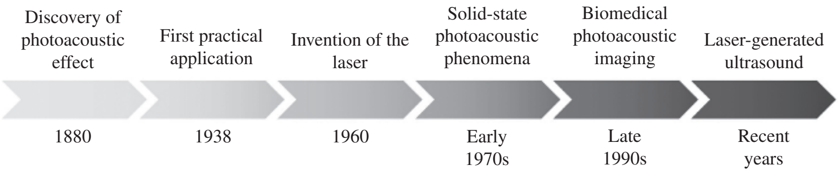

Figure 1.1 The development history from photoacoustic effect to LGUS.

LGUS devices are relatively straightforward to fabricate and possess notable characteristics including broad bandwidth, elimination of the need for direct electrical connections, and inherent immunity to electromagnetic interference [6]. These attributes confer immense promise upon LGUS within the biomedical field, while simultaneously underscoring its versatility for a broad spectrum of applications across diverse scientific and industrial sectors, particularly in scenarios demanding noninvasiveness, high-resolution imaging, or operation in electromagnetically sensitive environments [7].

To fully understand the technological trajectory of LGUS, it is necessary to look back at the origins of its fundamental mechanism. The photoacoustic effect, a distinct physical phenomenon that bridges optical and acoustic principles, has followed an evolutionary path spanning over a century. From its discovery in the late 19th century, through cycles of resurgence and theoretical development in the 20th century, to its active adoption in areas such as biomedicine in the 21st century, its progression illustrates both the persistence and complexity of scientific inquiry, as well as the dynamic potential of cross-disciplinary collaboration [8]. This chapter will track the chronological development of the photoacoustic effect, offering a systematic overview of its full historical trajectory (Figure 1.1) and examining critical innovations, technical evolutions, and expanding applications across distinct periods.

1.1 Discovery of the Photoacoustic Effect

The latter half of the 19th century was a golden era of rapid advancement in modern physics. Progress in electromagnetic theory, innovations in optical technology, and deepening studies in acoustics together established a robust scientific foundation for the eventual discovery of the photoacoustic effect. During this period, scientific exploration often grew from a dynamic interplay between serendipity and deliberate inquiry. It was within this context that the work of Alexander Graham Bell provided the direct catalyst for the emergence of the photoacoustic phenomenon. Motivated by the discovery in 1873 of selenium's photosensitivity—its electrical resistance varies with light intensity—he conceived the idea of using selenium to transform optical signals into electrical ones, thereby achieving wireless vocal communication [9]. After his groundbreaking invention of the telephone in 1876, Bell turned his focus to the possibility of transmitting speech using light [10, 11].

After two years of experimental effort, Bell and his assistant Charles Sumner Tainter succeeded in June 1880 in transmitting wireless voice communication over a distance of approximately 213 meters. Their apparatus, named the "photophone," consisted of a transmitter and a receiver [11]. In operation, sound waves induced vibrations in a glass mirror, thereby modulating the intensity of the reflected light. A selenium cell then converted this modulated optical signal back into an electrical signal, which was ultimately transformed into audible sound via a telephone receiver circuit. Widely recognized as the world's first practical wireless communication device, this invention also laid essential technical groundwork for the subsequent advancement of optical communications [12–14].

Of particular note is a serendipitous discovery made during the research on the photophone: when a solid material was irradiated with a rapidly interrupted beam of light, sound waves were generated at the same frequency as the light modulation [11]. Bell described this phenomenon in a letter to his father, and this observation represents the earliest recognized form of what is now known as the photoacoustic effect.

1.2 The Emergence of Photoacoustic Technology

Following Bell's discovery of the photoacoustic phenomenon, a considerable number of scientists dedicated themselves to exploring its fundamental mechanisms. In 1881, Lord Rayleigh introduced the "solid vibration theory," proposing that intermittent illumination induced non-uniform heating in diaphragms or plate-like structures within objects, resulting in vibrations that generated sound. This theory garnered endorsement from Bell [13, 14]. Concurrently, based on their experimental investigations, Mercadier and Preece advanced the "gas expansion theory," which attributed the origin of sound to the periodic expansion and contraction of air in contact with heated objects [15–17]. Subsequent contributions by Röntgen and Tyndall independently corroborated and further developed the gas expansion theory [18, 19]. Experimental evidence confirmed that the phenomenon also manifested in gases and vapors: Röntgen examined the photoacoustic effect in coal gas and ammonia, while Tyndall systematically studied various gases and vapors, even proposing that the effect held potential for detecting trace amounts of combustible gases in mining environments [19]. Bell further showcased the "spectrophone," an instrument capable of reflecting a sample's absorption spectrum, thereby establishing new pathways for spectral analysis [14]. However, constrained by limitations such as the lack of detection methods capable of precise quantification, research into the photoacoustic effect entered a phase of stagnation. It was not until the period spanning the 1930s to the 1960s that the effect underwent its first substantial revival, notably within the domain of gas analysis.

In the 1930s, Veingerov built upon the earlier work of Röntgen and Tyndall in the study of gas-phase photoacoustic effects [20], particularly emphasizing Tyndall's concept of "utilizing this effect for trace gas detection." In 1938, he introduced a photoacoustic gas analysis method: employing a capacitive microphone as the detector and a Nernst glower as a high-intensity blackbody infrared source, then he successfully measured the concentration of CO_2 in a nitrogen (N_2) matrix [21]. This achievement marked the formal transition of the photoacoustic effect from theoretical exploration to practical application. Over the subsequent years, related technologies progressed rapidly and eventually reached the stage of commercialization [22]. As the range of applications broadened, the theoretical framework of the photoacoustic effect continued to be refined. Beyond its use in gas concentration analysis, it was also applied to investigate gas vibrational relaxation rates and molecular energy transfer processes [23–26]. By the mid-20th century, however, the dominance of photoacoustic methods in gas analysis was supplanted by gas chromatography, owing to the latter's superior detection sensitivity.

The year 1960 marked a pivotal moment with the invention of the laser, which profoundly revolutionized the field of optics and, in turn, reinvigorated the research momentum behind the photoacoustic effect [27]. Lasers, characterized by their unique advantages—including high power, exceptional spectral purity, superior stability, and outstanding repeatability—provided an effective solution to the intrinsic limitations of conventional light sources in photoacoustic studies, such as inadequate energy output and suboptimal spectral properties.

The emergence of laser technology catalyzed the first major resurgence in photoacoustic gas analysis. In 1968, Kerr and Atwood pioneered the development of a laser-based absorption spectrophone for gas analysis [28]. Their experimental setup utilized a pulsed ruby laser and a modulated continuous-wave CO_2 laser as respective light sources, with acoustic signals being captured by a capacitive microphone. This approach enabled highly sensitive measurements of gas absorption characteristics. Equipped with distinct advantages such as ultrahigh sensitivity, excellent selectivity, and rapid response capabilities, laser-driven photoacoustic gas analysis technology demonstrated significant application potential across diverse fields including environmental monitoring, industrial process control, and atmospheric science research.

The advancement of laser technology in photoacoustic gas analysis coincided with a renewed scientific focus on the photoacoustic effect in solid materials. This resurgence can be largely credited to researchers at Bell Laboratories. Motivated by the remarkable sensitivity achieved in gas-phase photoacoustic detection, they initiated comprehensive investigations into the solid-state photoacoustic phenomenon in the early 1970s. In 1973, Rosencwaig successfully demonstrated photoacoustic spectra across a range of materials, extended the technique's applicability to the spectroscopic analysis of biological specimens, and contributed significantly to refining the theoretical understanding of the photoacoustic effect in solids [29, 30].

1.3 Photoacoustic Technology in Biomedical Applications

1.3.1 Photoacoustic Imaging Technology

In the 1980s, the photoacoustic effect began to progressively make its way into the biomedical field. Due to the strong optical scattering properties of biological tissues, conventional optical imaging techniques faced severe limitations in terms of penetration depth and spatial resolution. In contrast, photoacoustic imaging detects ultrasound waves, which experience significantly lower scattering and attenuation in biological tissues compared to light. This allows the technique to achieve deep-tissue imaging while preserving high resolution [31, 32]. This distinct advantage endowed the photoacoustic effect with tremendous application potential in biomedicine.

As early as 1964, Amar et al. conducted a pioneering experiment in which they observed laser pulse-induced elastic waves in the eyes of living rabbits for the first time. They employed a ruby laser to generate a pulse train with an average energy of 50 mJ and a pulse width of 1 microsecond, directing the laser onto the rabbits' retinas. A barium titanate-based ultrasound detector was placed on the rabbits' occipital bone, successfully capturing acoustic signals that had propagated through the brain and skull. The experiment confirmed that these acoustic signals corresponded to elastic waves within the ultrasonic frequency range, rather than shock waves, with a dominant frequency of approximately 40 kHz [33]. This study is widely regarded as the first attempt at biomedical photoacoustic imaging. Subsequently, researchers started exploring the application of the photoacoustic effect in the analysis of biological tissues. With the rapid advancement of laser technology, ultrasound detection methods, and data acquisition and processing systems, research on the photoacoustic effect entered a mature phase, and its focus fully shifted toward the biomedical field, sparking a revolution in biomedical imaging.

Since the late 1990s, photoacoustic imaging technology has entered a golden era of comprehensive development. Photoacoustic tomography (PAT) and photoacoustic microscopy (PAM) have emerged as the two core technical branches, continuously achieving breakthroughs in key performance metrics such as spatial resolution, penetration depth, and imaging speed [31].

Photoacoustic tomography (PAT) is primarily oriented toward deep-tissue imaging, achieving penetration depths of up to several centimeters (typically 1–5 cm in biological tissues) with submillimeter spatial resolution [34]. By comprehensively scanning the sample to collect photoacoustic signals from different positions, the technology reconstructs three-dimensional structural images using algorithms such as back-projection or iterative reconstruction. Furthermore, PAT can provide rich functional information: for example, based on the differences in absorption spectra of endogenous absorbers such as hemoglobin, oxyhemoglobin, and melanin, it enables quantitative measurement of physiological parameters such as tissue oxygen saturation and hemoglobin concentration. This offers important support for the early diagnosis of diseases. In contrast, photoacoustic microscopy (PAM) is mainly focused on microscopic imaging, achieving submicron-level spatial resolution but with a relatively shallow penetration depth (usually several hundred micrometers). By combining the high resolution of optical microscopy with the deep-penetration capability of ultrasound detection, PAM can visualize microstructures in biological tissues, such as capillary networks and cellular morphology [35].

Alongside the widespread adoption of photoacoustic imaging, its theoretical foundation has been continuously refined. Researchers have conducted more in-depth investigations into the physical mechanisms of the photoacoustic effect and established more precise mathematical models that account for complex factors such as tissue heterogeneity, optical scattering, and heat conduction. These advancements provide more reliable theoretical support for image reconstruction and quantitative analysis [36].

1.3.2 Laser-Generated Ultrasound Technology

In the evolutionary trajectory of photoacoustic imaging technology, researchers have made a critical observation: the bandwidth of photoacoustic signals generated via the photoacoustic effect is substantially broader than that of ultrasonic signals produced through the inverse piezoelectric effect [37]. This pivotal characteristic has unlocked new possibilities for the application of ultrasound technology in biomedicine—greater bandwidth enables higher temporal and spatial resolution, allowing for the visualization of finer structural details and dynamic changes within biological tissues, which holds irreplaceable value in contexts such as high-precision imaging and functional monitoring.

Building upon this foundational insight, LGUS technology has progressively matured. It inherits the core energy conversion logic of the photoacoustic effect, while achieving innovations in technical implementation. Unlike the passive mode of conventional photoacoustic imaging, which relies on the intrinsic optical absorption of biological tissues (e.g. endogenous absorbers such as hemoglobin and melanin), LGUS technology actively regulates the entire energy conversion process through the use of artificially engineered photoacoustic composite materials. By rationally designing the composition and structure of such materials, it becomes possible to precisely modulate key stages including optical absorption, heat conduction, and acoustic radiation, thereby achieving the generation of broadband, high-amplitude ultrasonic signals [38]. Furthermore, the inherent electrode-free design of LGUS provides natural immunity to electromagnetic interference (EMI), while its potential for miniaturization and flexibility—realizable through techniques such as thin-film deposition and optical fiber integration—makes it exceptionally well-suited to the varied demands of precision medicine for advanced ultrasound solutions [7].

In the realm of basic research, LGUS serves as a significant interdisciplinary platform bridging biomedical engineering, materials science, acoustics, and related disciplines. Its core conversion mechanism involves multiphysics-coupled processes such as optical absorption, thermal conduction, and elastic wave dynamics; in-depth investigation of this mechanism contributes to revealing fundamental principles of multiscale energy conversion. Simultaneously, the design and optimization of photoacoustic composite materials have stimulated technological advances in areas such as functional nanomaterials and polymer composites [38]. In biomedical applications, high-resolution imaging systems based on LGUS are anticipated to enable accurate detection of pathological structures such as vascular plaques [3]. Its capacity for precise ultrasonic modulation may also provide a single-neuron-level tool for neuroscience research, opening new pathways for the treatment of neurological disorders including Parkinson's disease and epilepsy [39]. Moreover, LGUS technology demonstrates considerable potential in fields such as minimally invasive surgery and targeted drug delivery, promising to drive the evolution of clinical diagnosis and treatment toward more precise, less invasive, and safer paradigms [6, 40, 41]. Therefore, advancing research on LGUS technology holds not only significant scientific and theoretical value but also notable potential for clinical translation and socioeconomic impact.

Subsequent chapters of this book will conduct systematic and in-depth thematic exploration of LGUS technology. First, the theoretical foundations and technical principles of LGUS will be comprehensively reviewed, summarizing key advances in physical modeling and mechanistic understanding. Next, focus will be placed on the structural designs and material systems of LGUS devices, highlighting pivotal directions for technological breakthroughs. Finally, practical application scenarios and implementation strategies of LGUS in domains such as biomedical imaging and precision therapy will be elaborated upon, with the aim of providing comprehensive technical support and academic reference to further academic investigation and industrial development of LGUS technology.

References

1 Zhou, Q., Lam, K.H., Zheng, H. et al. (2014). Piezoelectric films for high-frequency ultrasonic transducers in biomedical applications. *Progress in Materials Science*, 66: 87–111.

2 Engdahl, G. (ed.) (2000). *Handbook of giant magnetostrictive materials*. Academic Press.

3 Chen, S.L. (2016). Review of laser-generated ultrasound transmitters and their applications to all-optical ultrasound transducers and imaging. *Applied Sciences*, *7*(1): 25.

4 Bychkov, A., Simonova, V., Zarubin, V. et al. (2018). The progress in photoacoustic and laser ultrasonic tomographic imaging for biomedicine and industry: A review. *Applied Sciences*, *8*(10): 1931.

5 McDonald, F.A. (1980). Photoacoustic effect and the physics of waves. *American Journal of Physics*, *48*(1): 41–47.

6 Baac, H.W., Ok, J.G., Park, H.J. et al. (2010). Carbon-nanotube optoacoustic lens for focused ultrasound generation and high-intensity targeted therapy. *Applied Physics Letters*, *97*(23): 234104.

7 Kim, J., Kim, H., Chang, W.Y. et al. (2019). Candle-soot carbon nanoparticles in photoacoustics: advantages and challenges for laser ultrasound transmitters. *IEEE Nanotechnology Magazine*, *13*(3): 13–28.

8 Manohar, S. and Razansky, D. (2016). Photoacoustics: a historical review. *Advances in Optics and Photonics*, *8*(4): 586–617.

9 Smith, W. (1873). The action of light on selenium. *Journal of the Society of Telegraph Engineers*, 2: 31–33.

10 Mims, F.M. III, (1980). Alexander Graham Bell and the photophone: the centennial of the invention of light-wave communications, 1880–1980. *Optics News*, *6*(1): 8–16.

11 Bell, A.G. (1880). On the production and reproduction of sound by light. *American Journal of Science*, 118: 305–324.

12 Bell, A.G. (1880). Selenium and the photophone. *Nature*, 22: 500–503.

13 Bell, A.G. (1881). Production of sound by radiant energy. *Journal of the Franklin Institute*, 111: 401–428.

14 Bell, A.G. (1881). The spectrophone. *Bulletin of the Philosophical Society*, 4: 42.

15 Mercadier, E. (1881). Sur la radiophonie. *Journal de Physique Théorique et Appliquée*, 10: 53–68.

16 Mercadier, E. (1881). Sur la radiophonie (2e mémoire). *Journal de Physique Théorique et Appliquée*, 10: 147–154.

17 Preece, W.H. (1880). On the conversion of radiant energy into sonorous vibrations. *Proceedings of the Royal Society of London*, 31: 506–520.

18 Röntgen, W.C. (1881). Ueber Töne, welche durch intermittirende Bestrahlung eines Gases entstehen. *Annalen der Physik*, 248: 155–159.

19 Tyndall, J. (1880). Action of an intermittent beam of radiant heat upon gaseous matter. *Proceedings of the Royal Society of London*, 31: 307–317.

20 Veingerov, M.L. (1938). A method of gas analysis based on the Tyndall-Röntgen optico-acoustic effect. *Doklady Akademii Nauk SSSR*, 19: 687–688.

21 Veingerov, M.L. (1946). An optical-acoustic method of gas analysis. *Nature*, 158: 28–29.

22 Luft, K.F. (1975). Infrared techniques for the measurement of carbon monoxide. *Annals of Occupational Hygiene*, 18: 45–51.

23 Veingerov, M.L. (1945). Spectrophone – an instrument for investigation of infrared absorption spectra of gases and for quantitative and qualitative spectrum analysis of multi-component gas mixtures. *Doklady Akademii Nauk SSSR*, 46: 182.

24 Gorelik, G. (1946). On a possible method of studying the energy exchange time between the different degrees of freedom of molecules in a gas. *Doklady Akademii Nauk SSSR*, 54: 779.

25 Slobodskaya, P.V. (1948). Determination of the energy transfer rate from vibrational to translational molecular motion by means of a spectrophone. *Izvestiya Akademii Nauk SSSR*, 12: 656–662.

26 Cottrell, T.L. (1950). The absorption of interrupted infra-red radiation. *Transactions of the Faraday Society*, 46: 1025–1030.

27 Rosencwaig, A. (1980). *Photoacoustics and photoacoustic spectroscopy*. John Wiley & Sons.

28 Kerr, E.L. and Atwood, J.G. (1968). The laser illuminated absorptivity spectrophone: a method for measurement of weak absorptivity in gases at laser wavelengths. *Applied Optics*, *7*(5): 915–921.

29 Rosencwaig, A. (1975). Photoacoustic spectroscopy of solids. *Physics Today*, *28*(9): 23–30.

30 Harshbarger, W.R. and Robin, M.B. (1973). Opto-acoustic effect. Revival of an old technique for molecular spectroscopy. *Accounts of Chemical Research*, *6*(10): 329–334.

31 Beard, P. (2011). Biomedical photoacoustic imaging. *Interface Focus*, *1*(4): 602–631.

32 Xu, M. and Wang, L.V. (2006). Photoacoustic imaging in biomedicine. *Review of Scientific Instruments*, *77*(4).

33 Amar, L. (1964). Detection d'omes elastiques (ultrasonores) sur l'os occipital, induites par impulsions laser dans l'oeil d'un lapin. *CR Acad. Sc. Paris*, 259: 3653–3655.

34 Wang, L.V. and Yao, J. (2016). A practical guide to photoacoustic tomography in the life sciences. *Nature Methods*, *13*(8): 627–638.

35 Yao, J. and Wang, L.V. (2013). Photoacoustic microscopy. *Laser & Photonics Reviews*, *7*(5): 758–778.

36 Wang, L. (ed.) (2017). *Photoacoustic imaging and spectroscopy*. CRC Press.

37 Kruger, R.A. (1994). Photoacoustic ultrasound. *Medical Physics*, *21*(1): 127–131.

38 Lee, T., Baac, H.W., Li, Q., and Guo, L.J. (2018). Efficient photoacoustic conversion in optical nanomaterials and composites. *Advanced Optical Materials*, *6*(24): 1800491.

39 Du, Z., Chen, G., Li, Y. et al. (2024). Photoacoustic: a versatile nongenetic method for high-precision neuromodulation. *Accounts of Chemical Research*, *57*(11): 1595–1607.

40 Di, J., Kim, J., Hu, Q. et al. (2015). Spatiotemporal drug delivery using laser-generated-focused ultrasound system. *Journal of Controlled Release*, 220: 592–599.

41 Lee, T., Luo, W., Li, Q. et al. (2017). Laser-induced focused ultrasound for cavitation treatment: toward high-precision invisible sonic scalpel. *Small*, *13*(38): 1701555.