A Mini Review of Optical Component Design for Piezoelectric Transducers

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***Abstract*—Piezoelectric Transducers are most critical and sensitive sensor devices among the ultrasound/photoacoustic/acoustic instruments. Therefore, optical system components for piezoelectric transducers are important design issues to support the stable performances of the piezoelectric transducers because the light beam through optical component or systems affect the signal quality of the whole photoacoustic instruments. Therefore, various research approaches to improve the light beam characteristics have been developed. This review paper could be some guidance to introduce right selection of the optical components or systems or design customized optical components or systems for photoacoustic instruments. In this review paper, fundamental photoacoustic instruments, optical components, and optical systems are summarized.**

Keywords— Optical Components; Piezoelectric Transducers; Ultrasound Systems; Photoacoustic Systems; Acoustic systems; Optical Lens; Optical Systems

I. Introduction

Ultrasound instruments have been widely used from a variety of applications such as non-destructive testing (NDT), ultrasound imaging for small animals or humans, renewable energy instruments, mobile touch sensors, high intensity focused ultrasound, and photoacoustic instruments [1-5]. The ultrasound instruments could be utilized as therapeutic instruments for cancer therapy [6, 7]. In the ultrasound instruments, transmitting and receiving sources are ultrasound energies. In the ultrasound instruments, the sources are basically noninvasive and cost-effective compared to X-ray, Computed tomography (CT), and positron emission tomography (PET) [8-12].

The medical imaging Instruments have been rapidly developed due to semiconductor devices like electronic asynchronous semiconductor integrated circuit (ASIC) chips because graphic processing unit (GPU) units could support high frame rates to process the image data simultaneously [13-17]. The GPU units could be helpful to support machine and deep learning processes because these units are able to calculate the complex mathematical functions simultaneously with multiple processors [18, 19]. Recently, wireless or portable medical imaging instruments have been highlighted in the remote-consulting or remote-diagnosis [20, 21]. To transfer the large size data, the image compression algorithms have been developed [22-24]. Therefore, the encrypting algorithms have been rapidly developed to avoid the unwanted hacking for patient data [25].

Fig. 1 shows the general signal process in the photoacoustic instruments. The transmit sources are delivered to the target. For signal reception, the obtained signal is detected by the ultrasonic transducer. The weak echo signal is amplified by the preamplifier and variable gain or time-gain compensation amplifiers. The noise signals are reduced by the analog filter to process the data through the signal processing unit and then, the images are obtained in the computer.

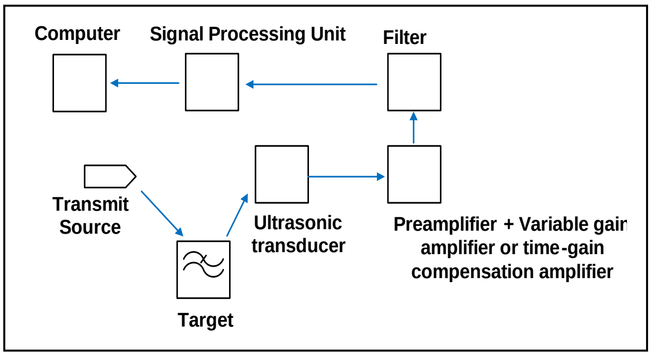

Fig. 1. *The signal process in the photoacoustic instruments.*

In the photoacoustic instruments, the short pulse like laser is approached to the tissues. The transmitted energy is absorbed into the soft tissues. The energy is transformed into the heat to generate the ultrasound waves. The waves are detected by the ultrasound (piezoelectric) transducers to be processed [26]. In the photoacoustic instruments, transmitting source is generally light and receiving source is ultrasound. Therefore, the high contrast characteristics due to transmitting light and high spatial resolution due to receiving acoustic signal could be obtained. Especially, the high contrast depends on the light absorption characteristics rather than the tissue characteristics. Therefore, photoacoustic instruments could provide the structure information like blood structure and functional information like blood flow data. In the instruments, the visible and near-infrared wavelengths between 550 nm and 900 nm have been typically utilized.

The optical component and system design are essential because they can steer, diverge, or focus the light beam into the desired target in the optical and photoacoustic instruments. However, there are no specific review papers to cover how to design optical components and systems and optimize their performances for piezoelectric transducers used in the photoacoustic instruments. Therefore, this review paper could be some guidance to improve the optical performances in the photoacoustic instruments efficiently.

Section 2 describes the fundamental concept of the ultrasound instruments, the design and simulation methods of the optical components and systems, and the implementation of the photoacoustic instruments using the optical components and systems with several previous research articles. Section 3 is the final conclusion of the paper.

II. MATERIALS AND METHODS

A. *Concept of the Ultrasound Instruments*

The ultrasound are basically non-visible, non-invasive, and less-harmful acoustic sources. However, the acoustic sources can be delivered to the soft tissues, however, they cannot be penetrated in aluminum or bone [27, 28]. The signal quality of the ultrasound instruments is mainly dependent to the operator skills compared to CT, magnetic resonance imaging (MRI), and PET [29-31]. The technology bottleneck of the ultrasound instruments are relatively lower compared to CT, PET, and MRI [32, 33]. Therefore, ultrasound instruments are one of four imaging instruments among the X-ray, PET/CT, ultrasound, and MRI [34-36]. In addition, advanced semiconductor technology enables the ultrasound instruments being portable and mobile instruments [37-39].

Recently, there are commercially available ultrasound instruments with small sizes such as smartphone or laptop sizes are widely used in the hospitals and factories [40, 41]. In the remote sensing and diagnostic instruments, ultrasound instruments are becoming more popular in a variety of applications such as portable ultrasound systems, portable scanners, and smart phone-based imaging systems [21, 42, 43]. The cost of those ultrasound instruments going lower due to recent semiconductor technology development [42, 44, 45]. In the ultrasound applications, there are several photoacoustic diagnostic instruments using light sources. In this review paper, we summarized recent technology development of the optical components or systems used for the photoacoustic instruments.

The piezoelectric transducers are one of the most sensitive and critical components in the ultrasound and photoacoustic systems [46, 47]. The equivalent circuit models of the piezoelectric transducers are purely non-linear capacitor devices with parasitic resistive, capacitive, and inductive components [48]. Therefore, unpredictable performances of the ultrasound/photoacoustic instruments are hard to be controlled by each various component such as the electronic systems and optical systems. Therefore, there have been several equivalent circuit models to improve the capability of the ultrasound and photoacoustic instruments.

The light beam intensities or chromatic aberrations of the light beam generated by the optical components could affect the signal quality of the piezoelectric transducers because the piezoelectric transducers are receiving devices and receiving electronics need to process the photoacoustic echo signals using preamplifier, filter, analog-to-digital converter, digital-to-analog converter through receiving beamforming electronics in the receivers of the photoacoustic instruments. Therefore, the engineers and designers for photoacoustic instruments need to consider the optical components, ultrasonic transducers, and electronics together.

B. *Optical Component and System Design*

In the photoacoustic instruments, the optical components which generate the light sources should be needed to converge, diverge, and focus the light to the desired target. A variety of the optical components such as singlet or optical systems which are composed of several singlet have been used to construct the optical parts in the photoacoustic instruments. The convex and concave lenses are fundamental optical components to diverge and focus the light beams. These lenses have been widely used to construct the general photoacoustic instruments from the research articles.

In the ultrasound instruments, the transmitting and receiving sources are both acoustic signals generated from the ultrasound (ultrasonic) transducers [49-51]. However, the light or radio frequency (RF) beam is transmitting source and acoustic beam is receiving source in the photoacoustic instruments [52, 53]. The light beam characteristics should affect the signal quality of the whole photoacoustic instruments [5]. Therefore, various researches have been conducted to improve the light beam characteristics using optical components or systems [54]. The light beam characteristics are mainly the intensity or chromatic aberration caused by the sizes and shapes of the optical lenses and lengths between the optical components [55]. The optical lens or system engineer need to be considered about these characteristics after optical component fabrication [56].

The optical system engineers could provide the performances of the modulation transfer function (MTF), light intensity distribution graph including effective focal length, back focal length, and focal distance using OpticStudio (Zemax,Kirkland, WA, USA) and LightTools and Code V (Moutain View, CA, USA) software [57, 58].The Code V is a kind of the optical lens design software based on optical ray tracing [59]. The LightTools is design software based on the optical lens. The optical engineers design the optical ray tracing with paraxial calculation and tolerance analysis using Code V and then, design and simulate the optical lens with optical sources and receivers using LightTools to obtain the expected performances of the optical systems [60, 61]. The Zemax software support two functions which are optical ray tracing and optical lens design together. For example, head-up display (HUD) design has required complex tilt/decenter calculation [62]. The CODE V software is more powerful than Zemax software to support the complex calculation requiring the surface location in three dimensional view for optical lens design [63].

The optical components or systems have been widely used to diverge, converge, and focus the light coming from various sources generated from light amplification by the stimulated emission of radiation (laser) and light emitting diode (LED) components. Therefore, the intensity, sensitivity, and resolutions of the optical and photoacoustic instruments are directly related by the optical components or systems [64, 65]. The optical components or optical systems are the essential devices in the photoacoustic (optoacoustic) systems because the laser sources are coherent and non-divergent and LED sources are divergent sources. Therefore, these LED source itself cannot be focused in the desired target without optical components.

The optical systems are composed of several optical components such as concave and convex singlet lenses (singlets). Therefore, highly focused or diverged beam could be implemented through the designed optical systems while scarifying the light intensities [66]. In the photoacoustic instruments, these optical systems have been developed to improve the light beam distribution or reduce optical chromatic aberrations to obtain high image resolutions.

C. Photoacoustic Instruments

Generally, the transmitting devices are quite bulky, sensitive, and expensive components in the photoacoustic instruments. In the instruments, various sources such as laser, LED, or RF sources have been used. Among the sources, lasers are most power sources but the cost of the lasers is very high so that it has a bottleneck to commercialize the cost-effective photoacoustic instruments compared to LED or RF sources. However, most research photoacoustic instruments have laser sources which support the multi-wavelength ranges.

Fig. 2 shows the simplified block diagram of the photoacoustic instruments with the optical component or system. The transmit source needs to be passed through the optical component or system to diverge or focus the light beam into the desired target. The received photoacoustic signals generated from the ultrasonic transducer are processed in the ultrasound receiver system to obtain the images in the computer. The ultrasound receiver system includes the preamplifier, variable-gain amplifier or time-gain compensation amplifier, filter, analog-to-digital converter, scan converter. The received photoacoustic signals with small and weak amplitude are amplified by the preamplifier, variable-gain amplifier or time-gain compensation amplifier and then, these amplified signals are filtered out by the low pass, high pass, or band pass filters. The analog-to-digital converter is converted from the received analog signals to digital signals to be saved in the scan converter unit. In the computer, users could process the photoacoustic signal data to plot the image data using programming tools such as LabView or MATLAB programs in the computer.

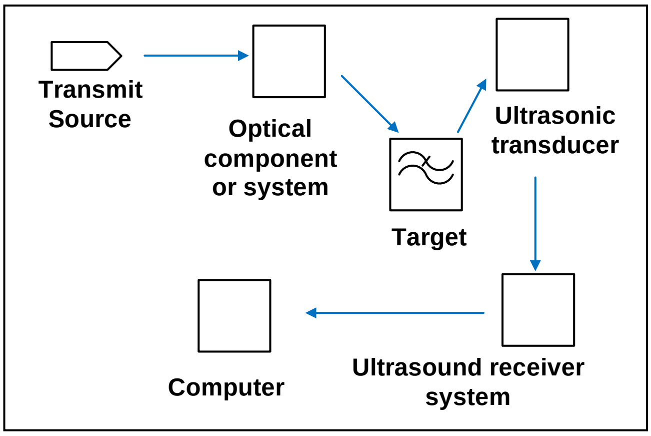

Fig. 2. *The photoacoustic instruments with optical component or system.*

Compared to laser sources, LED or RF sources are much cheaper so there are more chances to be commercialized. However, the intensity of the generating sources is relatively lower than the laser sources. Therefore, current research photoacoustic machines utilize the laser sources.

In the photoacoustic instruments, the fisheye optical system was used to diverge the light beam out of the focus regions to cover wide ranges of the target distances [67]. The constant MTF values up to 30^{o} was achieved with horizontal, vertical, and diagonal directions. Therefore, relatively clean echo waveform with lower than −60 dB noise levels was achieved. The relatively constant peak-to-peak values, pulse width, and bandwidth values were achieved in the pulse-echo measurement tests.

The double-Gauss optical system was developed to obtain relatively constant light beam [68]. The developed system provides the constant MTF values up to +/− 20 mm distances compared to singlet. The echo signal amplitudes up to +/− 20 mm distances were achieved accordingly. The constant optical beam intensity with wide distance ranges could be helpful to cover the wide distance ranges of the target in the photoacoustic instruments. For examples, the recently commercialized photoacoustic instruments support the whole animal images. To obtain the whole animal images, users need to utilize mechanical motors with substantial environment noises. The mechanical motors with light beams or ultrasonic transducers are rotated with 360^o to cover the whole animal areas. Therefore, developed double-Gauss optical systems might be helpful to reduce the coverage distances of the mechanical motors, thus minimizing the environment noises in the images.

The Macro optical system was developed to obtain very high light intensity and reduce the optical chromatic aberration [59]. The highly focused beam intensity with more than 40 times higher was achieved with Macro optical system. The stronger echo signal amplitudes with developed Macro optical system was obtained. Therefore, high amplitudes could be achieved when obtaining the echo signals, thus improving the sensitivity in the photoacoustic instruments. This optical system could be useful for the desired target in the deep location because most of the light beams without some special techniques could be absorbed in the surface of the target and received photoacoustic signal from the deep location has usually very weak amplitudes.

The multiwavelength or multispectral optical systems were developed to support the red, green, and blue light beam separately or simultaneously [53]. To use multispectral optical systems, chromatic aberration of the optical systems could be serious issue to combine the light beam of the red, green, and blue light beam. Therefore, the intensity distribution within the position need to be checked by paraxial design before optical system fabrications. The multispectral photoacoustic microscopy instruments were developed to cover several wavelength ranges [69, 70]. The developed multispectral photoacoustic instrument was based on ultraviolet, visible, and near infrared wavelength ranges. The light beams which is covered in these wavelengths were combined to generate one light beam to be arrived into the ultrasonic transducers. For LED sources, the LED drivers are used to change the light intensity with current variances controlled by DC bias voltages [71]. For LED sources in the photoacoustic instruments, the array type LEDs could be utilized to steer and focus the light beams [72]. Therefore, it is easier to control the light beam intensity compared to laser sources. Each tissue has different light beam absorption characteristics such as oxyhemoglobin, deoxyhemoglobin, water, lipid, melanin, collagen, protein, and elastin between 400 nm and 1800 nm wavelengths.

In the photoacoustic instruments, the fisheye optical system was used to diverge the light beam out of the focus areas [67]. The constant MTF values up to 30^o was achieved with horizontal, vertical, and diagonal directions. Therefore, relatively clean echo waveforms with lower than −60 dB noise levels were achieved. The relatively constant peak-to-peak values, pulse width, and bandwidth values of the photoacoustic echo signals were achieved.

Recently, several LED-based photoacoustic instruments papers would be highlighted. The LED arrays manufactured from PreXion Corporation were developed using AlGaAs, AlGaInp, InGaN materials [73]. The LED devices would have some benefits due to high speed drivers which are composed of the current power amplifiers. The high-speed power amplifier could be controlled by the high-speed oscillators such that very short pulse generated from LED arrays could be provided. However, LED arrays could generate some high-level noise signals such that these signals could affect the image resolutions in the photoacoustic instruments. In addition, the amplitudes of the LED arrays are relatively lower compared to lasers. Therefore, high gain and low noise preamplifier, time gain compensation amplifier, and variable gain amplifier need to be utilized because received echo signals triggered by the LED lights have very weak amplitudes.

Lasers are coherent so the optical designer must consider the safety rules for human tissues. However, LED lights are not coherent such that the optical designer possibly does not consider ANSI safety limitation. Therefore, LED lights would be safe for human and animal experiments. However, blue LED lights for eye exposures could be harmful. In addition, extremely short pulse is very hard to be generated from LED devices. However, the LED arrays could be much cheaper than the lasers so it could be potential clinical and imaging solutions to be commercialized in the future.

III. CONCLUSION

In this brief review paper, the optical systems and components for piezoelectric transducers used in the photoacoustic instruments are described. The design concept and programming tools of the optical components or systems are also introduced with the advantages and disadvantages of the programming tools. This review paper could be helpful for optical system engineer to optimize the performances of the optical components and systems for the piezoelectric transducers which are most critical and sensitive components used in the photoacoustic instruments.

The photoacoustic instruments use various light sources such as laser, LED, or RF sources. Recently, LED-based photoacoustic instruments are highlighted due to cost and safety issues. Therefore, the optical component or system engineers need to consider the performances of the ultrasonic transducers with proper low chromatic aberrations, high intensity distribution, or high resolutions of the optical components and systems to obtain appropriate echo signal qualities. Therefore, this brief review paper could be some useful guidance of the optical component and system designer for customized photoacoustic instrument development.

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