Focusing, imaging and sensing with optical scattering media

Tran, The Vinh

2019

Tran, T. V. (2019). Focusing, imaging and sensing with optical scattering media. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/137414>

<https://doi.org/10.32657/10356/137414>

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**FOCUSING, IMAGING AND SENSING WITH
OPTICAL SCATTERING MEDIA**

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SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

2019

FOCUSING, IMAGING AND SENSING WITH OPTICAL SCATTERING MEDIA

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SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

A thesis submitted to the Nanyang Technological University in partial
fulfillment of the requirement for the degree of Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarized materials, and has not been submitted for a higher degree to any other University or Institution.

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

August 23rd, 2019

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Date

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Asst. Prof Cuong Dang

Authorship Attribution Statement

This thesis contains material from three papers published in the following peer-reviewed journal in which I am listed as an author.

Chapter 3 is published as: “*Tran, V., Sahoo, S.K. & Dang, C. Fast 3D movement of a laser focusing spot behind scattering media by utilizing optical memory effect and optical conjugate planes. Sci Rep 9, 19507 (2019) doi:10.1038/s41598-019-56214-3*”

The contribution of the co-authors are as follows:

- Prof Cuong Dang initiated and supervised the project.
- I carried out all experiment and laboratory work with advices from Dr. Wang.
- I prepared the first draft of manuscript. Then Dr. Sahoo and Prof. Dang revised together with me.
- Dr. Sahoo provided some suggestions and discussed on the controlling of the phase and the experimental strategies.
- All authors have analyzed and discussed the results thoroughly and contributed to the final revision of the manuscript.

Chapter 4 is published as: “*D. Tang, S.K. Sahoo, V. Tran, C. Dang, Single-shot large field of view imaging with scattering media by spatial demultiplexing, Appl. Opt., 57 (2018) 7533-7538.*”

The contribution of the co-authors are as follows:

- Prof Cuong Dang initiated and supervised the project.

- I co-carried out the main experiment and laboratory work with Dr. Tang and Dr. Sahoo initially. Then, I carried out the last experiment to get the largest field of view imaging (Fig. 5 in the paper) when Dr. Tang left our research group.
- I, Dr. Tang and Dr. Sahoo prepared the draft of manuscript.
- Dr. Sahoo contributed in by giving advices on building mathematical formulas and analyzing experiment data.
- All authors have analyzed and discussed the results thoroughly and contributed to the writing of the manuscript.

Chapter 5 is published as: “ *V. Tran, S.K. Sahoo, D. Wang, C. Dang, Utilizing multiple scattering effect for highly sensitive optical refractive index sensing, Sensors and Actuators A: Physical, 301 (2020) 111776.*”

The contribution of the co-authors are as follows:

- Prof Cuong Dang initiated and supervised the project.
- I carried out all experiment and laboratory work with advices from other authors.
- I prepared the first draft of manuscript. Then Dr. Sahoo and Prof. Dang revised together with me.
- I made the Matlab code and run all the simulation work. Dr. Wang and Dr. Sahoo contributed some suggestion for simulation and experiment during daily discussion.
- Prof. Dang followed all the results during weekly meeting and provided guidance to finish the work.

- All authors analyzed and discussed the results thoroughly and contributed to the final revision of the manuscript.

August 22nd, 2019

A handwritten signature in black ink, consisting of stylized, overlapping loops and strokes, likely representing the name 'Tran The Vinh'.

Date

TRAN THE VINH

Acknowledgments

It has been a long but also meaningful journey for me in pursuing degree of Doctor of Philosophy at school of Electrical and Electronic Engineering, Nanyang Technological University Singapore. The period from the first time I arrived to Singapore to become a Ph.D candidate until I finished this thesis, will be an unforgettable journey in my whole life. In this journey, I have learnt not only lessons about science and knowledge, but also meaningful lessons about friendship and life of a researcher. During this period, sometimes I have lost and fallen. However, the fascination of doing scientific researches, the encouragement from my beloved family and specially, the kind support of my supervisor as well as my colleagues have provided me huge motivations to achieve meaningful goals which are not only presented here in this thesis, but will also follow me through future path.

First of all, I would like to give my deep gratitude to my supervisor Asst. Prof Cuong Dang as a teacher, a colleague and a big brother to me. Not only because of giving me the precious opportunity to become one of his first Ph.D students, he also taught me much knowledge about science and skills of doing research. Without his guidance, kind support and helpful advices, I would not be able to complete my researches and this thesis. Working and living in a research group led by him is the most precious experience in my life until now.

Then, I would like to give my thankfulness to Dr. Tang Dongliang as my first colleague at NTU. His wonderful skills and knowledge in doing research have impressed and inspired me to improve my skills and knowledge, which are very helpful for me to continue doing scientific research. Besides, he is also an interesting and thoughtful man who can give brilliant ideas as well as make discussion in our group more exciting. I also want to thank Dr. Sujit Kumar Sahoo for his advices and co-operation during my research time at NTU. In fact, he is

really a knowledge man in his area. Specially, his knowledge of math and programming language has helped not only me but also contributed an essential part to our research group's works. From his point of view in research, he has given many critical ideas which even led to new exciting research directions. Although he is sometimes quite aggressive in discussion and group meeting, but discussing as well as brainstorming with him are very inspiring to me. In contrast, he is a friendly and humor guy who has shared many precious life experience to me. Also I would like to express my appreciation to Dr. Li Dayan, Dr. Huy Quoc Lam, Sha Fangyuan and Zhu Xiangwen for their kindness and support. They are brilliant and kind colleagues in my research group. Time of working with them has given me useful knowledge, skills and experience which are unforgettable to me. In addition, I would like to thank my supervisor Asst. Prof Cuong Dang again for giving me opportunities to help and work with undergraduate students at NTU. Their interest in science and doing research has motivated me to improve my knowledge and my skills.

As a researcher in OPTIMUS Lab of school of Electrical & Electronics Engineering, I would like to express my gratefulness to staffs Mr. Yong Kim Lam, Mrs. Chia Hwee Keng, Mr. Yeoh Tiow Koon, Mrs. Yee Yang Boey and other staffs at school of EEE for their kind and helpful support during my time of doing research at NTU. Without their support and guidance, my research would have met many obstacles. Their friendly and cooperative attitude has formed a very attractive and comfortable environment for researchers at school of EEE in specific as well as at NTU in general.

Last but not least, I would like to give my deep gratitude to my family, specially my wife for their understanding, accompanying and cheering during my hard-working time at NTU.

Without their support in my back, I might not be able to finish my journey as a Ph.D student in Singapore.

Abstract

Propagation of light through scattering media such as glass diffuser or biological tissues is usually considered as a random process, challenging our optical access. My research demonstrates multiple approaches to not only overcome but also utilize the randomness of scattering media. First, I will demonstrate a phase modulation technique to focus light behind a scattering medium. Then, I will present a technique to move the focus spot swiftly in three-dimensional space behind the scattering medium by utilizing optical memory effect. With multiple focus spots, we can measure multiple point spreading functions to image the object behind the scattering medium computationally with expanded field of view. In the second part, I show a technique to utilize ground glass diffusers and their sensitivity with inhomogeneous refractive index to develop a simple and powerful optical sensor. Our detection limit of 12 ppm for glucose concentration or 3.87×10^{-6} refractive index unit is comparable to many optical resonant sensors, which require advanced manufacturing techniques.

Key words: optical memory effect, spatial light modulation, focusing, imaging, scattering media, refractive index sensing.

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corresponds to the speckle images in figure a, b, c, d. Black circled parts are stable states when glucose diffusion completes and we have a uniform solution to take a precise measurement of speckle correlation.119

List of Abbreviations

BP	Band-Pass filter
BS	Beam Splitter
CCD	Charge Coupled Device
CMOS	Complementary Metal–Oxide–Semiconductor
CSA	Continuous Sequential Algorithm
DMD	Digital Micro-mirror Device
DOPC	Digital Optical Phase Conjugation
FOV	Field Of View
FWHM	Full Width at Half Maximum
GA	Genetic Algorithm
IP	Illumination Plane
LED	Light Emitting Diode
LMSF	Lensless Micro-endoscopy by a Single Fiber
ME	optical Memory Effect
NA	Numerical Aperture
OCT	Optical Coherence Tomography
PA	Partitioning Algorithm
PBS	Polarized Beam Splitter
PSF	Point Spreading Function
QD	Quantum Dot

RIU	Refractive Index Unit
SBR	Signal to Background Ratio
SLM	Spatial Light Modulator
SNR	Signal to Noise Ratio
SP	Sample Plane
SSA	Stepwise Sequential Algorithm
TLI	Turbid Lens Imaging
TM	Transmission Matrix
TR	Time Reversal Matrix

Chapter 1: Introduction

Light has most interesting properties; not only does it carry energy but it also carries and transfers information of things with which it interacts. For our planet, light from the sun is an essential source of energy for life. It is the most important element for the photosynthesis which helps plants to produce oxygen and is the first vital stage in the food chain for every species on earth and even coal and oil are a stored form of sunlight energy. Nowadays, with coal and oil are running out, mankind is trying to exploit energy directly from sunlight which is abundant and safe. Due to the damage that the use of fossil fuels is doing to our planet, utilizing sunlight to produce energy is an increasingly important topic.

In addition to providing energy, light also has the ability to carry information. In astronomy, light is the key tool which can carry the information of events that happened a very long time ago, which could help us to understand the beginning and the development of universe. More obviously, light is the most familiar and useful tool for us to gain information of what is happening around us. Among the range of wavelengths of light, the part of it we observe directly with our eyes is so called visible light, which is like a bridge which connects us with an extremely colorful and beautiful environment around. Unfortunately, in some circumstances, visible light can be blocked, scattered or diffracted then the information which it carries is lost and/or scrambled.

In the past, before the compass was invented, viewing stars to find the direction was an essential skill for sailors at night. However, cloudy nights when light from stars was blocked caused huge problems for finding direction. Even now, the scattering effect caused by clouds

is a common problem when acquiring signals from sky. In other cases, the decrease in visibility caused by scattering on a rainy or foggy day can lead to terrible traffic accidents. In medical treatment and surgery, observation of body structure and organs that operate inside body is the essential key for success. For that purpose, X-rays were developed and became the most popular imaging tool; however, it can be harmful to our body and also lacks some information. At first sight, visible light in this application seems to be useless due to scattering and absorption effect inside biological objects. Instead of transmitting through like X-rays, visible light is scattered by biological tissues and at the end, the information which it carries will be scrambled. Besides, absorption effect of biological objects to radiation should be also considered carefully for any light propagation process. Indeed, that effect at some cases could dominate the scattering effect to limit the imaging technique through biological objects if the thickness of object or wavelength of radiation is not chosen properly. However, in this thesis, to concentrate in presenting researches which help to overcome the scattering effect of propagating light through scattering media, the absorption effect can be neglected due to the use of frosted glass as scattering medium target.

Obviously, visible light is very important and useful but it is also limited in some cases where its propagation is affected by scattering media. Therefore, understanding and overcoming that scattering can lead to a huge breakthrough and create useful applications in many fields. In principle, researches focus on two methods to overcome scattering; modulate the incident light to produce a desired output behind the scattering media or eliminate the scattering from the speckle pattern to retrieve back the information which has been scrambled. Interestingly, every coin has two sides, thus the random scattering is sometime not totally

useless, for example; using frosted glass to create private space. Therefore, by understanding the scattering effect well, scattering media can be useful in some circumstance where we need to add some randomness in the light propagation.

Inspired by the ideas above, my work in this thesis is to analyze the scattering and from that, propose methods to overcome the obstruction of scattering media or even find the way to make use of this effect. In this thesis, I will concentrate on solving scattering problems in two principle ways; focusing through scattering media and imaging through them. In the chapter 2 of this thesis, the first two sections will introduce and review outstanding research and works to overcome the scattering by studying the scattering media's properties. In the following section, some prominent research which exploits the randomness of scattering media will be discussed. In chapter 3, I will introduce my research work which proposes a simple but useful technique to create a focus spot and move it around behind the scattering media. Alternatively, a unique imaging technique for imaging through scattering media will be presented in chapter 4. Last, but not least, I will introduce a technique that is based on exciting properties of scattering media to create a refractive index sensing application in chapter 5. Finally, a summary and recommendation for future work which rely on my research presented here will be discussed in chapter 6.

Chapter 2: Literature review

2.1 Focusing through scattering media

As mentioned above, controlling light propagation through scattering media such as biological tissues or ground glass could lead to prominent applications in many fields. However, while scattering effect exists in those media, understanding its impact on light propagation is an essential key to overcome its obstruction. In principle, due to the heterogeneous complex structure, light is scattered casually when it propagates through turbid media. In consequence, random distortion causes losing track of incident light inside a scattering medium, even after a very short optical path (for example larger than $100\text{ }\mu\text{m}$ for a certain tissue thickness[1]) . However, the light field information (phase, amplitude and polarization) does not disappear completely but remains, mixed with unknown factors. Therefore, whether we eliminate those factors by adding in artificial factors to the input light field to compensate for scattering effect, or decrypting the output light field to retrieve back desired information, then light propagation is no longer affected by the scattering effect. Up to now, in general, there are three common methods which could solve the scattering effect for light propagation. One, which characterizes the scattering media as transmission matrices to clarify the randomness, is the most straightforward solution [2-6]. Another way, which is less direct, relies on the time reverse property of light. Indeed, making a phase conjugated field with output field or so called optical phase conjugation, then propagating it backward can re-create the original input wavefront [1, 7-11]. Another powerful approach to eliminate distortion of scattering effect is via an optimization technique known as feedback wavefront shaping [12, 13]. Their general mechanism treats the scattering medium as a black box then

optimizes from recorded varying output as a feedback signal to achieve suitable input for the desired target at the output.

Recently, a common technique for researches in this field is to make a focus spot behind the scattering media due to its simplicity and practicality. Creating a focus spot inside biological object is very useful for non-invasive laser therapy[11, 14, 15]. A focus spot which plays as a point source, can be utilized as a point-spreading function (PSF) for imaging through turbid media[16-18]. In other case, a focus spot can be used to draw any shape behind scattering media. Thus, the efficiency of making a focus spot with high level of contrast and fast processing time is the most critical factor for evaluate the success and usefulness of the proposed methods. The evaluation for the quality of the focusing method relies on the signal of the focus spot compared with average of background intensity, or so-called signal to background ratio (SBR). Fast processing time is also essential for any application in this field because the real scattering media are usually considered to be static over a short time period. In addition, the advantage of making a focus spot also conducts the ability to imagine through scattering media by moving achieved focus spot or forming simultaneously multiple spots in 3D space. Therefore, the ability to control the focus spot is also an important matter for every targeted application in this field. With the study of the optical memory effect, reviewed later in this thesis [2, 19, 20], it initiates a prominent and convenient approach for creating multiple spots from an original focus spot [8, 21].

2.1.1 Characterizing scattering medium as transfer matrix

In general, the propagation of light through a scattering medium is considered as a random process. However, we can still formulate that process as a Green's function between an initial

input field and an output field, which can be represented as a transmission matrix (TM) [22]. In a common procedure of characterizing a TM, a spatial light modulator (SLM) or digital micro-mirror device (DMD) is used to control incident light to the scattering medium and the output is measured on the other side. In practice, the TM defines the transfer between an array of light sources and array of intensity sensors. Therefore, conducting a TM as full transformation between two light fields usually requires an additional measurement such as the “phase shifting method” or the so-called “four phases method” [23] to achieve the phase information. Investigating the TM’s properties is a direct way to de-scatter the propagation of light through scattering media, which leads to interesting possibilities of utilizing scattering media.

Figure 2.1: Setup for measurement of TM by group of S. Gigan et al [5].

The input light field is a combination of amplitude modulation of a reference laser beam and phase modulation by the SLM. The input light field is then passed through a turbid medium sample before being observed by a charge coupled device (CCD) behind it. Polarizers are used there to correct the polarization of the beam modulated by SLM. The first objective

lens imaging the plane of the SLM on the scattering sample is used to reduce the number of degrees of freedom. The second objective lens transfers the output speckle pattern to the CCD. Therefore, the TM characterized there actually defines the complete optical system, including the scattering sample. Indeed, the TM can be understood as a matrix of complex coefficients k_{mn} relating the full field in the n th free mode of the input beam to the m th free mode of the output speckle. This relation is represented in the equation below:

$$E_m^{out} = \sum_n k_{mn} E_n^{in} \quad (2.1)$$

Where E_m^{out} and E_n^{in} are the output field and input field, respectively. The number of controlled segments on the SLM is defined as N . The minimum number of measurements for that setup to succeed is $4 \times N$. For their experiment, with $N = 256$, the processing time was approximately 3 minutes. As introduced above, the phase information was also retrieved by the “four phases” method [23]. The output speckle pattern interferes with a reference field to make an interference image on the CCD with amplitude of $E_m'^{out}$. Then by analyzing the interference pattern each time the phase of input field changed with specific value α , the information of output field is earned. The general formula for that relationship is:

$$\begin{aligned} I_m^\alpha &= |E_m'^{out}|^2 = |s_m + \sum_n e^{i\alpha} k_{mn} E_n^{in}|^2 \\ &= |s_m|^2 + \left| \sum_n e^{i\alpha} k_{mn} E_n^{in} \right|^2 + 2\Re \left(e^{i\alpha} \overline{s_m} \sum_n k_{mn} E_n^{in} \right) \end{aligned} \quad (2.2)$$

Where I_m^α is the measured pattern intensity, s_m is the amplitude of reference field. In their experiment, a set of Hadamard basis was used as input set for characterizing each element

k_{mn} of TM. The efficiency of measuring the TM was evaluated later by using it to create a focus spot. Here, they considered a time reversal matrix (TR) as a filter which maximized the energy both temporally and spatially at a desired position. In fact, the TR now becomes a phase conjugation and is implied straightforwardly from the TM. With the experimental result displayed in Fig 2.2, the focus spot is formed with $SBR = 54$. In analyzing the result, both phase-only modulation and the reference field for measuring the TM of scattering medium are quantified. Therefore, the effective focusing operator comprises a normalization for the phase-only modulation, for the example of a single focus spot: $O_{norm}^{foc} = K_{obs}K_{norm}^\dagger$ where $k_{ij}^{norm} = k_{ij}/|k_{ij}|$. As illustrated in Fig 2.2(c), any focus spot on CCD gives an output image with a corresponding line. The ability of focusing light at any point is demonstrated by the strong diagonal.

Figure 2.2: Experiment result of making focus spot by group of S. Gigan et al [5]. (a) Initial aspect of the output signal. (b) Measured TM was used to perform phase conjugation. (c) Norm of the focusing operator. (d) Multiple spots created simultaneously at different positions.

In conclusion, that experiment shows a measurement of the TM successfully done by using SLM and full-field interferometric measurement as it allows a focus spot to be created behind the scattering medium. However, there are two caveats to the work described above; the stability of system should remain stable long enough for characterization process to be carried out (in that case of $N = 256$, at least more than 3 minutes) and a higher number of controlled segments will require much more processing time.

Another approach of TM measurement had been done by group of Y. Park et al [6] in 2015. Although their setup did reproduce some essential parts for a typical TM measurement,

the advantage of the later method was the simplicity of the experimental system as it no longer required a reference beam or an interferometer to obtain the phase information. Instead, it required a technique improved from the parallel wavefront optimization method by M. Cui [24] which produced a full-field input beam for creating a focus spot behind the scattering medium. In their approach, the full-field speckle intensity maps were exploited to simultaneously achieve the optimized phase maps that gave ability to focus at different positions behind scattering media. As the principle of the method, each SLM pixel was defined on an orthonormal set $|x_1\rangle, |x_2\rangle, |x_3\rangle, \dots, |x_N\rangle$ while each camera's pixel was another orthonormal set $|y_1\rangle, |y_2\rangle, |y_3\rangle, \dots, |y_M\rangle$. N and M were the total pixel of SLM and camera, respectively. Then the whole system was expressed in the following equation:

$$\langle y_m | \psi \rangle = \sum_{n=1}^N \langle y_m | t | x_n \rangle \quad (2.3)$$

Where ψ is the output speckle light field and t represents for of TM of the whole optical system. The SLM pixels were utilized to play two different roles; one group of pixels modulated the impinging wavefront while the rest of them provided a fixed reference beam. For the balance of intensity between the reference field and the signal field at the camera's plane, the SLM panel was designed with phase information configured as a checkerboard pattern. The schematics for each step of the measurement are shown in Figure 2.3. Pixels in the signal group were assigned distinct modulating frequencies while for the rest, the frequencies were considered as zero. Thus, the whole optical field of the system could be represented as a sum of the reference field $|R\rangle$ and the signal field $|S\rangle$:

$$|\psi\rangle = |R\rangle + |S\rangle = \sum_{n=G+1}^N t |x_n\rangle + \sum_{n=1}^G t |x_n\rangle e^{i\omega_n t} \quad (2.4)$$

Where N is total number of pixel, G is total number of pixels assigned as a reference. By inserting (2.3) into (2.4), the observed intensity maps on the camera could be expressed as:

$$|\langle y_m | \psi \rangle|^2 = |\langle y_m | R \rangle|^2 + \sum_{p,q=1}^G t_{mp}^* t_{mq} e^{i(\omega_q - \omega_p)t} + |\langle y_m | R \rangle|^* \sum_{p=1}^G t_{mp} e^{i\omega_p t} + \langle y_m | R \rangle \sum_{p=1}^G t_{mp}^* e^{-i\omega_p t}. \quad (2.5)$$

From the above equation, the important term was the third one which contained information for constructing the TM and needed to be extracted separately. To do so, full-field intensity maps with a total $4G$ elements were measured with $\omega_p = \frac{G+p}{4G} \omega_0$, where ω_0 is the frame rate of camera. In addition, the range of $\left[-\frac{1}{2}\omega_0, \frac{1}{2}\omega_0\right]$ should be set for the harmonic frequency $\omega_q - \omega_p$ with condition to not overlap with ω_p . By exchanging the role of pixels in one group to the other, and vice versa, the whole SLM could be exploited for modulating the signal field. Then, the minimum requirement for the number of measurements is $4N$. From the achieved optimized phase patterns, the TM could be directly constructed by reference phase matching step demonstrated in Figure 2.3 (c) [6].

Figure 2.3: Procedure for each step of TM measurement done by group of Y. Park et al [6].

(a) Group 1 is set as modulated group. (b) Measurement as group 2 is modulated group. (c) Reference phase matching step.

Similar to previous work, the group of Y. Park et al also evaluated the efficiency of the TM measurement by utilizing it to create focus spots behind the scattering medium. Their result is illustrated in Figure 2.4. With a single focus spot, the SBR = 460 by using 990 SLM segments, of which was 59.2% of theoretical value. The time consumed to evaluate the TM of 990×36864 was 1.32×10^3 seconds. To generate multiple foci, the optimal phase pattern could be gained from a linear combination of individual phase patterns for creating each desired focus spot.

Figure 2.4: Experiment result of creating focus spots behind scattering medium by using TM measurement from group of Y. Park et al [6]. (a) Focus spots at different position. (b) Multiple focus spots created simultaneously.

2.1.2 Using Conjugated phase propagation to produce focus spot

Instead of putting effort into characterizing the TM, there are other more relevant ways to directly create focus spot which considers the optical system including the scattering medium as a black box; from this, the mechanism to achieve desired output field from initial input field is discovered. Establishing the conjugated phase propagation based on the reverse-time property of light propagation is one of them. The principle of this technique could be simply understood as follows: an input light field propagates through an optical system as a black box and generates an output field, then if a field which is phase conjugated with that output field is transferred backward through the notional black box, it will re-generate the initial input field. For the purposes of simplicity, the initial input field is simply a point source, which later would allow to produce focus spot at the same position. Most of the research is based on the principle of optical phase conjugation and the executed process is normally divided into two steps: achieve the targeted output field and then transfer back with the field phase conjugated. Similar

imaging system with a lens and objective lens, then output field was imaged on the first camera. That light path was displayed as beam from EO and then successively through lens 1, lens 2, BS 2 (beam splitter) and on to the CCD. The other light path, which required PBS (polarized beam splitter) in its path, was modulated by the SLM before passing on to the CCD as a reference beam. With both reference beam from SLM and targeted beam out of lens 2 being directed on to the same CCD, a set of interference patterns were recorded to obtain the full information for targeted beam. To achieve that information, the “phase shifting method” was exploited.

Figure 2.6: Procedure of matching precisely pixel by pixel for experiment done by group of Meng Cui and Changhui Yang [7].

However, the critical step in that experiment was to generate and transfer back exactly the achieved field through the scattering medium. To do so, a matching procedure was introduced in Figure 2.6. The goal of the matching step is to reproduce exactly whatever field measured on the CCD1 by the SLM. Therefore, it is required that the SLM plane should match the plane of CCD1, which was based on the plane of the scattering medium’s surface as reference. That accurate adjustment would require extremely stable and precise translation

stages for movement of the SLM and CCD1. In addition, each measured segment on CCD1 should be mapped precisely to each SLM segment. Therefore, a chrome mask for calibration was made with 10-micron diameter holes and 20-micron hole spacing. In the step (a) of Figure 2.6, the mask was placed in symmetric imaging with the SLM through a beam splitter (BS). Then the mask was also imaged on CCD1; thus, it informed the position of each mask hole on CCD1. In the next step, with the mask and SLM fixed, a beam was reflected on the SLM then observed by CCD2, as demonstrated in Figure 2.6 (b). For the phase displayed on SLM, each controlled segment has a phase difference of π with respect to adjacent segments, which would create a dark line at the edge of phase segments. That achieved checkerboard would tell the position of controlled SLM segments on CCD2. At the last step, instead of reflection on the SLM, the beam passed through the mask and continued on to the SLM. The recorded image was the map for the mask's hole position on CCD2. By comparing the image acquired in step 1, 2 and 3, the controlled segments on SLM were mapped onto CCD1 precisely.

Figure 2.7: Experiment result from work done by Meng Cui and Changhui Yang [7]. (a) DOPC measured phase profile. (b) DOPC reconstructed signal. (c) Measured signal with plane phase on SLM.

After the matching procedure and calibration were done, their experimental setup was qualified to create a focus spot behind scattering medium and the result is shown in Figure

2.7. The SBR for their experiment was approximately 600 with a controlled matrix of 634×634 . However, the SLM was a phase modulator only, so their experiment was only able to reconstruct the phase of full-field recorded and the amplitude was taken from reference beam.

Figure 2.8: Digital optical phase conjugation experiment done by group of Y. Park et al [25]. L1, L2, L3, L4 are lens; BS1, BS2, BS3 are beam splitter; M1, M2, M3 are mirror.

Another work to improve DOPC was done by the group of Y. Park et al [25]. Their setup is illustrated in Figure 2.8, and was similar to previous work by the group of Meng Cui and Changhui Yang [7]. However, in the reconstruction part, the SLM was aligned directly with CCD1 through the arm 3 of light path while, the mirror M1 was flipped out. Thus, their improvement was to reduce the setup complexity by directly mapping the pattern on the SLM with the pattern recorded on CCD1, which is explained in Figure 2.9. Instead of using an actual mask, their setup used a digital phase mask on the SLM as in Figure 2.9 (b) and then it was imaged on CCD1 in Figure 2.9 (c) and (d). Then, the correction phase was produced on SLM in Figure 2.9 (c) which generated a plane wave on CCD1. Therefore, after achieving

target pattern on CCD1, the DOPC was generated by the sum of the target pattern's phase and the correction phase pattern. After generating the DOPC by the SLM, it was propagated back to the system by mirrors M1 and M2. Therefore, the alignment of those mirrors is also critical and requires frequent calibration.

Figure 2.9: Alignment for matching SLM with CCD1 [25]. (a) Imaging path (between SLM and CCD1), indicated with a red arrow; (b) Test pattern written to SLM (writeable region 792×600 pixels); (c),(d) Measured responses at CCD1 to test pattern of (b) for different input-beam polarization states, permitting the one-to-one mapping from SLM to CCD1 to be determined; (e) Correction phase pattern applied to SLM (color bar in radians) in order to generate a plane phase front at CCD1

The experimental results for above setup are given in Figure 2.10. In the work done by group of Y. Park et al [25], they used an image as the target instead of a point source; however, the mechanism is the same for both cases. By experimenting with the image, their purpose was to evaluate the quality of the setup by observing whether the reconstructed DOPC was shifted laterally; the effect of this is shown in Figure 2.11. By illustrating that the quality of the reconstructed image is poor after very tiny mismatch of position (2 pixels or 200nm), the

experiment pointed out how critical the precision of the optical alignment is for the method to succeed. Although the method had reduced much complexity in alignment and calibration, the establishment of the setup was still challenging.

Figure 2.10: Experiment result observed by group of Y. Park et al [25]. (a) Target image on observation path. (b) Reconstructed image with plane phase on SLM. (c) Reconstructed image with optimized SLM control without “fine tuning”. (d) Reconstructed image with optimized and fine-tuned phase on SLM.

Unlike the TM characterization method for making the focus spot, DOPC here would require the modulation of both input phase and amplitude for perfect reconstruction. That strict requirement, however had not been served completely in those two works described. Obviously, in both experiment setups, only phase modulation from SLM is allowed when the amplitude is taken from a fixed reference beam. Therefore, for future improvement, the reviewed methods could be enhanced with methods utilizing full phase and amplitude for a desired field. In work carried out by the group of A. Tomita et al [10], they proposed a method for producing full field by using two phase-only SLMs in parallel. Briefly, in their method, a

desired full field was produced by the interference of two fields with same amplitude (reference beam) and two different suitable phases. On the other hand, group of M. Ritsch-Marte et al [26] demonstrated a similar achievement for constructing a desired full field with two SLMs, but in sequence. Despite using phase-only modulation, the first SLM could still deliver a field with desired amplitude, but random phase pattern to the plane of second one, by generating an appropriate phase pattern for the diffraction process between the two SLMs. Then, the known random phase pattern on the second SLM due to diffraction process could be corrected by a second phase modulation.

Figure 2.11: The reconstructed image while shifting reconstructed phase on SLM a distance Δx in the same direction. The value η stands for qualification index of reconstructed image in comparison with original one.

2.1.3 Feedback wavefront shaping optimization method to create focus spot behind scattering medium

As an alternative to considering the optical system, including the scattering medium, as a black box, the feedback wavefront shaping proposes a different approach which does not require a complex setup with precision of alignment in the order of hundreds of nanometers, as in the DOPC method. The principle of the method is simply explained in Figure 2.12 [13]. In the scattering medium is relatively static in terms of the measurement process, then

although the light scattering is random and unknown, it is definitely deterministic and linear. Therefore, instead of plane wave, when a suitable modulated wave-front propagates through scattering medium, it can produce behind a desired field, which in most cases is a focus spot.

Figure 2.12: Principle of feedback wavefront shaping method for creating a focus spot behind scattering medium [13]. (a) Phenomenon of propagating a plane wave through scattering medium with output speckle (b). (c) Using output speckle as a feedback to modulate input wavefront. (d) Achieved focus spot with optimized phase pattern (f). (e) Imaging process could be obtained by combing many single focus spots.

With sensors or camera placed behind the scattering medium, the output pattern can be observed to play as feedback guidance for the modulation in front by using iterative optimization algorithms. Overall, the issue appears to be the way in which way we shape the input wavefront to achieve the desired output field. In fact, the TM measurement can be considered as an optimization; however, the desired field is only achieved only after the whole process is completed. In the way of using iterative optimization algorithms, it is more

convenient to make focus spot because the spot intensity starts to glow up instantly and the SBR is usually higher.

Before digging into developed methods in this field, the principle of achieving a focus spot from wavefront shaping techniques should be reviewed. (2.1) which presents the process of propagating light through any linear medium in form of matrix, is recalled here. So in the simplest process, wavefront shaping techniques are developed to deal with the problem, which is the input field E_n^{in} to drive light transmission into desired output mode E_m^{out} . Here, the desired output mode can represent for a focus spot, plane wave or any other field pattern. However, in this section about the wavefront shaping technique, the desired output is considered as focus spot. To solve the problem, from (2.1), in term of intensity $I_m^{out} = |E_m^{out}|^2$, an inequation is derived by applying the Cauchy-Schwartz inequality:

$$I_m^{out} = |\sum_n k_{mn} E_n^{in}|^2 \leq \sum_n |k_{mn}|^2 \sum_{n'} |E_{n'}^{in}|^2 \quad (2.6)$$

The equality is only present if $E_n^{in} \propto k_{mn}^*$. If we assume that the total power of incident beam is fixed, then the required incident field, which leads the light propagation into desired output mode, is given as:

$$E_n = E_0 k_{mn}^* \quad (2.7)$$

Where E_0 is a normalization constant to maintain the total incident power at a fixed level. In particular, this solution is also exactly the phase conjugate of the field propagating from mode m back to n . As mentioned, the success of most focusing methods relies on the SBR or contrast of the focus spot. Due to the dependence on both intensity of the focus spot and the average intensity of background, the SBR can be increased by directing more light into the focus

position or eliminating the background intensity, or by both. However, it is theoretically impossible for any wavefront shaping technique to focus all output light into a point. From (2.6) and (2.7), it is obvious that:

$$\frac{I_m^{\text{out}}}{I_h^{\text{in}}} \leq K_m \text{ where } K_m \equiv \sum_n^N |k_{mn}|^2 \quad (2.8)$$

Here, K_m is the total power transmission into output mode m , averaged over all possible incident fields. Usually, $K_m \ll 1\%$ [13] due to the total contribution of various factors; back reflected light, only single polarization used, finite numerical aperture and finite extent of the system, light absorption of sample, number of controlled elements limited and so on. Fortunately, beside driving light into desired position, the SBR can also be increased if the intensity of background is lowered by creating destructive interference speckles around the focus spot. Therefore, in the optimization process for feedback wavefront shaping, the system can be regulated to focus light and/or eliminate the background intensity. Consequently, iterative optimization algorithms to usually give better SBR than methods rely on characterizing the TM.

Figure 2.13: Principle for three different feed-back iterative optimization algorithm[27]. (a) Stepwise sequential algorithm. (b) Continuous sequential algorithm. (c) Partitioning algorithm.

Among the many iterative approaches used to optimize the input field for creating a focus spot through scattering media, there are outstanding and simple iterative feedback algorithms summarized by I.M.Vellekoop and A.P. Mosk [27]. The principles of the three techniques are described briefly in Figure 2.13. The simplest and most straightforward algorithm is the stepwise sequential algorithm (SSA) which is exploited by I.M.Vellekoop and A.P. Mosk [14] and its principle is illustrated in Figure 2.13(a). It is based on the fact that the obtained intensity is the superposition of light scattered from all segments of incident field. Therefore, the optimal field can be achieved by optimizing phase in range of 0 to 2π for each segment to get highest SBR. However, the optimization of each segment is done iteratively, with the phase of the rest of controlled segments set as 0. The phase value of each segment is then stored and processed before moving on to the next one. In those conditions, the background remains nearly constant. In consequence, the optimized wavefront is the set of individual optimized phases, which obviously would only increase SBR by manipulating the intensity at the focus position. The achieved intensity for focus spot also cannot be a linear sum of intensity recorded at each step of the optimization process, which might decrease the quality of the focus spot to be lower than expected.

The other principle is displayed in Figure 2.13(b) is called continuous sequential algorithm (CSA); this algorithm is an improvement for the stepwise sequential algorithm. Instead of optimizing each individual segment with unchanged background, this algorithm continuously updates the whole field with a new phase value optimized for the segment in the previous step. Therefore, the SBR starts increasing instantly with both factors intensity of focus spot and averaged intensity of background being manipulated.

However, even with the improvement in updating background, contribution to background of each optimized segment is still too little in comparison with the rest of input wave-front. In addition, the convergence of the sequential algorithm is quite slow. Therefore, as an alternative, we can do optimization for a group of segments to reduce processing time by using the partitioning algorithm (PA) displayed in Figure 2.13(c). All segments now are divided in two groups equally at each iteration; one is set as a reference and the other is modulated with a same phase value ranging from 0 to 2π to get highest SBR. At the beginning of each iteration the segments in the group for optimization are chosen randomly, while the others keep their phase value from the previous step. Then the process is repeated indefinitely until all segments are chosen for optimization or the target value of SBR is achieved.

A comparison of the enhancements of the algorithms described can be found in Figure 2.15. In Figure 2.15(a), with the low noise lever, the CSA shows faster and better enhancement for creating focus spot as spot intensity is decisive factor for optimization. Otherwise, with high noise level, PA demonstrates its advantage in increasing the SBR by simultaneously eliminating the background intensity and enhancing the intensity of the focus spot above the noise level. In contrast, the CSA (also SSA) requires more steps to deliver appropriate phase due to optimizing only a small element at a time. However, after some iterations the optimization process of PA gives slower enhancement as the partitions are not actually orthogonal. In addition, as half of the total elements are modulated with same phase, if an error of π occurs from noise measurement, the quality of focus spot could decrease suddenly. Therefore, in the process of optimization, the system should be able to back-up to the previous state if the focus spot gets dimmer.

Figure 2.14: A block diagram showing the steps of the genetic algorithm: (1) A population of phase masks is created. (2) The cost function of each mask is measured and the masks ranked. (3) Breeding is implemented, with the breeding parent phase mask being selected with a higher probability if it is higher ranked. The new offspring mask is created by combining the ma and pa masks using the breeding template, T , and mutating x input modes of the new mask. (4) The cost function of this new offspring mask is then measured and used to place it within the population. (5) The process repeats for a certain number of iterations or until a satisfactory solution is achieved [12].

The three iterative optimization algorithm described have demonstrated simplicity in making the focus spot behind the scattering medium; however, their mechanisms require much more time for processing. Therefore, an iterative optimization method called genetic algorithm (GA) was first introduced by group of R. Piestun et al [12], which has been proven to have

many advantages [12, 13, 28] in focusing light through a scattering medium. Its principle is inspired by the evolution process in nature where each generation is better than the previous one. The Figure 2.14 illustrates the diagram for GA. Similar to previous mentioned algorithm, GA also solves the problem: which is phase pattern for all elements of incident field that can maximize the SBR of focus spot. Basically, the algorithm iteratively optimizes the phase pattern through a breeding and mutation operation. Firstly, a set of N phase masks is generated randomly with value from 0 to 1, corresponding to phase values from 0 to 2π . A random binary breeding template array, T , is also created and fixed during the optimization process. This template plays as a factor for producing offspring phase masks from chosen parent phase masks (called “pa” and “ma”). At the first step of the iteration, each phase mask in the set of N is displayed on the SLM as the phase pattern of an incident wavefront; it then creates a corresponding output pattern behind the scattering medium. Here, from the pattern on camera, we can chose the focus position to measure the SBR. Therefore, the SBR of intensity at focus position is exploited as feedback for the GA. Higher SBR will give the input phase mask on the SLM higher rank among the set of N phase masks. Then, two parent phase masks are randomly selected from the set of N phase masks which follows the rule that higher ranked phase masks are given higher probability of selection. The chosen parents accommodate with template T to create a new offspring by the formula: $= ma \cdot T + pa \cdot (1 - T)$. The newborn phase mask is then mutated by randomly changing the phase of a set number of input modes. Certainly, to prevent mutating too many phase modes, the percentage of modes mutated, R , decreases as the algorithm runs and nears the optimal phase mask.

Figure 2.15: The comparison for the enhancement of each feedback wavefront shaping to make focus spot behind scattering medium in simulation model [12]. (a) and (b) represents different level of noise for experiment. GA: genetic algorithm; CSA: Continuous sequential algorithm; TM: transmission matrix; PA: random portioning algorithm

In this case, R is defined as:

$$R = (R_0 - R_{end}) \cdot \exp(-n/\lambda) + R_{end} \quad (2.9)$$

Where R_0 is the initial mutation rate, R_{end} is the final mutation rate, n is measurement number and λ is the decay factor. Then the offspring phase mask is set for the phase of the incident field to measure the output pattern on a camera and imply its rank among the phase masks in

the existing set through a generation method. For each generation, a half -population size of the existing set which have the lower rank, are replaced by the new offspring phase mask set.

Figure 2.16: The experiment done by group of R. Piestun et al [12]. (a) LC-SLM: liquid crystal spatial light modulator; f_A , f_B , f_t : lenses; 100X, 20X: objective lenses; S: scattering sample; P: polarizer. (b) Output pattern on camera as unmodulated beam passing through scattering medium. (c) Focus spot achieved by using GA method with SBR = 50. (d), (e), (f) Experiment results with different noise level 7%, 18% and 25% of average intensity, respectively.

As proven by simulations [12], this GA method has a faster convergence rate than other popular algorithms, which are demonstrated in Figure 2.15. The parameters used in real experiments can be deduced from suitable simulation for GA. Especially at high noise levels, GA surpasses not only other iterative optimization algorithm but also even the TM method due to its advantages. By modulating random phase patterns and measuring the output as the merit of whole input field, it can quickly enhance the quality of the focus spot and also reduce

the power distributed in the background. From the experimental results illustrated in Figure 2.16, the GA also provide its advantage to create focus spot behind scattering medium.

2.2 Imaging through scattering media

Focusing light through scattering media seems to be the most convenient way to overcome the distortion caused by scattering effect. Beside of various useful application, making focus spot also leads to form desired images behind scattering media by creating multiple spots. However, that is indirect approach for imaging through scattering media which is also limited by many factors such as processing time, complex setup and so on. In this thesis, I will propose research work to resolve those problems of making images from multiple focus spot. Although the solution is very prominent but there are also other direct approaches which can allow imaging through scattering media. The most common and outstanding methods for imaging through scattering media will be reviewed in this section are: measuring TM, constructing adaptive optics to compensate scattering effect and utilizing deconvolution.

The principle of characterizing TM has already discussed earlier in section 2.1.1. Beside the applications for making focus spot, TM measurement is also helpful for imaging through scattering media. Beyond that, some properties of scattering media themselves even bring some advantages in comparison with normal optical devices. One of them had been investigated by group of W. Choi et al [3] and so called using scattering medium to overcome the diffraction limit. In their work, TM was mentioned as turbid lens imaging which can overcome traditional optical lens by enhancing the spatial resolution for optical system. NA of a normal lens is fixed which only allow it to capture light in limited solid angle. In case of scattering medium, there is more light obtained due to multiple scattering effect, which lead

to enlargement of NA in comparison with NA of a normal lens. Then it turns out that the spatial resolution of optical system with scattering medium can be improved more than using normal lens.

Another field which can utilize a scattering medium with the TM approach for imaging is endoscopic imaging through a single multimode optical fiber. Endoscopy is widely known for its vital role in the industrial, military and medical fields because it enables image capture at positions where conventional imaging systems with normal optical devices cannot reach. Nowadays, commercial endoscopes usually incorporate a standard fiber bundle. In principle, increasing higher resolution for imaging demands a greater number of fibers, which results in increasing diameter of the endoscope, therefore creating a limitation to its accessibility. A proposed solution for that is to replace the fiber bundle by single multimode fiber due to its mode density with two or three orders of magnitude higher than the pixel density of a fiber bundle. However, another problem arises as the requirement of reflection configuration for obtaining the object will produce a two-fold distortion (light in and out) for imaging system. To solve that issue, an approach with a TM characterization for fiber was proposed by the group of W. Choi et al[29]. In their method, the endoscopic imaging technique is developed to operate in wide-field reflection mode with a single multimode optical fiber, which is also called a lensless micro-endoscopy by a single fiber (LMSF). In conclusion, measuring the TM is a direct approach to solve problems related to imaging through scattering media. However, limited by processing time for a huge number of measurements, it is only capable in applications which deal with static scattering media.

In other parts of this section, constructing adaptive optics to compensate scattering effect and utilizing deconvolution will be discussed more in detail. However, in the first part of this section, an important property related to light propagation through scattering media which is called optical Memory Effect (ME), will be discussed first. Then its contribution to related imaging techniques will be explained later.

2.2.1 Optical Memory Effect

Optical memory effect or also known as spatial correlation in turbid medium has been first discovered by group of S. Feng, C. Kane and et al [30] during the investigation of coherent wave transmission through distorted media and then officially stated by group of I. Freund, M. Rosenbluh, and S. Feng [19]. Its model, characteristic and application have been explored and exploited to do imaging through scattering media by many group [20, 31-34]. In principle, the idea of “Optical memory effect” applied for an appropriate thin turbid medium is based on the spatial correlation: when an incident wavefront to turbid medium is tilt or shift in a limited range of angle or distance, its output wavefront on the other side will tilt or shift with the same angle or distance. Therefore, it has an extremely useful advantage for focusing and imaging through scattering medium, that is: if a wavefront profile which creates a pattern behind scattering medium is known, then it could be modified by applying optical memory effect to create another pattern similar to original one at different positions within an appropriate space. Therefore, in term of focusing through scattering media, there is no need to find different wavefront by optimization or measurement to create focus spot at different positions, which in application will save a lot of effort and time. In term of imaging, if an

incident wavefront for creating a speckle pattern is known, it can be used as reference to create any desired patterns within the area around original one according to the ME.

Figure 2.17: Three different types of Optical Memory Effect in turbid media. (a) The optical “tilt” memory effect. (b) The anisotropic “shift” optical memory effect. (c) both “tilt” and “shift” memory effect.

There are three types of spatial correlation in turbid media demonstrated in Figure 2.17: “tilt”, anisotropic “shift” and the combination of both. Based on the work done by group of G. Osnabrugge, R. Horstmeyer and et al [20], mode of “generalized memory effect” presents a full description of combined shift/tilt correlations within turbid media. Moreover, it also explains and estimates characteristics of optical memory effect such as: limited range for shifting/tilting, size of the aplanatic patch in microscopy.

Overall, the formula for calculating ME range in 3D space has been constructed by group of Y. Silberberg et al [35] as below. In plane which is parallel to the surface of scattering medium, correlation equation is:

$$C(\theta, L) = \frac{k_0 \theta L}{\sinh(k_0 \theta L)} ; \sinh(x) = \frac{e^x - e^{-x}}{2} \quad (2.10)$$

Where C is the image intensity (in this case, it is spot's intensity), $k_0 = 2\pi/\lambda$, θ is the angle difference from the original optimized spot and L is an effective thickness of scattering medium.

Assume angular field of view (FOV) is angle θ where C decreased by half:

$$\theta_{(1/2)} = 1.4915 \frac{1}{k_0 L} \quad (2.11)$$

$$FOV (angular) = 2 \theta_{(1/2)} \quad (2.12)$$

$$Longitudinal FOV = z_0 \times FOV_{(angular)} \quad (2.13)$$

Where z_0 is distance from original focus spot to scattering medium. In Z-axis (or axial axis) which is normal to surface of scattering medium:

$$\Delta z_{FOV} \approx 2 \frac{z_0}{D} FOV_{(longitudinal)} \quad (2.14)$$

Where D is diameter of beam shined on surface of scattering medium.

2.2.2 Adaptive optics for imaging through scattering media

Recently, beside the TM approach to retrieve back information for imaging through scattering media, there exist other methods which directly utilize some specific speckle patterns at output as reference to do the imaging. A scattering-imaging method relying on a known object and its speckle pattern caused by the scattering is referred to as adaptive optics. The principle of this is to find a correction wavefront for compensating the scattering which enables retrieval of the original object image behind the scattering medium. In principle, a known object is imaged through a scattering medium; then its speckle pattern is observed by

a camera. Any wavefront shaping device, such as an SLM, is placed in between scattering medium and the camera to act as a correction device. An adaptive optics algorithm is applied with the correction device to produce a phase mask which can change the speckle pattern on camera to be similar to the reference object. As stated before, if the light propagation through scattering medium is relatively static, then imaging process can be described by a TM. Therefore, that TM can be reversed by producing an appropriate phase mask on a correction device placed behind the scattering medium. Once the correction phase mask is found, it can be used to do imaging for any object through scattering medium, under some limitations which will be discussed later.

Research done by group of Y. Silberberg et al [35] has proposed an adaptive optics approach for imaging through scattering medium. Their mechanism is illustrated in Figure 2.18. Based on the stated principle above, this approach uses a point source as a reference object. In Figure 2.18(c), without applying phase mask on the SLM, output speckle of a point source in front of scattering medium is observed on a camera through a lens. With an appropriate phase mask on the SLM, that speckle pattern can be converted to a focus spot with high contrast. Therefore, the system now operates similarly to a lens; this is a so-called scattering lens which enables imaging through a scattering medium as in a normal lens system. In process of achieving an appropriate phase mask for wavefront correction, a genetic algorithm (GA) [12, 14] is used for its outstanding advantages. Using camera the camera, GA optimizes the phase mask on the SLM to focus light into a chosen position, as well as to cancel out the intensity of the background. A focus spot with high SBR is then achieved. After the calibration step, the whole system, which includes optimized phase mask on the SLM,

becomes a scattering lens. Understanding the optical memory effect (ME) above, we can recognize that a scattering lens has limited space for imaging. In detail, to do imaging a target object needs to be placed within a space which is defined by ME around the original point source. Results for imaging a letter A with an optimized phase mask are shown in Figure 2.19.

Figure 2.18: An adaptive approach for imaging through scattering medium proposed by group of Y. Silberberg et al[35]. (a) Imaging of an object with a normal lens. (b) Output speckle pattern at scattering surface is imaged to a camera by a lens. (c) Using SLM and lens to reverse the scattering effect which makes the system as a scattering lens. BP is a band-pass filter which has bandwidth of 3.4 nm (FWHM) around wave-length of 633.4 nm.

Figure 2.19: Result for adaptive optics imaging method through scattering medium from group of Y. Silberberg et al[35]. (a) Speckle pattern generated by a point source without correction phase mask. (b) Focus spot on camera with optimized phase mask on SLM. (c) Image of letter A illuminated by a white-light source is observed on camera for a conventional imaging. (d) Image observed on camera by applying optimized phase on SLM. (e) Image from the case (d) without band-pass filter. (f) Similar to case d but light source is a HeNe laser beam. Scale bar is 3 mm

There are two fundamental limitations for above adaptive optics approach, these are frequency bandwidth and image contrast. The frequency bandwidth for imaging with a scattering lens depends on the frequency bandwidth of the focus spot created by the correction phase mask, and the property of scattering medium for speckle spectral correlation width Δf . In Figure 2.19(e), without a band-pass filter, light with frequencies outside of Δf reduces the contrast of the final image on the camera. For the adaptive optics approach, all the corrected

optical paths are set to be the same, which allows imaging with an incoherent light source. For a high contrast image, only spectral components within Δf should be used. Another calibration with a focus spot is required for extending the usable wavelength range. On the other hand, image contrast is also affected by perfection of optimized focus spot. An optimized phase mask for a sharper focus spot will produce higher quality for image reconstruction.

The adaptive optics method above is also applied for looking around corners with incoherent light. The experiment scheme and its result are demonstrated in Figure 2.20. The field of view (FOV) and resolution for imaging system in both the case of reflection and transmission geometry are the same. However, the scattering medium used in the reflection mode is thinner, which leads to shorter FOV of ~ 5.7 mrad. While in transmission mode, the FOV is ~ 12 mrad.

Figure 2.20: Application of adaptive optics method done by group of Y. Silberberg et al[35]. (a) Setup for reflection imaging with scattering medium as a scattering mirror. Scattering medium is a white paper. Calibration step for a point source is done before object (letter G) is placed within the ME range around that point source. (b) Back-scattered light. (c), (d) Images on camera without and with distortion correction, respectively. (e-i) Obstructed object is tracked in real-time ($240\ \mu\text{m}$ pinhole). Scale bars of 1 mm.

Another scattering-imaging method relied on a known object is proposed by group of J. Zhou et al[36]. Their experimental setup is shown in Figure 2.21. In their setup, the object image is transferred through the scattering medium and then its output speckle pattern is modulated by the SLM before being captured by the camera. At the calibration step, their procedure is similar to the adaptive optics method discussed above, with appearance of a reference object and GA for optimizing appropriate phase mask on the SLM. However, instead of using point source as the reference object, in this method, any object which is small enough in range of the ME, could be used. The running process and results are shown in Figure 2.22.

Figure 2.21: Experiment setup proposed by group of J. Zhou et al[36]. Back surface of scattering medium is imaged on SLM surface by 4f lens system.

With reference object letter “S” known in advance, the target for modulating phase on the SLM is to reproduce a similar letter “S” on the camera. According to the system setup and speckle feature, the size of target image on the camera can be evaluated. Cost function for optimization process, which demonstrates the relative comparison between target image and observed image is a the Pearson correlation coefficient [37]:

$$\gamma = \frac{\sum_{s=1}^P \sum_{t=1}^Q [f(s,t) - \bar{f}] [w(s,t) - \bar{w}]}{\left\{ \sum_{s=1}^P \sum_{t=1}^Q [f(s,t) - \bar{f}]^2 \sum_{s=1}^P \sum_{t=1}^Q [w(s,t) - \bar{w}]^2 \right\}^{\frac{1}{2}}}. \quad (2.15)$$

Where $\bar{f} = \frac{1}{PQ} \sum_{s=1}^P \sum_{t=1}^Q f(s,t)$, and $\bar{w} = \frac{1}{PQ} \sum_{s=1}^P \sum_{t=1}^Q w(s,t)$. s and t denote the coordinates of the image. $f(s,t)$ and $w(s,t)$ are the target image and the observed image by the camera, respectively. This cost function has already been proved to work well for different complex patterns and even with grayscale image. The optimization process for the correlation coefficient is given in Figure 2.22(c) which gives the value of 0.8 after 3000 iterations. Then the optimized phase mask is achieved and stored for reconstructing the letter “S” in Figure 2.22(d). With the new target image of letter O and E, the results are demonstrated in Figure 2.22(e) and (f), respectively.

Figure 2.22: Experiment process and results for work done by group of J. Zhou et al[36].

(a) Reference object. (b) Speckle pattern right behind scattering medium for reference object. (c) Optimization process for correlation coefficient. (d) Retrieved image on camera with optimized phase pattern on SLM. (e), (f) Retrieved images for object as letter O and E, respectively.

Furthermore, with the experiment above, by enhancing it with the ME, the field of view (FOV) of the system is also enlarged. The mechanism and results are illustrated in Figure 2.23. From the optimized phase mask for reconstruction of letter S only, if the whole object in Figure 2.23(b) is illuminated, it is only able to reconstruct a small area around the letter S. However, with ME enhancement which will be described in more detail later, the FOV of the system is enlarged as it is able to reconstruct both letter O and A as results shown in Figure 2.23(e) and (f), respectively. In principle, to reconstruct the letter O for example, the beam should be bent to pass through letter O, then shine on the same area for the case of letter S. In that case, the optimized phase mask for reconstruction of the letter S is also used for

reconstruction of the letter O: however, the quality of reconstructed image is reduced as it is a property of the ME.

Figure 2.23: Principle and results for FOV enlargement from group of J. Zhou et al[36].

(a) Experiment principle. (b) Target object. (c) Reconstructed image for center part of object with letter S. (d) Reconstructed image when the whole object shined by laser beam. (e) and (f) individual parts of object reconstructed by enhancement of ME. (g) Whole object is reconstructed with ME to enlarge FOV.

2.2.3 Deconvolution for imaging through scattering media

Figure 2.24: Deconvolution processing with PSF method is developed by group of E. Edrei, G. Scarcelli [38]. (a) Experiment setup: $d = 16\text{cm}$, turbid medium is a 120 grit ground glass diffuser. (b) Original image object (Scale bar of $200\mu\text{m}$). (c) Recorded speckle pattern of the object on camera. (d) PSF of the system, measured by replacing object by an iris. (e) Reconstructed image by using deconvolution.

Deconvolution processing is a well-developed and outstanding method which is widely applied in many field such as microscopy [39], astronomy [40] and non-optical imaging [41]. Its principle is derived from the linear property of an imaging system. The output image capture by a camera can be represented as the convolution of the original object function with the point spread function (PSF) of that imaging system. Actually, the PSF is the output image, which is produced through the imaging system from a point source. If the output image is

distorted, then the original one can be restored at the observation plane by deconvolving from its distorted image and known PSF. In the case of a scattering medium, with knowledge of the ME, deconvolution with a measured PSF can be used to do imaging within an appropriate range.

Utilizing deconvolution with PSF, group of E. Edrei, G. Scarcelli [38] has introduced a method to do super-resolution imaging through scattering media. Their principle and initial result is displayed in Figure 2.24. Firstly, the speckle pattern generated through the system from a point source is recorded as a PSF. Then by placing an object at the position of point source, its speckle pattern is acquired. Finally, by using deconvolution processing between the object's speckle pattern and the PSF, the original image of the target object can be reconstructed. To analyze the imaging process of this method, the Huygens-Fresnel field propagation can be used as follows:

$$E(\rho_I) = A \iiint E(\rho_O) e^{\frac{ik}{2d}(\rho_T - \rho_O)^2} P(\rho_T) T(\rho_T) e^{\frac{ik}{2(S_O - h)}(\rho_L - \rho_T)^2} L(\rho_L) e^{\frac{ik}{2S_I}(\rho_I - \rho_L)^2} d\rho_O d\rho_T d\rho_L \quad (2.16)$$

Where $\overline{\rho_O}$, $\overline{\rho_T}$, $\overline{\rho_L}$, $\overline{\rho_I}$ are the transverse coordinate at the plane of the object, turbid medium, lens and image on the camera, respectively. To limit the aperture of the optical system, an explicit pupil function P is used, thus all the integrals can be calculated without loss of generality on an infinite interval. $T(\rho_T)$, $L(\rho_L)$ and A are functions of the turbid medium, lens operator and proportionality constant, respectively. The focal length of the lens is chosen to satisfy the condition $\frac{1}{S_O} + \frac{1}{S_I} = \frac{1}{f}$. Applying the condition of a thin lens, (2.16) can be simplified to:

$$E(\rho_I) = \iint E(\rho_O) e^{\frac{ik}{2d}\rho_O^2} P(\rho_T) T(\rho_T) e^{-\frac{ik}{d}\rho_T(\rho_O + \rho_I \frac{S_O}{S_I})} d\rho_O d\rho_T \quad (2.17)$$

(2.17) can be reduced to describe for intensity at camera plane by applying Fourier transform integral as follow:

$$I(\rho_I) = \int |E(\rho_O)|^2 |\tilde{T}(\rho_O, \rho_I)|^2 d\rho_O \quad (2.18)$$

Where $\tilde{T}(\rho_O, \rho_I) = \int P(\rho_T) T(\rho_T) e^{-\frac{ik}{d}\rho_T(\rho_O + \rho_I \frac{S_O}{S_I})} d\rho_T$ is a Fourier transform integral. Therefore, by applying the delta function $\delta(\rho_O - \rho_{iris})$ at the object plane, the PSF of the system can be presented as below:

$$PSF(\rho_I) = \left| \int P(\rho_T) T(\rho_T) e^{-\frac{ik}{d}\rho_T(\rho_{iris} + \rho_I \frac{S_O}{S_I})} d\rho_T \right|^2 \quad (2.19)$$

From (2.19), it is clearly recognized that PSF is the convolution of the turbid medium function with the pupil function of the imaging system. More important, obviously a spatial-invariant PSF for the whole system is deduced from a linear phase gradient obtained by $T(\rho_T)$ as the one appearing within the memory effect angular range.

To demonstrate the spatial invariance of the PSF, an iris is shifted laterally across the object plane. The speckles patterns at different positions according to the lateral shift are shown in Figure 2.25. Apparently, the ME is proved as the PSF is shifted but not distorted. In Figure 2.25(d), the cross-correlation and autocorrelation of the patterns at different positions within FOV are compared to quantify the PSF variation.

Figure 2.25: (a-c) PSF of the system is shifted as illuminated iris is shifted laterally. (d) “Comparison of autocorrelation and cross correlations of different patterns at different iris positions demonstrating nearly unaltered PSFs within the memory-effect field-of-view.”

Another breakthrough method developed by group of A. P. Mosk et al [42] has shown a way to enable non-invasive imaging through thin turbid layers by utilizing the intrinsic angular-correlation, also known as the ME. In their developed principle, if the object is placed within the angular memory effect range, then its speckle pattern behind a scattering medium is actually the convolution between it and the system’s PSF. Here, the PSF is a reference speckle pattern, which is produced behind the scattering medium by any point source placed within object.

Following that idea, a research group of A. P. Mosk [16] presented a method called single-shot speckle-imaging to recover incoherently objects behind the scattering medium, which only requires the position of the reference object. Their method relies on the fact that speckle pattern generated by a single point on a reference object is “a high-contrast interference pattern similar to laser speckle [43] as long as the coherence length of the light is longer than the typical difference in path lengths of the scattered light”. The speckle pattern of reference object is then illuminated by incoherent light; it is actually the superposition of many speckle patterns corresponding to a single point on the object. Here, the light from object is incoherent to deliver simpler calculation for speckle pattern as the complex of phase is ignored. Utilizing the ME for imaging through a thin scattering medium, if the object lies within the range of the ME, the speckle pattern for each point source on it has the same shape and is only shifted. Therefore, if the PSF is known, reconstruction of object behind scattering medium can be achieved from the deconvolution of the PSF and the speckle pattern of object. That reconstruction is instant and which requires no optimization process and can be successful, even with only a part of object’s speckle pattern.

Figure 2.26: Experiment setup proposed by group of A. P. Mosk et al[16]. Light source is a light emitting diode (LED).

The experiment setup for single-shot speckle-imaging method is demonstrated in Figure 2.26 and is very simple and straightforward. By using incoherent light, the reference speckle

S_R of the object can be represented as a convolution of its intensity pattern and the PSF of scattering medium (here it is a diffuser):

$$S_R = I_R(x, y) * \text{PSF}(x, y) \quad (2.20)$$

Where $*$ denotes for convolution product. If another object I_T is positioned next to the reference object within the ME range, the overall speckle pattern is the sum of intensities between individual speckle patterns of each object:

$$S_{\text{sum}} = S_R + S_T = (I_R + I_T) * \text{PSF} \quad (2.21)$$

From that relationship, the image of an unknown object T behind the scattering medium can be retrieved. In term of the spatial frequency domain, the convolution is transferred to multiplication as below:

$$F\{S_R\} = F\{I_R(x, y)\} \times F\{\text{PSF}(x, y)\} \quad (2.22)$$

$$F\{S_{\text{sum}}\} = F\{I_R + I_T\} \times F\{\text{PSF}(x, y)\} \quad (2.23)$$

Where F is Fourier Transform and $\times$ is the multiplication. Then the reconstructed intensity pattern I_D is deduced from observed speckle pattern S_O on the camera by:

$$I_D = F^{-1} \left\{ \frac{F\{I_R\} \times F\{S_O\}}{F\{S_R\}} \right\} \quad (2.24)$$

Where F^{-1} is inverse Fourier Transform. The (2.20) includes the division in the frequency domain, which is an effective and stable Wiener deconvolution algorithm against noise [44]. Here the resolution of reconstructed object is defined by the spatial frequency content of the reference object.

Figure 2.27: Reconstruction result for the letter H as reference object and letter T as unknown object. Work is done by group of A. P. Mosk et al[16]. (a), (b) are reference object and its speckle pattern, respectively. (c), (d) are object with letter T and H, and its speckle pattern, respectively. (e) The reconstructed image for object in (c).

A reconstruction result is displayed in Figure 2.27. The magnification of the system also decides the quality of the reconstruction process. Experimental results for the dependence of reconstructed image on different magnification factors are illustrated in Figure 2.27. With the magnification factor of 0.53, the corresponding reconstructed image is the most clean and clear among others with different magnification factors. In fact, the magnification factor is defined by the two distance d_1 and d_2 in which d_2 relates to the ME for the effective area for reconstruction process. Therefore, knowing d_2 exactly helps to define correct shift of speckle patterns, which will lead to precise calculation for reconstruction process. Indeed, the magnification of 0.53 gives actual position for the plane of the object and camera.

Figure 2.28: Reconstructed images with different part of speckle pattern for experiment setup proposed by group of A. P. Mosk et al[16]. (a), (b) Half speckle patterns from reference object only and reference object with nearby unknown object, respectively. (c) Reconstructed image from (a) and (b). (d), (e) Quarter speckle patterns from reference object only and reference object with nearby unknown object, respectively. (f) Reconstructed image from (d) and (e).

In addition for above experiment, in the case of the PSF size being wider than the object, reconstruction of the object can be processed successfully with only a fraction of the observed speckle pattern, which indicates holographic properties of the speckle pattern. The result for that partial reconstruction is displayed in Figure 2.28. Apparently, the quality of the reconstructed image is reduced as the size of used the part from the speckle pattern is decreased.

For almost all speckle-based imaging techniques, there is a basic requirement which demands the statics for each measurement, specially measurement used as reference. However, in the method discussed above, the experiment can still succeed in the case of taking measurement while the object is not definitely static. The experiment for showing that advantage is demonstrated in Figure 2.29. Collector lenses used in the setup are a complex of objective lenses and tube lenses that give a better signal to noise ratio (SNR). The magnification factor for that setup is 0.1. The object contains two parts; one is static reference and the other is unknown but moving around within range of the ME. Only the speckle measurement for the reference part has no difference to previous experiment. However, the speckle of whole object with moving part is handled in a specific way. With an unknown object moving around, there is a series of speckle patterns obtained by the camera. Then the final speckle used as reference of whole object is time-averaged from that set of speckle patterns. Finally, a reconstructed image is produced from the reference speckle patterns with corresponding acquired speckle pattern. Therefore, the reconstructed image shows both the unknown object and its position for corresponding speckle pattern.

Figure 2.29: Experiment for imaging dynamic object through scattering media [16].

Figure 2.30: Experiment result for imaging dynamic unknown object through scattering media [16]. A bifurcation as reference object and a disk as unknown object. (b) Averaged speckle pattern as reference pattern (taking mean from 360 patterns corresponding to different positions of the disk). (c), (d), (e) object with disk at different positions. (f), (g), (h) reconstructed images for object in (c), (d), (e), respectively.

In Figure 2.30, an unknown and moving part of an object is a disk which moves around a bifurcation as the reference part of object. While the disk is moving around, there are 360 speckle patterns of whole object obtained by the camera. Then the averaged speckle pattern is deduced, as shown in Figure 2.30(b). With the time-averaged speckle pattern used as reference, the reconstructed image, which corresponds to a different position of the disk, is

formed. The required number of frames for measurement to form reference speckle pattern relies on the complexity of the dynamic object. That method is even suitable for a dynamic scattering medium as long as its variation is relatively static as the PSF is unchanged appreciably during the observation process of an adequate number of reference patterns. Besides, the moving speed of an unknown object also needs to be considered in relation with exposure time of camera. If the object moves within the exposure time, the reconstructed image will be blurred.

In conclusion, the reviewed techniques above have delivered some prominent developments for imaging through scattering media. However, these still have some limitation as the small FOV is limited by the ME and also rely on knowing a reference object to do imaging for unknown ones. Therefore, their possibility for being applied in non-invasive cases, such as inside biological tissues, still needs more enhancement.

2.3 Sensing by utilizing scattering media

Speckle patterns produced by scattering are usually considered as an obstruction for imaging quality through scattering media. However, the speckle pattern itself also carries within it physical information of the medium which might be very useful in some circumstances. The field of research which exploits useful information from speckle pattern is known as speckle metrology. This research field has a potential to estimate various physical quantities of the medium and optical characteristic of light [4, 5, 45-47]. In principle, when light propagates through a medium, its wavefront can be distorted by the changes of refractive index, angular tilt [48] or surface deformation [49]. Utilizing the speckle pattern to detect the

changes in wavefront enables the design of different kinds of optical sensor for various applications such as evaluating displacement [50], strain [51], temperature [52] or concentration [53].

Figure 2.31: Measurement of glucose concentration change done by group of A. Anand et al[53].

In the work done by group A. Anand et al [53], scattering is used to detect the concentration change of glucose solution. Their experimental setup is shown in Figure 2.31. In their work, a laser beam is passed through a tank which contains a glucose solution. Then the output beam continuously propagates through a scattering medium and results a speckle pattern on a camera. With the work done by group of C.-Y. Tan and Y.-X. Huang [54], we understand that the change in glucose solution is actually the change of medium's refractive index, which directly affects the propagation of light through it. With a non-parallel incident beam, the output wavefront will be distorted if the refractive index of the medium changes. Then that distortion is analyzed by using a camera to observe the speckle pattern produced behind a diffuser. With different concentrations of glucose solution, the speckle pattern on camera will change as it is an interference image of different distorted wavefronts. By comparing those speckle patterns, their system is able to interpret the change of corresponding

concentration. In fact, that comparison is also known as correlation coefficient which is calculated by the equation below:

$$C = \frac{\sum_{k=1}^N \sum_{l=1}^N [I_R(k,l) - \bar{I}_R][I_M(k,l) - \bar{I}_M]}{\sqrt{\{\sum_{k=1}^N \sum_{l=1}^N [I_R(k,l) - \bar{I}_R]^2\} \{\sum_{k=1}^N \sum_{l=1}^N [I_M(k,l) - \bar{I}_M]^2\}} \quad (2.25)$$

where $I_R(k,l)$ and $I_M(k,l)$ are the intensities at the pixel (k,l) of the speckle pattern R (reference for concentration c_1) and M (measurement for concentration c_2).

Figure 2.32: Change in correlation coefficient value as a function of glucose concentration [53].

The concentration of glucose solution is changed intentionally while the corresponding correlation coefficient is recorded for each value of concentration. The relationship between the concentration and its corresponding correlation coefficient is shown in Figure 2.32. The correlation coefficient is calculated between recorded speckle pattern when solution changes and the initial speckle pattern of the starting concentration. The system has a resolution which is defined as the standard deviation of the correlation coefficient. Another parameter for

evaluating the efficiency of system is the sensitivity which is obtained “by taking the difference between the consecutive values of the correlation coefficient and taking average of it over the concentration difference”. Then, the resolution and sensitivity are 0.0011g/ml and 6.433ΔC/(g. ml), respectively.

Another work which also relies on speckle pattern analysis to detect the distortion in wavefront is done by group of Y. Park et al [55]. Their principle for speckle pattern analysis is described in Figure 2.33. Their mathematical formulation of speckle intensity correlation is derived below:

$$g_r^{(2)} = I_a * I_b \quad (2.26)$$

where $g_r^{(2)}$ is intensity cross-correlation coefficient between two output speckle patterns I_a and I_b . Let denote r and r' as the coordinates at the output and input facets of a scattering layer. Assume that two monochromatic fields $x_1(r')$ and $x_2(r')$ impinge on to the scattering layer, and the corresponding scattered fields are $y_1(r)$ and $y_2(r)$, respectively. Applying a Green's function $G(r, r')$ to describe the scattering layer related to the incident and output fields, the exact form of the output scattered field is given as:

$$y_{1,2}(r) = \int_{r'} dr' G(r, r') x_{1,2}(r') \quad (2.27)$$

Because an image sensor measures the scattered intensity image rather than field the intensity correlation, $g_r^{(2)}$ is calculated as:

$$g_r^{(2)} = \frac{\langle y_2^* y_2 y_1^* y_1 \rangle}{\langle y_2^* y_2 \rangle_r \langle y_1^* y_1 \rangle_r} \quad (2.28)$$

where $\langle \cdot \rangle_r$ represents an ensemble over r space. To progress beyond this point, an important assumption is required: all the scattered fields exhibit complex Gaussian distribution over r space. Then, according to the Reed's moment theorem [56, 57], (2.28) can be expressed as

$$g_r^{(2)} = 1 + \frac{|\langle y_2^* y_1 \rangle_r|^2}{\langle y_2^* y_2 \rangle_r \langle y_1^* y_1 \rangle_r} \quad (2.29)$$

Which is the well-known Siegert relation applied in spatial domain[58]. By substituting (2.26) into $\langle y_2^* y_1 \rangle_r$ term we can directly connect the scattered field correlation with incident field correlation via autocorrelation of Green's function:

$$\langle y_2^* y_1 \rangle_r = \int_{r', r''} dr' dr'' \langle G^*(r, r'') G^*(r, r') \rangle_r x_2^*(r'') x_1(r') \quad (2.30)$$

Where $\langle G^*(r, r'') G^*(r, r') \rangle_r$ can be regarded as $\langle |G|^2 \rangle_r \delta(r'' - r')$ for full rank transmission geometry with sufficiently large r space, (2.30) can be simplified as:

$$\langle y_2^* y_1 \rangle_r = A_{r'} \langle |G|^2 \rangle_r \langle x_2^*(r') x_1(r') \rangle_{r'} \quad (2.31)$$

Where $\langle |G|^2 \rangle_r$ is a constant ranged in $[0,1]$, and $A_{r'}$ represents $\int_{r'} dr'$. Please note similar calculation also holds for $\langle y_1^* y_1 \rangle_r$ and $\langle y_2^* y_2 \rangle_r$ term. Substituting (2.31) into (2.29), for all second order moments of scattered field we get:

$$g_r^{(2)} = 1 + \left| g_{r'}^{(1)} \right|^2 \quad (2.32)$$

Where $g_{r'}^{(1)}$ represents the normalized first-order correlation function of input field over r' space. The (2.32) shows $g_r^{(2)}$ only depends on the change in the incident fields, not the properties of the scattering layer. In other words, when any diffusive scattering layer satisfies Reed's theorem, the speckle correlation directly represents the field correlation of incident

fields, which verifies the field sensing ability for speckle metrology. Therefore, following that principle of using scattering layers as a tool to analyze the distortion of wavefront, choosing or adding scattering layers will not make any significant improvement for the sensing system.

Figure 2.33: The effects of a scattering layer, which converts an indistinguishable phase difference between incident fields to the distinguishable changes in speckle pattern [55].

Instead of detecting the concentration change of a solution, group of Y. Park et al [55] use the scattering medium to recognize the deformation of medium when a coherent light propagates through. Their experiment setup is illustrated in Figure 2.34. In that setup, a coherent beam is passed through a microfluidic channel where the pressure inside can be controlled by a syringe pump. Then the beam keeps propagating through a scattering medium and the speckle pattern is recorded by an image sensor. When the pressure inside the microfluidic channel is changed to new value, or in other words the channel's volume is deformed, then it will result in a different wavefront. By using the described principle above to differentiate observed speckle pattern, the wavefront difference can be revealed which enables to establish the relation between pressure change and correlation coefficient of the speckle patterns.

Figure 2.34: Experiment setup for detecting deformation of a volume [55].

The result for experiment in Figure 2.34 is reported in Figure 2.35 where results for tests with different scattering media and pressure change are shown. The first test is done with two states of pressure: air pressure and pressure at 3kPa. Without using a scattering medium (Figure 2.35 a-b the speckle patterns seemed to be not different before and after applying the deformation. The correlation coefficient for the speckle was 0.971. That slight drop is caused by diffraction which affects the beam propagation in free space. By adding in different kind of scattering medium, the correlation coefficient values obtained verify the effect of scattering layers for converting wavefront distortion into speckle pattern change. In addition, those values also confirm the mentioned principle above that the speckle changes are dependent on the thickness and properties of the scattering media. Indeed, the correlation coefficients for

paired speckle patterns in Figure 2.35(c-h) were 0.393, 0.387, 0.392, respectively. On the other hand, tests for measuring correlation coefficient with continuous increase of pressure were also carried out and their results are given in Figure 2.35(i). The pressure was increased from air pressure until the limit of sensor was reached. The standard deviation of the experiment was also denoted by an error bar and calculated from 5 measurements. Obviously, the appearance of scattering media made the drop of $C_r^{(2)}$ much faster than the case without them. The similar trend of those curves in that experiment once again certified that “the decorrelation graphs coincide regardless of the thickness or type of the scattering layer” [55].

Figure 2.35: Intensity images with various scattering media [55]. (a), (b) no scattering layer used. (c) (d) 1 layer of Scotch tape. (e), (f) 10 layers of Scotch tapes. (g), (h) 15° diffuser.

The images are taken for air pressure or at 3kPa. (i) the change of $C_r^{(2)}$ correlation coefficient when pressure is increased.

References

- [1] Z. Yaqoob, D. Psaltis, M.S. Feld, C. Yang, Optical phase conjugation for turbidity suppression in biological samples, Nature Photonics, 2 (2008) 110.

- [2] Y. Choi, T.D. Yang, C. Fang-Yen, P. Kang, K.J. Lee, R.R. Dasari, M.S. Feld, W. Choi, Overcoming the Diffraction Limit Using Multiple Light Scattering in a Highly Disordered Medium, *Physical Review Letters*, 107 (2011) 023902.
- [3] M. Kim, W. Choi, Y. Choi, C. Yoon, W. Choi, Transmission matrix of a scattering medium and its applications in biophotonics, *Opt. Express*, 23 (2015) 12648-12668.
- [4] C. Park, J.-H. Park, C. Rodriguez, H. Yu, M. Kim, K. Jin, S. Han, J. Shin, S.H. Ko, K.T. Nam, Y.-H. Lee, Y.-H. Cho, Y. Park, Full-Field Subwavelength Imaging Using a Scattering Superlens, *Physical Review Letters*, 113 (2014) 113901.
- [5] S.M. Popoff, G. Lerosey, R. Carminati, M. Fink, A.C. Boccarda, S. Gigan, Measuring the Transmission Matrix in Optics: An Approach to the Study and Control of Light Propagation in Disordered Media, *Physical Review Letters*, 104 (2010) 100601.
- [6] J. Yoon, K. Lee, J. Park, Y. Park, Measuring optical transmission matrices by wavefront shaping, *Opt. Express*, 23 (2015) 10158-10167.
- [7] M. Cui, C. Yang, Implementation of a digital optical phase conjugation system and its application to study the robustness of turbidity suppression by phase conjugation, *Opt. Express*, 18 (2010) 3444-3455.
- [8] C.-L. Hsieh, Y. Pu, R. Grange, G. Laporte, D. Psaltis, Imaging through turbid layers by scanning the phase conjugated second harmonic radiation from a nanoparticle, *Opt. Express*, 18 (2010) 20723-20731.
- [9] C.-L. Hsieh, Y. Pu, R. Grange, D. Psaltis, Digital phase conjugation of second harmonic radiation emitted by nanoparticles in turbid media, *Opt. Express*, 18 (2010) 12283-12290.

- [10] A. Shibukawa, A. Okamoto, Y. Goto, S. Honma, A. Tomita, Digital phase conjugate mirror by parallel arrangement of two phase-only spatial light modulators, *Opt. Express*, 22 (2014) 11918-11929.
- [11] Y. Liu, C. Ma, Y. Shen, J. Shi, L.V. Wang, Focusing light inside dynamic scattering media with millisecond digital optical phase conjugation, *Optica*, 4 (2017) 280-288.
- [12] D.B. Conkey, A.N. Brown, A.M. Caravaca-Aguirre, R. Piestun, Genetic algorithm optimization for focusing through turbid media in noisy environments, *Opt. Express*, 20 (2012) 4840-4849.
- [13] I.M. Vellekoop, Feedback-based wavefront shaping, *Opt. Express*, 23 (2015) 12189-12206.
- [14] I.M. Vellekoop, A.P. Mosk, Focusing coherent light through opaque strongly scattering media, *Opt. Lett.*, 32 (2007) 2309-2311.
- [15] J. Yang, Y. Shen, Y. Liu, A.S. Hemphill, L.V. Wang, Focusing light through scattering media by polarization modulation based generalized digital optical phase conjugation, *Applied Physics Letters*, 111 (2017) 201108.
- [16] X. Xu, X. Xie, H. He, H. Zhuang, J. Zhou, A. Thendiyammal, A.P. Mosk, Imaging objects through scattering layers and around corners by retrieval of the scattered point spread function, *Opt. Express*, 25 (2017) 32829-32840.
- [17] A. Boniface, M. Mounaix, B. Blochet, R. Piestun, S. Gigan, Transmission-matrix-based point-spread-function engineering through a complex medium, *Optica*, 4 (2017) 54-59.
- [18] D. Tang, S.K. Sahoo, V. Tran, C. Dang, Single-shot large field of view imaging with scattering media by spatial demultiplexing, *Appl. Opt.*, 57 (2018) 7533-7538.
- [19] I. Freund, M. Rosenbluh, S. Feng, Memory Effects in Propagation of Optical Waves through Disordered Media, *Physical Review Letters*, 61 (1988) 2328-2331.

- [20] G. Osnabrugge, R. Horstmeyer, I.N. Papadopoulos, B. Judkewitz, I.M. Vellekoop, Generalized optical memory effect, *Optica*, 4 (2017) 886-892.
- [21] X. Yang, C.-L. Hsieh, Y. Pu, D. Psaltis, Three-dimensional scanning microscopy through thin turbid media, *Opt. Express*, 20 (2012) 2500-2506.
- [22] C.W.J. Beenakker, Random-matrix theory of quantum transport, *Reviews of Modern Physics*, 69 (1997) 731-808.
- [23] A. Dubois, L. Vabre, A.-C. Boccara, E. Beaurepaire, High-resolution full-field optical coherence tomography with a Linnik microscope, *Appl. Opt.*, 41 (2002) 805-812.
- [24] M. Cui, Parallel wavefront optimization method for focusing light through random scattering media, *Opt. Lett.*, 36 (2011) 870-872.
- [25] T. Hillman, T. Yamauchi, W. Choi, R. Dasari, Z. Yaqoob, Y. Park, Digital optical phase conjugation for delivering two-dimensional images through turbid media, in: *Asia Communications and Photonics Conference 2013*, Optical Society of America, Beijing, 2013, pp. AF1J.2.
- [26] A. Jesacher, C. Maurer, A. Schwaighofer, S. Bernet, M. Ritsch-Marte, Full phase and amplitude control of holographic optical tweezers with high efficiency, *Opt. Express*, 16 (2008) 4479-4486.
- [27] I.M. Vellekoop, A.P. Mosk, Phase control algorithms for focusing light through turbid media, *Optics Communications*, 281 (2008) 3071-3080.
- [28] I.M. Vellekoop, C.M. Aegerter, Scattered light fluorescence microscopy: imaging through turbid layers, *Opt. Lett.*, 35 (2010) 1245-1247.

- [29] Y. Choi, C. Yoon, M. Kim, T.D. Yang, C. Fang-Yen, R.R. Dasari, K.J. Lee, W. Choi, Scanner-Free and Wide-Field Endoscopic Imaging by Using a Single Multimode Optical Fiber, *Physical Review Letters*, 109 (2012) 203901.
- [30] S. Feng, C. Kane, P.A. Lee, A.D. Stone, Correlations and Fluctuations of Coherent Wave Transmission through Disordered Media, *Physical Review Letters*, 61 (1988) 834-837.
- [31] S.K. Sahoo, D. Tang, C. Dang, Single-shot multispectral imaging with a monochromatic camera, *Optica*, 4 (2017) 1209-1213.
- [32] S.K. Sahoo, D. Tang, C. Dang, Enhancing security of incoherent optical cryptosystem by a simple position-multiplexing technique and ultra-broadband illumination, *Scientific Reports*, 7 (2017) 17895.
- [33] A. Jesacher, C. Maurer, A. Schwaighofer, S. Bernet, M. Ritsch-Marte, Full phase and amplitude control of holographic optical tweezers with highefficiency, *Optics Express*, 16 (2008) 4479-4486.
- [34] S. Schott, J. Bertolotti, J.-F. Lger, L. Bourdieu, S. Gigan, Characterization of the angular memory effect of scattered light in biological tissues, *Opt. Express*, 23 (2015) 13505-13516.
- [35] O. Katz, E. Small, Y. Silberberg, Looking around corners and through thin turbid layers in real time with scattered incoherent light, *Nature Photonics*, 6 (2012) 549.
- [36] H. He, Y. Guan, J. Zhou, Image restoration through thin turbid layers by correlation with a known object, *Opt. Express*, 21 (2013) 12539-12545.
- [37] A. Goshtasby, *Image registration. Principles, tools and methods*, 2012.
- [38] E. Edrei, G. Scarcelli, Memory-effect based deconvolution microscopy for super-resolution imaging through scattering media, *Scientific Reports*, 6 (2016) 33558.

- [39] P. Sarder, A. Nehorai, Deconvolution methods for 3-D fluorescence microscopy images, *IEEE Signal Processing Magazine*, 23 (2006) 32-45.
- [40] J.L. Starck, E. Pantin, F. Murtagh, Deconvolution in Astronomy: A Review, *Publications of the Astronomical Society of the Pacific*, 114 (2002) 1051-1069.
- [41] T. Taxt, Restoration of medical ultrasound images using two-dimensional homomorphic deconvolution, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 42 (1995) 543-554.
- [42] J. Bertolotti, E.G. van Putten, C. Blum, A. Lagendijk, W.L. Vos, A.P. Mosk, Non-invasive imaging through opaque scattering layers, *Nature*, 491 (2012) 232.
- [43] I. Freund, Joseph W. Goodman: Speckle Phenomena in Optics: Theory and Applications, *Journal of Statistical Physics*, 130 (2008) 413-414.
- [44] R.C. Gonzalez, R.E. Woods, *Digital Image Processing (3rd Edition)*, Prentice-Hall, Inc., 2006.
- [45] M. Mazilu, T. Vettenburg, A. Di Falco, K. Dholakia, Random super-prism wavelength meter, *Opt. Lett.*, 39 (2014) 96-99.
- [46] B. Redding, H. Cao, Using a multimode fiber as a high-resolution, low-loss spectrometer, *Opt. Lett.*, 37 (2012) 3384-3386.
- [47] B. Redding, S.F. Liew, R. Sarma, H. Cao, Compact spectrometer based on a disordered photonic chip, *Nature Photonics*, 7 (2013) 746.
- [48] H.J. Tiziani, A study of the use of laser speckle to measure small tilts of optically rough surfaces accurately, *Optics Communications*, 5 (1972) 271-276.
- [49] J.A. Leendertz, Interferometric displacement measurement on scattering surfaces utilizing speckle effect, *Journal of Physics E: Scientific Instruments*, 3 (1970) 214.

- [50] E. Archbold, A.E. Ennos, Displacement Measurement from Double-exposure Laser Photographs, *Optica Acta: International Journal of Optics*, 19 (1972) 253-271.
- [51] I. Yamaguchi, A laser-speckle strain gauge, *Journal of Physics E: Scientific Instruments*, 14 (1981) 1270.
- [52] P.V. Farrell, D.L. Hofeldt, Temperature measurement in gases using speckle photography, *Appl. Opt.*, 23 (1984) 1055-1059.
- [53] S. Mahajan, V. Trivedi, V. Chhaniwal, M. Prajapati, Z. Zalevsky, B. Javidi, A. Anand, Measurement of concentration of sugar in solutions with laser speckle decorrelation, in: *SPIE Optical Metrology*, SPIE, 2015, pp. 6.
- [54] C.-Y. Tan, Y.-X. Huang, Dependence of Refractive Index on Concentration and Temperature in Electrolyte Solution, Polar Solution, Nonpolar Solution, and Protein Solution, *Journal of Chemical & Engineering Data*, 60 (2015) 2827-2833.
- [55] K. Kim, H. Yu, K. Lee, Y. Park, Universal sensitivity of speckle intensity correlations to wavefront change in light diffusers, *Scientific Reports*, 7 (2017) 44435.
- [56] I. Reed, On a moment theorem for complex Gaussian processes, *IRE Transactions on Information Theory*, 8 (1962) 194-195.
- [57] K. Lee, Y. Park, Exploiting the speckle-correlation scattering matrix for a compact reference-free holographic image sensor, *Nature Communications*, 7 (2016) 13359.
- [58] B. Saleh, Photoelectron statistics with applications to spectroscopy and optical communication., *Springer Series in Optical Sciences*
Berlin: Springer 1978 1, 1978.

Chapter 3: Fast 3D movement of a laser focusing spot behind scattering media by utilizing optical memory effect and optical conjugate planes

This work is published as: “*Tran V., Sahoo, S.K. & Dang, C. Fast 3D movement of a laser focusing spot behind scattering media by utilizing optical memory effect and optical conjugate planes. Sci Rep 9, 19507 (2019) doi:10.1038/s41598-019-56214-3*”

3.1 Introduction

Delivering high power light into a small region inside biological tissues or translucent materials can allow us to do optical imaging, laser cutting, or light therapy. One can simply utilize near-infrared light (optical window for biological tissues) which has less absorption and scattering to focus deeply inside the body [1, 2]. Even though, increasing accessible depth for practical applications still remains a very challenging task. On the other hand, the most interesting light matter interactions happen at the spectrum region where scattering is inevitable. The. A solution to control light to overcome scattering in various media such as skin, biological tissue or frosted glass could provide a useful approach to enable many photonic applications in various fields such as biomedical imaging or advanced manufacture.

There are several techniques which could help to cancel out the scattering effect but the most common and efficient one is known as Wavefront shaping technique with the use of SLM or DMD [3, 4]. This technique requires the input information to create the desired phase or amplitude pattern. That information can be achieved by measuring transfer matrix of turbid medium [4-10], applying optical phase conjugation [11-18] utilizing optimization process known as Feed-back wavefront shaping [3, 18-20]. The advantages and disadvantages of those methods has already discussed in the chapter 2 of this thesis.

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In this chapter, the work done by me with help from my research group aims to reduce the time consumption of the phase conjugation approach [11-13, 16-18] or optimization process [21] for moving focus spot around or drawing a pattern with multiple focus spot. Starting with only a single optimized phase pattern for generating an initial focus spot, our previous approach utilizing the optical memory effect [22, 23] could focus a portion of a laser beam through a scattering medium into any other spots on the 2D plane, which is perpendicular to the optical axis. By tilting and shifting the pre-optimized phase pattern digitally, we can aim to any spots within the memory effect region [24]. However the further the target spot is from the initial spot, the smaller is the portion of the laser that is utilized. This limited utilization of the laser beam, together with the small memory effect region, make the intensity of focusing spot reduce quickly with the distance from the target spot to the initial spot. Here, we demonstrate a method that utilize a 4F optic system to swiftly move the focus point in not only the 2D plane, but also the 3D memory effect volume with full utilization of the laser beam. We are able to create any desired 3D contours on the other side of the scattering medium by moving the focus spot sequentially or generating multiple spots simultaneously. More importantly, the low intensity of the focus point at the edge of memory effect region can be quickly optimized with GA by inheriting the SLM phase patterns from the original optimization. A fast optimization process for the second spot enlarges the region beyond the memory effect limitation for our moving spot. The simplicity and advantages of our method suggest a practical approach for many applications such as opto-genetic excitation, minimal invasive laser surgery, or imaging.

3.2 Experiment

Figure 3.1: Experimental setup to control light through scattering media. BS: Non-polarized beam splitter. L1, L2: Convex lenses with focal length $f_1 = 150$ mm and $f_2 = 50$ mm, respectively. d : distance between diffuser and camera.

The experiment setup with 4F system is illustrated in Figure 3.1. An expanded He-Ne laser beam with wavelength of 632.8 nm is guided by a non-polarized beam splitter to shine at the center of the SLM. The laser beam, after reflecting from the SLM, passes through an optical system of two convex lenses, L1 and L2, with focal lengths of 150 mm and 50 mm, respectively. A ground glass diffuser (Thorlabs N-BK7 DG10-120), used as a scattering layer, is placed at the focal plane of L2 while the SLM is at the focal plane of L1 to create a 4F system where the SLM plane is relayed on to the diffuser plane. The SLM plane and the diffuser plane are conjugated with a magnification of $1/3$ to increase the spatial sampling rate of the SLM on the diffuser effectively. A monochromic CMOS camera (Thorlabs DCC1645C) is set behind the diffuser at an observation plane to provide feedback signals for the optimization process and then observe the quality of the focus spots. Moving the camera along the optical axis allows us to visualize the focus spots in 3D.

3.3 Result and discussion

3.3.1 Initial Focus Spot by Genetic Algorithm.

For creating an initial focus spot behind a scattering medium, we utilize the feedback wavefront shaping technique with genetic algorithm (GA) (its block diagram presented in Fig 2.14). In our setup, we combine 2 by 2 SLM pixels to be one controllable element for shaping the wavefront, so there are 540×540 elements. The typical GA iteratively shapes the wavefront of input laser beam to increase the brightness contrast between the desired position and average background, which is defined as peak-to-background ratio (PBR) as below:

$$PBR = I_S / \bar{I}_B \quad (3.1)$$

Where PBR is peak-to-background ratio value; I_S is intensity of the focus point and $\bar{I}_B$ is the mean value of background intensity. We noted that our definition of PBR is the same as defined in the work done by group of J. Xu et al[25]. With our uncooled 8-bit CMOS camera, the measurement fluctuation of pixel intensity during the optimization could largely affect the results. Here, we take an average intensity of 5 by 5 pixels around the target focus spot as I_S and $\bar{I}_B$ is the mean value of the captured image excluding 25 pixels counted for I_S . The area of 5 by 5 pixels is chosen to cover the diffraction limit area of the focus spot and the averaging strategy can minimize the effect of random noise in intensity measurement at pixel level; this makes our GA more stable and converge faster.

The result of feedback wavefront shaping with GA for creating a focus spot behind scattering medium is illustrated in Figure 3.2. Our GA achieves the focus spot size (FWHM) of $20 \mu\text{m}$ with the brightest pixel at the center of 5 by 5 pixel area. The ratio between intensity of the brightest focus pixel and average background intensity is 112, which reaches the

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limitation of our 8-bit camera because the detected intensity on each pixel is already from 1 to 5 counts in a dark condition (closing the camera cap). A better camera with higher bit depth, higher photon capacity and lower noise (cooled sensor chip) would allow us to get better results. The quality of focus spot can also be improved by utilizing more elements for optimization and extending the number of iteration loops. However, this will cost more optimization time. With our current parameters, the optimizing time is about 10 minutes (with computer used: Intel Xeon E5-2640 v3, 8GB RAM); running repeated optimization process is not feasible for creating multiple spots in 3D space or drawing desired shapes. We would like to note that the speed of our optimization process is largely limited by the SLM updating rate and the readout time of our camera.

Figure 3.2: Shaping the incident beam wavefront to create a focus spot behind a scattering medium by GA. (a) Optimized phase pattern on SLM. (b) The optimized focus spot, the two arrows show the cross section line to measure the intensity. (c) Intensity profile along the horizontal line through the spot, presented by the two arrows in (b).

3.3.2 Moving Focus Spot inside Memory Effect Region

Here, we utilize optical memory effect to move the focus spot to multiple positions swiftly with only one initial optimization process. The position of the initial focus spot is considered at the origin of a Cartesian coordinate system. In order to move the focus spot to a position (x, y) on the camera, the incoming wavefront on the diffuser surface needs to be tilted around the X-axis and Y-axis by angles of α_x and α_y , respectively: $\tan(\alpha_x) = x/d$ and $\tan(\alpha_y) = y/d$, where d is the distance between the camera plane and the diffuser. Because camera surface is sampled by a 2D pixel array, the position x and y can be expressed by: $x = n_x \times p$ and $y = n_y \times p$ where n_x and n_y are number of pixels moved in X-axis and Y-axis, p is the pixel size of camera. The magnification from the SLM plane to the diffuser plane is $1/3$, hence the real angles for tilting phase pattern on SLM are $\beta_x = \alpha_x/3$ and $\beta_y = \alpha_y/3$. Precise measurement of the distance d directly is challenging. Here, by a quick scanning process with several tilting angles β_x and β_y and observing the spot positions $(x$ and $y)$ on the camera, the distance d can be estimated precisely to be 3.91 cm in our experimental setup. The mechanism of scanning method is: with a shifted distance on camera, by scanning the distance d within a predicted range, there will be an angle β to produce a corresponding tilting pattern on SLM which give the brightest focus point at shifted position on the camera. This scanning method runs automatically and produces result quickly based on the relationship between d , α and β . If the scattering layer is perfectly aligned in parallel with the plane of camera, it only takes a scanning process for a spot at any position on camera. In case of misalignment, it requires at least four scanning processes for focus spot at two positions on each X and Y axis to estimate precisely the relative plane of scattering layer from the plane of camera. With the profile of tilting angle α and the shifting distance d for every pixel, it is capable to create the point at

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any position in X-Y plane behind the scattering medium with minor loss of intensity. From here, the phase profile on the SLM for moving the focus spot in 2D plane can be calculated easily as the combination of original optimized phase pattern and a tilting phase pattern.

Figure 3.3: Intensity distribution of moving spot in a 2D plane. (a) Image of focus spots in different positions. Relative intensity of the moving spot along X-axis (b) and Y-axis (c).

Moving the focus spot based on memory effect is presented in Figure 3.3 with the distribution of intensity in X-Y plane. The brightest spot at the center of the image (Figure 3.2(a)) is the original focusing spot, which is optimized by GA. All other dimmer spots are achieved by adding the appropriate tilting phase on the original phase pattern. We achieve one spot for each calculated SLM pattern, then the multiple result images are superposed to present as a single image in Figure 3.3(a). The relative intensity of various spot along X and Y

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direction compared to the original spot is presented in *Figure 3.3(b)* and (c), respectively. The intensity quickly drops with small movement from the original focusing spot and is then slower when the distance is larger than 100 μm . According to definition and formulas for estimating memory effect region in section 2.2.1, from ME region we can imply the effective thickness of our scattering medium as 96 μm by using our calculation method [26, 27].

In order to move the focus spot in Z direction, we add a quadratic phase modulation on the original phase pattern. For a small movement of ΔZ , the added quadratic phase pattern is:

$$Phase(\Delta Z) = k \times (\sqrt{(n_x^2 + n_y^2) \times p^2 + (d + \Delta Z)^2} - \sqrt{(n_x^2 + n_y^2) \times p^2 + d^2} - \Delta Z) \quad (3.2)$$

where $k = 2\pi/\lambda$ is the wave-number, p is the pixel size of SLM. In case of ΔZ is much smaller than d , the (3.2) could be approximately derived to quadratic phase $[k\rho^2\Delta Z/2d^2]$ [28], where $\rho^2 = (n_x^2 + n_y^2) \times p^2$. The quality of the moving focus spot in Z-axis is demonstrated in *Figure 3.4(a)*. We are able to move the spot in front and back of the original spot which is the brightest and optimized by GA algorithm. 2D images of the spots are captured by moving the camera on a precise moving stage to the expected position of each spots. Similar to X-Y plane, the intensity distribution in Z-axis is not symmetric either. This observation can be explained by the difference between the moving direction of camera and the axis of moving focus spots and other imperfections in our optical setup. The efficient distance of moving the spot here is about 3.3mm forward and backward, which is 54 times larger than the longitudinal memory effect in X-Y plane (Δx_{ME}) or (Δy_{ME}). Such large memory effect in the Z axis (Δz_{ME}) is expected in our focusing system with its low NA: $\Delta z_{ME} \approx 2 \frac{d}{D} \Delta x_{ME} = \frac{1}{NA} \Delta x_{ME}$, where d

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(3.91cm) is distance from scattering medium to observation camera and D (1.5 mm) is the diameter of beam illuminating the surface of the scattering medium.

Figure 3.4: a) Intensity of the moving spot along Z-axis. b) Moving the focus spot in 3D space to draw a helix curve within memory effect volume. All the small insets in both a) and b) are the 2D images taken by a camera at corresponding Z planes.

With the ability to move the focus spot in the X-Y-Z directions, our approach is capable of drawing any contours in 3D space with only single optimization process. One example is shown in Figure 3.4(b), where every spot is designed to draw a helix curve displayed as red dashed line. We display one spot at a time within a 3D volume space of memory effect around

the original spot. Again, the camera is moving along the Z axis to capture the 2D image at different planes as displayed in the insets.

3.3.3 Display Multiple Focus Spots Simultaneously.

In addition to moving the focus spot in 3D space sequentially, it is possible to create multiple focus spots simultaneously by using just a single phase pattern on the SLM, which can be calculated by the expression below:

$$P = \arg \left[\sum_{j=1}^m \left(\exp(iP_j) \right) \right] \quad (3.3)$$

where P is the phase pattern to be used for creating simultaneously multiple points; P_j is the phase pattern for creating j -th single point, which is calculated from the optimized phase pattern for initial focus point. We create 3 spots on 3 different Z planes simultaneously by combining three corresponding phase patterns according to equation (3.3). Figure 3.5 presents the experimental results where the camera captures 2D images at different planes. At the specific plane corresponding to the targeted spot, the other two spots appear as blurry dim spots, which are presenting defocused spots (or out-of-focus spots). The result shows the ability to form multiple spots simultaneously, eventually creating 3D shapes within the memory effect region from a single optimization process. The efficiency of our strategy depends on both spot positions and the number of spots. The spot closer to the original focus spot will have a higher intensity due to memory effect. If number of spots increases, the quality of the 3D shape decreases rapidly due to the lower intensity of each spots (splitting of laser beam intensity into multiple spots) and increased intensity the background (interference of multiple backgrounds, one for each individual focus spots). In addition, due to phase only

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modulation (Eq. 3.3), the generated light field and sum of all light fields for individual focusing have different amplitudes, which reduce the efficiency. One can do better with complicated setup for both phase and amplitude modulation. Nevertheless, the intensity of three spots in Fig. 3.5 are almost similar with 22.1% of original focus spot's intensity.

Figure 3.5: Creating 3 focusing spots simultaneously at different positions in 3D space.

(a) Positions of 3 spots in Cartesian coordinate. (b-d) Image at the plane of the 1st, 2nd, and 3rd focus spot, respectively.

3.3.4 Increase Focus Spot Intensity with Reduced Optimization Time

With a limited memory effect, we need a quick solution to increase intensity for the spots at a far distance from the initial optimization point. Here, we utilize the GA to optimize the intensity again for one of the dim spots, however, with a much better initial state. All the phase patterns (i.e. the population in GA [3, 19]) used for optimization of the original spot are added with a similar phase pattern to move the target to the new position within the memory effect

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volume. The optimization process by GA, starting with the new group of phase patterns immediately, achieves the dim bright spot, therefore, we expect an improvement of the optimization speed.

Figure 3.6: (a) The original focusing spot and the second focusing spot. (b) Optimization process to enhance the contrast of original focusing spot with background. There are 3 abrupt drops of contrast corresponding to 3 changes of exposure time due to camera saturation. (c) Optimization process comparison between the original focusing spot and the second focusing spot.

Figure 3.6(a) shows no difference between the original focusing spot at the center and the second focusing spot. Figure 3.6(b) presents the optimization process for the original focus spot, which shows the increase of contrast after each iteration. We can also notice 5 abruptly dropping points for contrast after 45, 56, 73, 98 and 175 iterations, at which our algorithm automatically reduces the exposure time (80%) due to saturation of camera (255 gray level). Lower exposure time makes the contrast drop abruptly because of reduced signal on the background noise. It is worth noting that for our 8-bit camera (no cooling), we need to start with a reasonable exposure time to gain a good signal for optimization, the intensity of focus

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spot increases and saturates the camera multiple times during the optimization process. Just to visualize the progress of optimization, we linearly shift the contrast up at each drop to get a monotonically increasing curve, presented as the blue curve in Figure 3.6(c). A similar procedure is applied to the optimization for the second spot, which starts with contrast of 35 (orange curve in Figure 3.6(c)). There is no difference on the focusing quality; however, the optimization time is reduced by 50% for the second optimization, which inherits the set of phase patterns from the first optimization. The second focus spot can now become a center of another memory effect volume. The process can be repeated for optimizing multiple focusing spots, thus, expanding the effective scanning area for our focusing spot beyond the memory effect region.

3.4 Conclusion

We have demonstrated an efficient approach to move the focus spot to different positions in 3D space behind the strongly scattering media. No mechanical movement is involved in our process. All the control is handled digitally with phase patterns on SLM, which is relayed on scattering medium surface through 4F optical system. More importantly, our approach relying on optical memory effect eliminates the need for multiple time-consuming optimization processes. Starting with only one original focusing spot by GA, we can move the spot around in 3D volume which is limited by the memory effect. By inheriting the phase patterns from the initial optimization, we can optimize other focusing spots again at reduced time, thus, expanding the scanning region far beyond the memory effect. Finally, by combining the phase patterns for individual focusing spots on SLM, we have demonstrated multiple focus spots simultaneously. Our proposed approach could largely reduce the time for

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moving the focusing spot or optimizing the second spot, however, the speed is still largely limited by the updating rate of the SLM. With a new solution for faster SLM such as piezo technology [29-32], our demonstration could potentially make various biological applications possible where the focusing time can be done in milliseconds.

References

- [1] Y. Liu, P. Lai, C. Ma, X. Xu, A.A. Grabar, L.V. Wang, Optical focusing deep inside dynamic scattering media with near-infrared time-reversed ultrasonically encoded (TRUE) light, *Nature Communications*, 6 (2015) 5904.
- [2] L.M. Miller, P. Dumas, Chemical imaging of biological tissue with synchrotron infrared light, *Biochimica et Biophysica Acta (BBA) - Biomembranes*, 1758 (2006) 846-857.
- [3] I.M. Vellekoop, Feedback-based wavefront shaping, *Opt. Express*, 23 (2015) 12189-12206.
- [4] J. Yoon, K. Lee, J. Park, Y. Park, Measuring optical transmission matrices by wavefront shaping, *Opt. Express*, 23 (2015) 10158-10167.
- [5] Y. Choi, T.D. Yang, C. Fang-Yen, P. Kang, K.J. Lee, R.R. Dasari, M.S. Feld, W. Choi, Overcoming the Diffraction Limit Using Multiple Light Scattering in a Highly Disordered Medium, *Physical Review Letters*, 107 (2011) 023902.
- [6] M. Kim, W. Choi, Y. Choi, C. Yoon, W. Choi, Transmission matrix of a scattering medium and its applications in biophotonics, *Opt. Express*, 23 (2015) 12648-12668.
- [7] C. Park, J.-H. Park, C. Rodriguez, H. Yu, M. Kim, K. Jin, S. Han, J. Shin, S.H. Ko, K.T. Nam, Y.-H. Lee, Y.-H. Cho, Y. Park, Full-Field Subwavelength Imaging Using a Scattering Superlens, *Physical Review Letters*, 113 (2014) 113901.

Chapter 3:Fast 3D movement of a laser focusing spot behind scattering media by utilizing optical memory effect and optical conjugate planes

- [8] J.-H. Park, C. Park, H. Yu, J. Park, S. Han, J. Shin, S.H. Ko, K.T. Nam, Y.-H. Cho, Y. Park, Subwavelength light focusing using random nanoparticles, *Nature Photonics*, 7 (2013) 454.
- [9] S. Popoff, G. Lerosey, M. Fink, A.C. Boccara, S. Gigan, Image transmission through an opaque material, *Nature Communications*, 1 (2010) 81.
- [10] S.M. Popoff, G. Lerosey, R. Carminati, M. Fink, A.C. Boccara, S. Gigan, Measuring the Transmission Matrix in Optics: An Approach to the Study and Control of Light Propagation in Disordered Media, *Physical Review Letters*, 104 (2010) 100601.
- [11] M. Cui, C. Yang, Implementation of a digital optical phase conjugation system and its application to study the robustness of turbidity suppression by phase conjugation, *Opt. Express*, 18 (2010) 3444-3455.
- [12] C.-L. Hsieh, Y. Pu, R. Grange, G. Laporte, D. Psaltis, Imaging through turbid layers by scanning the phase conjugated second harmonic radiation from a nanoparticle, *Opt. Express*, 18 (2010) 20723-20731.
- [13] C.-L. Hsieh, Y. Pu, R. Grange, D. Psaltis, Digital phase conjugation of second harmonic radiation emitted by nanoparticles in turbid media, *Opt. Express*, 18 (2010) 12283-12290.
- [14] O. Katz, P. Heidmann, M. Fink, S. Gigan, Non-invasive single-shot imaging through scattering layers and around corners via speckle correlations, *Nature Photonics*, 8 (2014) 784.
- [15] X. Yang, C.-L. Hsieh, Y. Pu, D. Psaltis, Three-dimensional scanning microscopy through thin turbid media, *Opt. Express*, 20 (2012) 2500-2506.
- [16] Z. Yaqoob, D. Psaltis, M.S. Feld, C. Yang, Optical phase conjugation for turbidity suppression in biological samples, *Nature Photonics*, 2 (2008) 110.

Chapter 3:Fast 3D movement of a laser focusing spot behind scattering media by utilizing optical memory effect and optical conjugate planes

- [17] A. Shibukawa, A. Okamoto, Y. Goto, S. Honma, A. Tomita, Digital phase conjugate mirror by parallel arrangement of two phase-only spatial light modulators, *Opt. Express*, 22 (2014) 11918-11929.
- [18] Y. Liu, C. Ma, Y. Shen, J. Shi, L.V. Wang, Focusing light inside dynamic scattering media with millisecond digital optical phase conjugation, *Optica*, 4 (2017) 280-288.
- [19] D.B. Conkey, A.N. Brown, A.M. Caravaca-Aguirre, R. Piestun, Genetic algorithm optimization for focusing through turbid media in noisy environments, *Opt. Express*, 20 (2012) 4840-4849.
- [20] I.M. Vellekoop, C.M. Aegerter, Scattered light fluorescence microscopy: imaging through turbid layers, *Opt. Lett.*, 35 (2010) 1245-1247.
- [21] H. Yu, K. Lee, J. Park, Y. Park, Ultrahigh-definition dynamic 3D holographic display by active control of volume speckle fields, *Nature Photonics*, 11 (2017) 186.
- [22] I. Freund, M. Rosenbluh, S. Feng, Memory Effects in Propagation of Optical Waves through Disordered Media, *Physical Review Letters*, 61 (1988) 2328-2331.
- [23] G. Osnabrugge, R. Horstmeyer, I.N. Papadopoulos, B. Judkewitz, I.M. Vellekoop, Generalized optical memory effect, *Optica*, 4 (2017) 886-892.
- [24] V. Tran, S.K. Sahoo, D. Tang, C. Dang, Swiftly moving focus points and forming shapes through the scattering media, in: *SPIE BiOS*, SPIE, 2018, pp. 9.
- [25] J. Xu, H. Ruan, Y. Liu, H. Zhou, C. Yang, Focusing light through scattering media by transmission matrix inversion, *Opt. Express*, 25 (2017) 27234-27246.
- [26] D. Tang, S.K. Sahoo, V. Tran, C. Dang, Single-shot large field of view imaging with scattering media by spatial demultiplexing, *Appl. Opt.*, 57 (2018) 7533-7538.

Chapter 3:Fast 3D movement of a laser focusing spot behind scattering media by utilizing optical memory effect and optical conjugate planes

- [27] S.K. Sahoo, D. Tang, C. Dang, Single-shot multispectral imaging with a monochromatic camera, *Optica*, 4 (2017) 1209-1213.
- [28] O. Katz, E. Small, Y. Silberberg, Looking around corners and through thin turbid layers in real time with scattered incoherent light, *Nature Photonics*, 6 (2012) 549.
- [29] N. Callamaras, I. Parker, Construction of a confocal microscope for real-time x-y and x-z imaging, *Cell Calcium*, 26 (1999) 271-279.
- [30] A.M. Weiner, Femtosecond pulse shaping using spatial light modulators, *Review of Scientific Instruments*, 71 (2000) 1929-1960.
- [31] M. Dal Maschio, A.M. De Stasi, F. Benfenati, T. Fellin, Three-dimensional in vivo scanning microscopy with inertia-free focus control, *Opt. Lett.*, 36 (2011) 3503-3505.
- [32] C. Stockbridge, Y. Lu, J. Moore, S. Hoffman, R. Paxman, K. Toussaint, T. Bifano, Focusing through dynamic scattering media, *Opt. Express*, 20 (2012) 15086-15092.

Chapter 4: Single-shot large field of view imaging with scattering media by spatial demultiplexing.

This work is published as follow: “*D. Tang, S.K. Sahoo, V. Tran, C. Dang, Single-shot large field of view imaging with scattering media by spatial demultiplexing, Appl. Opt., 57 (2018) 7533-7538.*”

4.1 Introduction

Optical imaging is one of the most simple and straightforward ways to recognize the surrounding world with a large amount of information. The developments of the telescope, microscope, and camera technology have driven innovations in numerous fields from astronomical observation [1, 2] to biomedical research [3, 4] and in our daily lives. Unfortunately, in our real lives, the atmospheric fog, biological tissues, and rain curtains on car glass will degrade visibility of the object of interest at different levels. These scattering media contain inhomogeneities of a refractive index or absorption coefficient to generate random phase or amplitude distortions on the ideal light paths from the original objects. These result in complex speckle patterns on detectors and impair optical observations. Thus, imaging through those scattering media has become a hot topic and an important technical challenge over the past decades.

To overcome these limitations, various novel, breakthrough, and practical approaches have been proposed with the advances of optical scattering theory and optoelectronic devices. One of the successful techniques, optical coherence tomography (OCT), can utilize

the unscattered ballistic light and a scanning gate window to capture static images; conversely, the required amount of the ballistic photons will limit the penetration depth through scattering media [5, 6]. As the scattering media mainly scramble the phase information after light propagation in most cases, the phase perturbation can be compensated by using another straightforward methods. Those outstanding methods for imaging through scattering media have been discussed in chapter 2 such as: adaptive optics from the astronomical observation [2] with use of SLM [7-10] feedback wavefront shaping technique and transfer matrix characterization [11-17].

Another set of ideas were proposed by exploiting the speckle intensity correlation for imaging, thanks to the memory effect (ME) [18-30]. By estimating this ME region, a sparse object of size smaller than this can be recovered noninvasively with ultra-narrowband illumination. Because of the ME and randomness of the speckle pattern, the autocorrelation of the object mostly preserves through the scattering medium. A single-shot speckle pattern is enough to reconstruct the object with the help of a phase-retrieval algorithm [22-27]. The radius of the ME region on the object plane is inversely proportional to the thickness L of the scattering medium and proportional to the illuminating wavelength λ of the object [19, 20]. It is according to the formula:

$$r \propto \frac{u\lambda}{\pi L} \quad (4.1)$$

Where u is the distance from the object plane to the scattering medium. Objects larger than the ME region produce unwanted speckle patterns, the object autocorrelation cannot be preserved, and the phase retrieval is no longer possible. Deconvolution imaging becomes

useful in this case, where the scattering medium could be treated as a scattering lens [28, 29]. One can make full use of the intrinsic ME region by suitably positioning the scattering medium and optical components [29]. However, the FOV of the optical imaging system is still limited by the ME region of the strongly scattering medium, and unwanted speckle patterns only result in the reconstruction artifacts.

In this work, we demonstrate a deconvolution imaging technique to produce a larger FOV from a single-shot image with a scattering medium. By utilizing decorrelation among the regional PSFs, the proposed technique reconstructs various object regions from a single-shot image. Then, an automatic weighted averaging in an iterative process is performed to obtain the object with significantly enlarged FOV. These regional PSFs are fixed and only need to be recorded once for all-time use. We make use of those uncorrelated speckle patterns generated by objects beyond the ME region, which are previously considered as unwanted noise. The motivation is to maximize the utilization of the information captured by the imager, which is the superposition of multiple speckle patterns coming from the different regions of an extra-large object. Our results present an important step toward an advanced imaging technique with strongly scattering media. The detailed principle is described in the following section.

4.2 Principle

The object is simply a composition of point sources with various positions and intensities. For a linear optical imaging system, an image is expressed as a superposition of the multiple PSFs from different spatial positions with corresponding intensity. A

mathematical representation of the image formation $I(x, y) = \sum_{(i,j)} O(i, j) PSF_{ij}(x - i, y - j)$ where O is the object, and PSF_{ij} is the optical response function of a point source located at position i, j . In an ideal scenario, the image becomes identical to the object $I = O$ when these PSFs are identical impulse functions, which denote an ideal optical imaging system. In contrast, the scattering medium produces not only random but also variable PSFs, which are completely uncorrelated for far-apart point sources. However, because of ME, the point sources within a small ME region of the object plane will generate similar but shifted speckle patterns (i.e., PSFs) on the image plane. The image formation can be restated considering the ME as $I(x, y) = \sum_R \sum_{(i,j) \in R} O(i, j) PSF_{ij}(x - i, y - j)$, where R is the ME region having nearly identical PSF_{ij} as PSF_R . Taking advantage of the shift-invariant property of PSF_{ij} , the superposition can be expressed as a convolution of different regions of the objects with their corresponding PSFs. $I(x, y) = O_R * PSF_R = \sum_{(i,j) \in R} O(i, j) PSF_{ij}(x - i, y - j)$, where O_R is the portion of the object within the ME region, i.e., $O(i, j)$ for all $(i, j) \in R$. The object O_R can be recovered by deconvolution ($O_R = deconv(I_R, PSF_R)$) using PSF_R of the optical system, if we know its speckle pattern I_R . The deconvolution process is ideally expressed as follows:

$$O_R = \text{FFT}^{-1} \left(\frac{\text{FFT}(I_R) \text{FFT}(PSF_R)^c}{|\text{FFT}(PSF_R)|^2} \right) \quad (4.2)$$

where $(.)^c$ is the complex conjugate, $\text{FFT}(\cdot)$ and $\text{FFT}^{-1} \cdot$ are the Fourier transform and its inverse, respectively. The deconvolution in equation 4.2 is possible because the convolution in the spatial domain becomes the multiplication in the Fourier domain: $\text{FFT}(O_R * PSF_R) =$

$FFT(O_R)FFT(PSF_R)$. This deconvolution technique has been demonstrated to recover highquality images of an object within the ME region of the scattering medium [28, 29].

In the case of the object O extending beyond the ME region, its speckle pattern I of the object is a composite response of the scattering light coming from the various regions of the object $\forall_R\{O_R\}$. Thus, the captured image can be expressed as follows:

$$I = \sum_R I_R = \sum_R O_R * PSF_R \quad (4.3)$$

Because of the random structure of the scattering medium, it produces independent and identically distributed speckle patterns drawn from Rayleigh distribution [31]. The speckle patterns produced by two spatially separated point sources beyond the ME regions become completely uncorrelated. This can be mathematically expressed as follows:

$$PSF_{R1} \star PSF_{R2} = \begin{cases} 0 & \text{if } R1 \neq R2 \\ \delta & \text{if } R1 = R2 \end{cases} \quad (4.4)$$

where $\star$ is the correlation operator, and δ is the spatial impulse function. This spatial decorrelation behavior is similar to the spectral decorrelation behavior of the scattering medium [32]. Using this decorrelating property of the regional PSFs, the following relationship can be deduced:

$$FFT(I)FFT(PSF_R)^c = FFT(I_R)FFT(PSF_R)^c \quad (4.5)$$

Because of the relation $FFT(A \star B) = FFT(A)FFT(B)^c$. Therefore, each region R of the object can be reconstructed from a single-shot monochromatic image I , with the help of its regional PSFs as below:

$$\forall_R\{O_R\} = \text{deconv}(I, \text{PSF}_R) \quad (4.6)$$

In essence, each PSF_R can reconstruct the object within its limited FOV on the object plane, as shown later in experiment result. Actually, the scattering medium might have different effective thickness for different incident angles; therefore, ME could slightly vary at different spatial positions on the object plane, where spatial points have their own range of spatial shifted invariance PSFs and unique spatial FOV. At the same time, all the spatial information of an object is multiplexed inside a single speckle image captured by the camera. One could use the unique regional PSF to reconstruct the spatial object O_R for each region R and obtain a full reconstruction of the large object by arranging the respective object regions in space. However, we have arranged the respective object regions by weighted averaging the overlapping region, where the weights are obtained using an iterative technique, as detailed in the following section.

4.3 Experiment

A schematic of our complete optical setup is presented in Figure 4.1. A common projector creates a desired object as the input. In our experiment, the object is composed of groups of letters “NTU EEE OPTIMUS!” on a horizontal axis. Light coming from the object passes through a narrow bandpass green filter (center wavelength: 550 ± 2 nm, FWHM: 10 ± 2 nm), an iris, and a scattering medium that generates a scattering speckle image on the camera (Andor Neo 5.5, 2560×2160 , pixel size $6.5 \mu\text{m}$). The iris with diameter 2 mm is used to remove the background light and control the intensity, numerical aperture, speckle size, and signal-to-noise ratio of the speckle pattern. The distances from the object to the

scattering medium and that from the scattering medium to the camera are $u \approx 170$ mm and $v \approx 77.5$ mm, respectively. Therefore, the magnification of the setup is $M = v/u \approx 0.456$. We have used a piece of ground glass (Edmund 120 grids ground glass diffuser) as the scattering medium, whose effective thickness can be calculated using (3.6), i.e., $L = \frac{u\lambda}{r\pi}$. Taking the measured radius of the central ME region which relies on definition given in section 2.2.1, $r = 720$ μm , the effective thickness is calculated to be 41.3 μm (3.6). A detailed description on measurement of the ME radius can be found in the next paragraph. The thickness of the scattering medium reduces the ME and therefore limits the central FOV, as shown by the dashed red circle in Fig. 4.1. Thus, only a partial object located within this FOV could be reconstructed with the central PSF through the deconvolution process. As the light from a point source (a single projector's pixel) going to the camera sensor is quite weak, the exposure times for spatial PSF measurements are set as 10 s; for the object with multiple point sources, the exposure times are about 0.03 s–0.4 s. The Wiener deconvolution algorithm [33] is applied for the simplicity of implementation, which takes only about 0.5 s for each reconstruction with MATLAB on a normal PC (Intel Core i7, 16 GB memory). However, there are many robust and effective deconvolution algorithms that can replace the Wiener for better reconstruction quality. For each speckle pattern and PSF, we divide them by their low frequency envelop to remove the halo effect and sharpen the speckles. The resolution of the imaging system is defined by the speckle grain size, which depends on the numerical aperture of the system. Wiener deconvolution is performed by setting the noise level as the mean value of the deconvolving PSF.

Figure 4.1: Experimental setup. A common projector displays letters “NTU EEE OPTIMUS!” as an object for the imaging system. Light coming from the object passes through a green bandpass filter, an iris, and the scattering medium and then generates a scrambled speckle pattern on a camera. Memory effect of the scattering medium gives a limited FOV on the object plane, as shown in the red dashed circle on the object plane. SC, scattering medium. The distances from the object to the scattering medium and those from the scattering medium to the camera are $u \approx 170$ mm and $v \approx 77.5$ mm, respectively.

First, we need to quantify and measure the central FOV in this setup. PSFs with respect to various positions of point sources on the object plane are measured as the projector successively lights up one pixel from the central position toward the corner along the x direction. The cross-correlation coefficients between the PSF at the center and PSFs at different positions are calculated to confirm the available central FOV according to the magnification between the object and image plane. Figure 4.2(a) shows these cross-correlation coefficients as a function of the shifted distance on the object plane. We can see that only the object located in the cyan region is reconstructed with high fidelity. Thus, we define that the FOV is the region with a cross-correlation coefficient greater than 0.5. This measured ME region is corresponding to a strongly scattering medium with the effective

thickness of $41.3\text{ }\mu\text{m}$. To demonstrate this limited FOV, we use the central PSF [Figure 4.2 (b)] and the speckle image [Figure 4.2 (c)] of the object in *Figure 4.1* to do a deconvolution. The reconstructed result and the intensity across the central horizontal direction are shown in Figure 4.2(d) and Figure 4.2(e), where we clearly obtain high-quality recovery of the object in the limited $720\text{ }\mu\text{m}$ radius FOV, as with the cyan region in Figure 4.2(a). For the reconstruction process, we remove the background with intensity less than 15% of the maximum intensity for the clear display. The background noise comes from reconstruction artifacts, which depend on the relationship between the actual signal of interest and the noise (in this work, noise is mainly from the uncorrelated speckle image generated by nearby regions of the object). The full dimension of the speckle image and the PSF is used for the reconstruction because an increase in number of speckles would reduce the reconstruction noise. However, the background noise is still unavoidable because the nonsparse object makes a poor speckle contrast within the dynamic range of camera. Beyond the FOV, partial recovery of the object could also be identified, but the intensity is dim due to the low cross-correlation coefficient (less than 0.5).

Figure 4.2: Measurements and image recovery for the limited FOV in our optical system. (a) Cross-correlation coefficient between the central PSF and various spatial PSFs to identify the FOV on the object plane. Cyan region indicates a high-quality reconstructed area with cross-correlation coefficients larger than 0.5. (b) and (c) Central PSF and a captured speckle image of the object on the camera. (d) Reconstruction through a post-process algorithm indicates successful recovery of the objects located in the dashed red circle, corresponding to the cyan region in (a). (e) Intensity distribution along the central horizontal direction. Scale bars: 1000 μm . The arrow indicates the central row of the image.

The above central PSF in Figure 4.2 only guarantees a successful recovery image in the optical system with the linear shift-invariant property within a small region, where the deconvolution process reconstructs the object with high quality. Normally, the optical imaging system with scattering media is limited within the central FOV determined by the

central PSF. However, the speckle image in Figure 4.2(c) actually is the sum of the various PSFs from every point source on the object plane. In this work, we explore more information from the non-paraxial region and find an alternative way to extend the FOV while imaging with a strongly scattering medium using a single shot. There are multiple spatial FOVs satisfying the convolution operation in equation (4.3) for different spatial regions on the object plane. Equation (4.6) shows that information from various spatial regions could be recovered from the recorded single speckle image. We present various spatial point sources on the object plane and measure the corresponding PSFs; this is done by actuating a single pixel at the center of a desired region of interest on the projector plane. Then, various object regions are extracted from the same single-shot speckle image in Figure 4.2(c) by a deconvolution process. Figure 4.3 shows four typical reconstructions with four different spatial PSFs; further, the high quality central reconstructions and surrounding dim recoveries have the same effects as in Figure 4.2(d). At the bottom of each reconstructed image, we have plotted 1D intensity of the pixel line running along the center. Note that the available reconstruction regions (ME range) on the image plane are not the same for different spatial position PSFs. This is due to the non-uniform effective propagating thickness through the scattering medium for different regions on the object plane. Therefore, one could observe the different reconstruction FOV; for example, the FOV in Figure 4.3(c) seems larger than that in Figure 4.3(a).

Figure 4.3: Limited FOVs with various spatial PSFs. (a)–(d) A group of successful reconstructions of the object and corresponding 1D intensity distributions along the central rows. Scale bars: 1000 μm . The arrow indicates the central row of the image.

We have demonstrated our principle to de-multiplexing the spatial information multiplexed into one single speckle image through various spatial PSFs in Figure 4.3. However, for each individual reconstructed image, the information of interest is shifted to the center, and it is necessary to arrange the information to form a single image with an enlarged FOV. We need to shift the reconstructed images according to the region associated with the PSFs, whose positions are predetermined. In fact, PSFs could record the shift of the speckle patterns, and one could confirm their positions through calculating the cross-correlation coefficient (even though the value may be very low) to arrange the regional reconstructed images. If the regional PSF is measured for the point at position (ux, uy) , the recovered region on the image plane should be centered at position (vx, vy) where v/u is the magnification. Now the challenge is to superpose these reconstructed regions to form the entire FOV.

Figure 4.4: Flow graph of the imaging technique. Three steps at the beginning are the initial calibrations; the following steps are for the image acquisition and reconstruction.

In reality, ME does not mean identical PSFs in the regional FOV. The cross-correlation coefficient between two PSFs reduces monotonically with their inter distance. In each FOV region, the cross correlation coefficient of the central PSF with other PSFs reduces when the point goes from the center to the edge [Figure 4.2 (a)]; therefore, the intensity of the recovered image decreases from the center to the periphery. As presented above, we only need a single PSF for each regional FOV to present the function of a scattering lens. The position of the point source to take the PSF defines the center of the lens, and the PSF is the representative for this region. Any other point sources on the object plane also create their own PSFs whose cross-correlation coefficients with representative PSF represent the “transmission coefficient” of light from the point through the regional scattering lens in the deconvolution process. These transmission coefficients form a matrix T for each scattering lens. The scattering medium is fixed; the cross-correlation coefficients for each region are

not much different from the center regions. We assume that a single matrix T can be used for all regions, and it can be written as $O_R = T O_{\text{shift}R}$, where $O_{\text{shift}R}$ is the object O being shifted to the center of the region R . Unfortunately, both O and T are unknown and need to be recovered. Inspired by embedded pupil function recovery for Fourier ptychographic microscopy [34, 35], we adopt an iterative updating strategy to obtain both O and T as below:

$$O_{\text{shift}R}^{(n+1)} = O_{\text{shift}R}^n + \alpha \frac{T^n}{\max(T^n)} (O_R - T^n O_{\text{shift}R}^n) \quad (4.7)$$

$$T^{n+1} = T^n + \beta \frac{O^n}{\max(O^n)} (O_R - T^n O_{\text{shift}R}^n) \quad (4.8)$$

We start with the O^0 matrix having all entries as 0 and the T^0 matrix having entries as 1. Then, we perform the stitching operation by iterating between (4.7) and (4.8) for shifting all the regional PSF locations. This process is repeated twice for better convergence. It is important to have a significant amount of overlap between the adjacent regions for better stitching and lesser artifacts. In our experiment, we have ensured an overlap of 35% of the area between the adjacent reconstruction regions. A systematic flow chart is presented in Figure 4.4 for better understanding of the technique.

Figure 4.5: Superposed reconstruction to enlarge the limited FOV. (a) Spatial distribution of the objects on the object plane. Red circles indicate the spatial positions of point sources for measuring the various spatial PSFs. (b) Superposed reconstruction image. Dashed red circle indicates the enlarged FOV. Scale bars: 1000 μm .

In the next experiment, the point sources used for the PSF measurement are shifted along the x and y directions with a fixed spacing of 770 μm , which ensures more than 35% overlap between the adjacent regions. Then, we retrieve the large FOV image from these reconstructed smaller FOV images in accordance with the shift in the imaging plane by the aforementioned procedure. Groups of letters “welcome TO our lab” and “NTU EEE OPTIMUS!” on the vertical and horizontal axes are displayed as the object. The spatial PSFs for our optical system are from the point sources located at the various positions on the object plane, shown with red circles in Figure 4.5(a). The width of a superposed reconstruction in Figure 4.5(b) is 6650 μm , which is much larger than the reconstructed region by the central PSF alone $2 \times 720 \mu\text{m}$. We have demonstrated the aim of the proposed technique: enlarging the FOV, which is done by utilizing the full capacity of the imager.

The limit on the maximum FOV is given by the following factors: The number of active points (sparsity) and spectral bands of the object, the dynamic range, pixel size, number of pixels (resolution) of the camera, and the diffusing angle of the scattering medium. The first two factors determine the speckle contrast and therefore affect the recovery quality. The last factor defines the maximum angle of the light coming from the object then going to the camera. In the end, the dynamic range pixel size and number of pixels (resolution of the camera) become the main factors that decide the quality of the information captured from these low contrast speckle patterns.

4.4 Conclusion

We demonstrate an enlarged FOV for imaging with scattering media by utilizing multiple ME regions. A single-shot speckle pattern contains essential spatial information of the large object. All the information is multiplexed into a single image randomly but pre-deterministically by the scattering medium. Any object region of interest can be retrieved by using the corresponding PSF of that region. The regional PSFs are fixed and only need to be recorded once for all-time use. The deconvolution algorithm utilizes the shift invariance (i.e., spatial correlation) of the PSFs for image reconstruction, while the orthogonality between the regional PSFs (i.e., spatial decorrelation) makes them play the role of spatial information demultiplexer. An iterative process for automatic weighted averaging is used to stitch the multiple regional images and form a large FOV image. The propose technique utilizes the imager to its full capacity in terms of both dimension and dynamic range to enlarge an FOV imaging with strongly scattering media.

References

- [1] R.J. Noll, Zernike polynomials and atmospheric turbulence*, J. Opt. Soc. Am., 66 (1976) 207-211.
- [2] R.K. Tyson, Principles of Adaptive Optics, CRC press, (2015).
- [3] C. Gabriel, S. Gabriel, E. Corthout, The dielectric properties of biological tissues: I. Literature survey, Physics in Medicine and Biology, 41 (1996) 2231-2249.
- [4] V. Ntziachristos, Going deeper than microscopy: the optical imaging frontier in biology, Nature Methods, 7 (2010) 603.
- [5] D. Huang, E.A. Swanson, C.P. Lin, J.S. Schuman, W.G. Stinson, W. Chang, M.R. Hee, T. Flotte, K. Gregory, C.A. Puliafito, a. et, Optical coherence tomography, Science, 254 (1991) 1178.
- [6] M.B. Nasr, B.E.A. Saleh, A.V. Sergienko, M.C. Teich, Demonstration of Dispersion-Canceled Quantum-Optical Coherence Tomography, Physical Review Letters, 91 (2003) 083601.
- [7] I.M. Vellekoop, A. Lagendijk, A.P. Mosk, Exploiting disorder for perfect focusing, Nature Photonics, 4 (2010) 320.
- [8] O. Katz, E. Small, Y. Silberberg, Looking around corners and through thin turbid layers in real time with scattered incoherent light, Nature Photonics, 6 (2012) 549.
- [9] H. He, Y. Guan, J. Zhou, Image restoration through thin turbid layers by correlation with a known object, Opt. Express, 21 (2013) 12539-12545.
- [10] R. Horstmeyer, H. Ruan, C. Yang, Guidestar-assisted wavefront-shaping methods for focusing light into biological tissue, Nature Photonics, 9 (2015) 563.

- [11] M. Cui, E.J. McDowell, C. Yang, Observation of polarization-gate based reconstruction quality improvement during the process of turbidity suppression by optical phase conjugation, *Applied Physics Letters*, 95 (2009) 123702.
- [12] X. Xu, H. Liu, L.V. Wang, Time-reversed ultrasonically encoded optical focusing into scattering media, *Nature Photonics*, 5 (2011) 154.
- [13] K. Si, R. Fiolka, M. Cui, Fluorescence imaging beyond the ballistic regime by ultrasound-pulse-guided digital phase conjugation, *Nature Photonics*, 6 (2012) 657.
- [14] I.M. Vellekoop, M. Cui, C. Yang, Digital optical phase conjugation of fluorescence in turbid tissue, *Applied Physics Letters*, 101 (2012) 081108.
- [15] B. Judkewitz, Y.M. Wang, R. Horstmeyer, A. Mathy, C. Yang, Speckle-scale focusing in the diffusive regime with time reversal of variance-encoded light (TROVE), *Nature Photonics*, 7 (2013) 300.
- [16] S.M. Popoff, G. Lerosey, R. Carminati, M. Fink, A.C. Boccara, S. Gigan, Measuring the Transmission Matrix in Optics: An Approach to the Study and Control of Light Propagation in Disordered Media, *Physical Review Letters*, 104 (2010) 100601.
- [17] A. Boniface, M. Mounaix, B. Blochet, R. Piestun, S. Gigan, Transmission-matrix-based point-spread-function engineering through a complex medium, *Optica*, 4 (2017) 54-59.
- [18] S. Feng, C. Kane, P.A. Lee, A.D. Stone, Correlations and Fluctuations of Coherent Wave Transmission through Disordered Media, *Physical Review Letters*, 61 (1988) 834-837.
- [19] I. Freund, M. Rosenbluh, S. Feng, Memory Effects in Propagation of Optical Waves through Disordered Media, *Physical Review Letters*, 61 (1988) 2328-2331.

- [20] I. Freund, Looking through walls and around corners, *Physica A: Statistical Mechanics and its Applications*, 168 (1990) 49-65.
- [21] J. Bertolotti, E.G. van Putten, C. Blum, A. Lagendijk, W.L. Vos, A.P. Mosk, Non-invasive imaging through opaque scattering layers, *Nature*, 491 (2012) 232.
- [22] O. Katz, P. Heidmann, M. Fink, S. Gigan, Non-invasive single-shot imaging through scattering layers and around corners via speckle correlations, *Nature Photonics*, 8 (2014) 784.
- [23] E. Edrei, G. Scarcelli, Optical imaging through dynamic turbid media using the Fourier-domain shower-curtain effect, *Optica*, 3 (2016) 71-74.
- [24] A. Porat, E.R. Andresen, H. Rigneault, D. Oron, S. Gigan, O. Katz, Widefield lensless imaging through a fiber bundle via speckle correlations, *Opt. Express*, 24 (2016) 16835-16855.
- [25] A.K. Singh, D.N. Naik, G. Pedrini, M. Takeda, W. Osten, Exploiting scattering media for exploring 3D objects, *Light: Science & Applications*, 6 (2017) e16219.
- [26] Y. Shi, Y. Liu, J. Wang, T. Wu, Non-invasive depth-resolved imaging through scattering layers via speckle correlations and parallax, *Applied Physics Letters*, 110 (2017) 231101.
- [27] T. Wu, O. Katz, X. Shao, S. Gigan, Single-shot diffraction-limited imaging through scattering layers via bispectrum analysis, *Opt. Lett.*, 41 (2016) 5003-5006.
- [28] E. Edrei, G. Scarcelli, Memory-effect based deconvolution microscopy for super-resolution imaging through scattering media, *Scientific Reports*, 6 (2016) 33558.
- [29] H. Zhuang, H. He, X. Xie, J. Zhou, High speed color imaging through scattering media with a large field of view, *Scientific Reports*, 6 (2016) 32696.
- [30] M. Cua, E. Zhou, C. Yang, Imaging moving targets through scattering media, *Opt. Express*, 25 (2017) 3935-3945.

- [31] J.W. Goodman, Speckle Phenomena in Optics: Theory and Applications, Roberts & Company, 2007.
- [32] S.K. Sahoo, D. Tang, C. Dang, Single-shot multispectral imaging with a monochromatic camera, *Optica*, 4 (2017) 1209-1213.
- [33] R.C. Gonzalez, R.E. Woods, Digital image processing, 2018.
- [34] G. Zheng, R. Horstmeyer, C. Yang, Wide-field, high-resolution Fourier ptychographic microscopy, *Nature Photonics*, 7 (2013) 739.
- [35] X. Ou, G. Zheng, C. Yang, Embedded pupil function recovery for Fourier ptychographic microscopy, *Opt. Express*, 22 (2014) 4960-4972.

Chapter 5: Utilize multiple scattering effect for highly sensitive optical refractive index sensing

Chapter 5 is published as: “ V. Tran, S.K. Sahoo, D. Wang, C. Dang, *Utilizing multiple scattering effect for highly sensitive optical refractive index sensing, Sensors and Actuators A: Physical*, 301 (2020) 111776.”

5.1 Introduction

Optical sensing is one of the most common and essential sensing techniques for various applications, from daily activities to advanced industries, because of its capabilities to sense remotely, non-destructively and conveniently. Optical sensors in many wearable devices today can quietly monitor many physiology parameters of our body, such as heartbeat and oxygen saturation level. Among the optical sensing techniques, the refractive index sensing is often implemented for estimating concentration of a substance inside a solution or gas volume because of the direct relationship between refractive index and substance concentration [1]. Various refractive index sensing techniques have been proposed with advancement in high sensitivity and fast response such as optical resonators [2-5], plasmonic resonance [6-9], or optical fiber structure [10, 11]. However, the requirements of advanced manufacture to fabricate resonant devices or complex optical configurations could hinder the technology deployment.

Among all optical components, optical diffusers or strongly scattering media such as ground glass are very simple to make and have recently become useful passive optical components for various applications. Light passing through scattering media creates random

optical speckles on the other side. Such natural random patterns can be used to enhance security in optical cryptography applications [12]. The speckle pattern through scattering media also carries some information of incoming light, which might be extracted for various applications. As discussed in chapter 2, by utilizing the small memory effect in thin scattering media, one can use them as a scattering lens for imaging [13-16], with resolution even better than typical lens when using image reconstruction algorithm [17-20].

Both spatial and spectral information of the object are multiplexed then de-multiplexed in a single speckle pattern. By reducing the spatial information of an object to a single point, more spectral information can be multiplexed and then extracted; thus, optical diffuser can be used as a spectrum analyzer [16, 21-23]. A typical optical diffuser distorts the wavefront in a vigorous and deterministic way. Therefore, analyzing the change in speckle pattern provides information about the change of incoming optical wavefront, which is associated with various physical parameters of the light propagating environment. An early research [24] investigated the relationship between speckle correlation and refraction index variation to determine the surface roughness. Another approach [25] measured the optical path difference from peak correlation coefficient with and without the presence of an optically flat, regularly shaped glass slab to determine the glass's refractive index. Recently, the correlation coefficient of the speckle patterns has been utilized to indicate the glucose concentration change [26, 27] or volume change under different pressure [28]. Those exciting methods have been discussed in section 2.3.

Inhomogeneous refractive index of a medium is the main reason that an optical diffuser scrambles incoming light. A photon going into that medium is scattered (or refracted) multiple

times before getting out, which is similar to a diffusion process. Sandblasted glass or ground glass has a randomly rough surface at micrometer scales, creating an inhomogeneous refractive index interface between glass and surrounding environment. The different refractive index between glass ($n = 1.5$) and air ($n = 1$) or water ($n = 1.3$) enables a strongly scattering medium. One can turn translucent ground glass into normal transparent glass simply by putting it in refractive index matching oil ($n = 1.5$). In other words, the surrounding environment is a part of the scattering medium and its refractive index determines the scattering effect. The speckle pattern is the interference result of multiple scattering photons at various interface angles of inhomogeneous surface between glass and surrounding environment. Such a small change in refractive index of environment will be amplified by scattering media and reported in the speckle pattern.

Here, we utilize ground glass to demonstrate a simple refractive index sensing technique, which is highly sensitive for practical applications. In contrast to detection of wavefront change with conventional static scattering media [26, 28], we exploit dynamic scattering media whose scattering effect is strongly determined by and sensitive to refractive index of measured environment. The correlation of two speckle patterns can quantify a tiny difference of corresponding environment's refractive indexes. As an example of practical and useful applications, we demonstrate our sensing technique for glucose solution with measured concentration change as low as 12 ppm. More interestingly, we can boost the sensitivity of our technique simply by adding more ground glass diffusers to increase scattering interface between measured environment and the glass. Our demonstrated sensitivity is 516.85 per refractive index unit (RIU) and the detection limit of 3.87×10^{-6} RIU with three diffusers and

a standard commercial imaging sensor. Our simple optical sensing technique with a very high sensitivity level, which is equivalent to that of fabrication-intensive resonant optical structures, could potentially enable advanced applications with cost advantages.

5.2 Experiment and result

Figure 5.1 : Principle of sensing refractive index change by correlation analysis of output speckle patterns

As light transmits through the interface between two media, the input angle (θ_1) and output angle (θ_2) are related to each other by Snell law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$, where n_1 and n_2 are refractive indexes of incoming and outgoing medium, respectively. One can measure angles directly to derive refractive index. However, because of $\Delta n_2 \approx -n_1 \sin \theta_1 \frac{\cos(\theta_2)}{\sin^2(\theta_2)} \Delta \theta_2$, the refractive index sensing is determined by our ability to measure angles precisely, which is typically challenging. Light passing through the interface between ground glass and the environment follows the same principle except that there are various angles at different

positions and possibly multiple refraction of a single photon. The transmitted light then interferes and creates a speckle pattern on a flat imaging sensor. Analyzing the change in this speckle pattern allows us to quantify the change in refractive index.

The principle of our simple sensing technique is sketched in Figure 5.1, where a coherent laser beam propagates through one or several ground glass diffusers (refractive index n_1), and an imaging sensor captures the speckle pattern. All the diffusers are immersed in a characterizing medium, whose refractive index change will be measured. To understand and evaluate our sensing technique, we have constructed a simulation model for our experiment's principle. In our model, we digitally sample the ground glass surface in discrete small sectors. The glass thickness of each sector is produced by a pseudo-random generator in a specific range around the average thickness of real diffusers. A Gaussian laser beam with a flat wavefront propagating through the diffuser will have a distorted wavefront according to the glass thickness and index of environment as presented in Figure 5.1. The Gaussian beam is supposed to be generated from a HeNe laser with wavelength of 632.8 nm. The output light with distorted wavefront continues propagating to other diffusers and then finally creates a speckle pattern (light intensity only) on the imaging sensor. In Fig.1, $n_1 = 1.5168$ and $n_2 = 1.3325$ are the refractive index of glass diffuser and the water in contact with that diffuser, respectively. We then change the medium's refractive index and record the corresponding speckle patterns.

To describe the light propagation in the system, we use Fresnel approximation for diffraction process. The correlation coefficient (C) between two speckle patterns is measured to quantify the difference in medium's refractive index:

$$C = \frac{\sum_{k=1}^N \sum_{l=1}^N [I_R(k, l) - \bar{I}_R][I_M(k, l) - \bar{I}_M]}{\sqrt{\{\sum_{k=1}^N \sum_{l=1}^N [I_R(k, l) - \bar{I}_R]^2\} \{\sum_{k=1}^N \sum_{l=1}^N [I_M(k, l) - \bar{I}_M]^2\}}} \quad (5.1)$$

where $I_R(k, l)$ and $I_M(k, l)$ are the intensities at the pixel (k, l) of the speckle pattern R (reference for index n_2) and M (measurement for index n_2'). If there's no change in refractive index ($n_2 = n_2'$), the two speckle patterns are the identical and correlation coefficient $C = 1$; and if the refractive index change is large enough ($|\Delta n_2| = |n_2' - n_2| \gg 0$), the two speckle patterns are the results of two independent random propagations, the correlation coefficient $C = 0$. The correlation coefficient C between 0 and 1 needs to be calibrated with the corresponding refractive index change for real sensing applications. The absorption of media also causes decorrelation of the speckle pattern and make the problem more complex. Here, we consider only the transparent solution or medium such as water or air. In simulation, the light intensity is calculated with default precision of Matlab and no noise is taken into consideration.

Figure 5.2: Simulation result of our sensing technique. **(a)** Speckle correlation change as function of medium's refractive index for 1, 2, and 3 ground glasses inside solution tank respectively; 1 ground glass outside after the tank is for reference purpose. **(b)** Absolute value of derivative of correlation curves for 1, 2, 3 ground glasses inside solution tank and 1 ground glass outside after the tank. **(c)** Speckle correlation and its derivative absolute value for solution's refractive index changing around ground glass's refractive index (1.52) with 1 ground glass inside solution tank

Figure 5.2(a) presents the results of speckle correlation as a function of medium's refractive index. Starting with a reference speckle pattern for refractive index of 1.3325 (i.e. water), then we increase the medium's refractive index, the correlation of the speckle pattern with the reference one reduces monotonically as expected. The correlation coefficient is almost 1 for refractive index of nearly 1.3325 (the reference point) then approaches zero for refractive index greater than 1.339 when we use only one optical diffuser. Furthermore, the dependency of correlation coefficient on medium's refractive index becomes steeper (more sensitive) if we add more ground glasses into the optical path while keeping all other parts the same. This observation can be easily understood as more number of refractive index dependent scattering media are involved in forming the speckle pattern. As for reference purpose, we simulate a static diffuser by putting an optical diffuser outside and after the characterizing medium. Diffuser plays the role of a wavefront analyzer as presented in other works [26, 28], its scattering characteristics is independent from refractive index of characterizing medium. The light source is considered as a perfect laser beam whose flat wavefront remains the same after passing through a medium of uniform refractive indexes. Therefore, we do not detect any change in correlation coefficient ($C = 1$) with respect to any refractive index as presented in Figure 5.2(a). It is worth to note that if the laser is not a perfect coherent beam, i.e. the wavefront is not flat, the refractive index of medium will alter the wave front and the outside optical diffuser (the wavefront analyzer) will detect it. However, adding multiple refractive-index-independent scattering media does not affect the sensitivity of the system. This approach of utilizing an optical diffuser after the measurement medium as a wave front detector to measure refractive index change has been demonstrated

by Mahajan and et al [26]. In later parts of our work here, we will show the significant improvement in sensitivity when we make refractive index dependent diffuser by bring ground glasses inside the measurement medium.

The nonlinear dependence of correlation coefficient on refractive index implies the different sensitivity of our sensing approach at different refractive index. The sensitivity $S = |\Delta C / \Delta n|$ of our sensing mechanism with only one ground glasses presented in Figure 5.2(b) indicates that the highest sensitivity can reach 267.9 per RIU at the middle region where the correlation coefficient is about 0.58. On the other hand, the sensitivity is very low when the refractive index is too close or too far from the reference point. This implies an optimum range of refractive index change to be measured in our sensing approach for each reference refractive index. The configurations with 2 and 3 ground glasses enhance the sensitivity to 363.3 and 441.1 per RIU, respectively. As the range of correlation coefficient is fixed from 0 to 1, sensitivity enhancement reduces the measurable range for refractive index as expected. Such simplicity and flexibility to adjust the sensitivity of our sensing techniques cannot be achieved by a ground glass placed after the characterizing medium as a wavefront change detector [26]. It is important to note that the refractive index difference is measured here, not the actual refractive index. This important point is an advantage for real applications as we have flexible choices of reference refractive index so that the region of interest is in the optimum range for measurement. Changing actual refractive index for the reference medium does not create noticeable difference in the observed behavior as long as the scattering medium is functioning as expected, i.e. $|n_1 - n_2| \gg 0$. However, the behavior changes dramatically when the reference refractive index is approaching the ground glass's refractive index, i.e. the ground glass is

approaching the transparent condition or $|n_1 - n_2| \sim 0$ (Fig. 2c). The sensitivity is smaller especially when refractive index of the medium crosses that of glass ($n_2' = 1.52$). This is not preferable for sensing applications.

To examine our concept for useful applications, we setup and demonstrate our technique to detect the concentration of glucose solution. As demonstrated earlier, the refractive index of glucose solution is related directly to its concentration [1]. Therefore, detecting the refractive index of glucose solution leads to determination of glucose concentration, which is one of the most important parameters for diabetes diagnostic and health monitoring. It is important to note here that our technique measures the refractive index difference between distilled water (the reference) and glucose solution (the sample). Then the refractive index of glucose solution is determined by knowing the water's refractive index. In our experiment setup, a glass tank filled with 200 ml of distilled water is placed on an optical table to be the starting solution for measurement. Here, we use the ground glass diffusers (Thorlabs N-BK7 DG10-120) inside the solution tank. The light source is He-Ne laser with wavelength of 632.8 nm. To increase the stability of the laser wavefront, we use only select the fundamental mode of laser by using a spatial filter, which is comprised of 2 microscope objectives (10X) and a pinhole of 50 μm diameter placed at the common focal point of two objectives. More practically, one can also achieve a stable wavefront with laser beam coupled through a single mode fiber. The stability of the laser wavefront is important to get a stable sensing technique. The whole system is placed inside a dark enclosure to prevent any stray light and especially avoid any air turbulence from the room. An iris with diameter size of 4 mm is placed between the tank and the monochromatic camera to control the size of observed speckles. A larger

speckle size will increase the observable speckle area and reduce the speckle size, therefore increase the sensitivity of correlation with refractive index.

Figure 5.3: Experiment results of our sensing technique. **(a)** Speckle correlation change as a function of medium's refractive index for 1, 2, 3 ground glasses inside solution tank and 1 ground glass outside, after the tank. **(b)** Absolute value of derivative of fitted speckle correlation curve with respect to solution's refractive index.

We decided to do experiment with iris size of 4 mm to make sure all the speckles are well resolved by our CMOS sensor with pixel size of 8 μm . This is important to have

accurate speckle correlation measurement. In our experiment procedure, we changed the refractive index of the solution inside the tank by consequently dropping in 5 ml glucose solution with concentration of 50 mg/ml.

Figure 5.3(b) and (c) shows the results of correlation coefficient as a function of glucose concentration for different optical configurations: 1, 2, 3 ground glasses inside the solution tank, and 1 ground glass after the solution tank. The experimental results are very well agreeable to our simulation results in Figure 5.2. For the ground glass outside the tank playing the roles of wavefront change detection, the correlation coefficient does not response to the change of glucose concentration as expected. Also in Figure 5.3(a), when the ground glasses are emerged inside the solution tank, we are able to detect the glucose concentration difference based on the change in speckle correlation coefficient, which is predicted in our simulation. Following the work of C.-Y. Tan and Y.-X. Huang [1], we deduce the refractive index of glucose solution based on its concentration and put in our graphs. We are able to detect very small change of refractive index and by adding more ground glasses into solution, we can easily increase the sensitivity. Figure 5.3(b) presents the sensitivity of our technique for configuration with 1, 2, and 3 ground glasses. The sensitivity (S) is described by both $(\Delta C / \Delta n)$ or $(\Delta C / \Delta Con)$, where ΔCon is the change of glucose concentration. The highest sensitivity is in the middle of the detection range when the ΔC is about 0.55. For 1, 2, and 3 ground glasses, our highest sensitivity can reach $0.143 \text{ (mg/ml)}^{-1}$, $0.15 \text{ (mg/ml)}^{-1}$ and $0.165 \text{ (mg/ml)}^{-1}$, which is equivalent to 476.7, 485.2 and 516.9 per RIU, respectively. Our results with “refractive index dependent” diffusers show 2 orders of sensitivity improvement from previous report ($6.43 \times 10^{-3} \text{ (mg/ml)}^{-1}$) using a “static” diffuser [26] to detect optical wavefront change. In

principle, we can enhance the sensitivity further by adding more scattering media inside the tank. However, mechanical vibration, temperature drift, environment turbulence, laser and camera noise, etc will set a practical limit for sensitivity enhancement.

The sensitivity is important to justify a sensing technique but not possible to justify the detection limit or resolution. Our proposed approach shows 2 orders of magnitude sensitivity improvement in comparison to the approach using a ground glass as a detector for wavefront change. We can conclude that our detectable limit will be 2 orders of magnitude improvement because we measure speckle correlation in both techniques. However, it is not possible to compare directly with other refractive index sensing techniques, which do not measure speckle correlation coefficient for example resonant wavelength shift or transmission coefficient. The detectable level (or resolution) is more important to justify the quality of a sensing technique, where the standard derivation of the measured parameter is taken into consideration. The detectable level is defined as $D = Std(C)/S$, where $Std(C)$ is the standard deviation of correlation coefficient measurement. In our sensing technique, $Std(C)$ depends on some factors such as the noise level of the CMOS sensor to measure the speckle pattern, the fluctuation of laser wave front for which we minimize by a spatial filter, the environment fluctuation of temperature or airflow through the light path or system vibration. Some of the conditions relate to long term stability of the system such as the environment fluctuation of temperature or airflow through the light path which need to be addressed in the development. Our current system with CMOS imaging sensor (MV1-D2080-160-G2) in lab environment shows very stable measurement of speckle correlation coefficient as presented in Figure 5.4.

Figure 5.4: a-d) Zoomed-in images at the center of speckle patterns, whose correlation with reference pattern corresponds to stability states in (e). e) The diffusion dynamics and stability for experiment measurement. Two experiments are conducted under the same conditions: The first one is blue line and the second one is orange line. Green circled parts are diffusion process after dropping distilled water into distilled water tank. Red circled parts are dynamic states as glucose diffuses slowly after dropping glucose in solution. The letters a, b, c, d indicate the states that corresponds to the speckle images in figure a, b, c, d. Black circled parts are stable states when glucose diffusion completes and we have a uniform solution to take a precise measurement of speckle correlation.

We first test the stability and repeatability of our experiment by dropping 5ml distilled water into the distilled water tank. Many effects cause the sudden decorrelation of the speckle pattern upon dropping action (green circled in Figure 5.4(e)) such as air bubbles, tank

vibration, air turbulence upon opening and closing the enclosure, and the temperature difference between added water and the existing water. However, the correlation coefficient recovers to the stable original state after stabilization, implying no change in refractive index and highlighting the stability and reproducibility of the experiments. After that, we introduce glucose and speckle correlation drops immediately. A series of measurement (1 second interval) is taken to show the glucose diffusion process which is presented as fluctuation of correlation coefficient to reach a stable state after hours. We can accelerate the process if we stir the solution. In Fig. 5.4(a-d), we present the zoomed-in area at the center of speckle patterns that corresponds to stability states in Fig. 5.4(e). Some main features of the speckle pattern seem not changing but the small details do vary depending on concentrations. We do two experiments in the same condition. And naturally, the correlation fluctuations are different when we first drop glucose solution in. However, after completing diffusion process, the uniform solution is achieved, the correlation for both experiments are stable within standard deviation (0.002) of each other, which presents the noise of our system. The measurement range for correlation is from 1 to 0, making the dynamic range of 500 (~ 27 dB). The ability to measure the speckle correlation coefficient precisely allows us to achieve detection limit for 3-ground glasses configuration as low as 1.21×10^{-2} mg/ml (or 12 ppm) for glucose which is equivalent to 3.87×10^{-6} RIU. These high sensing resolutions make our simple technique comparable with other advanced sensing approaches based on optical resonant [2-5] or plasmonic structures [2, 3, 6-9], which require advanced fabrication technique. Comparing to other sensing techniques using scattering media, our demonstration with multiple diffusers presents a significant enhancement of about 2 orders in both sensitivity and

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resolution limit with flexibility to tune the sensitivity. It is also worth to emphasize that our technique measures refractive index changes at the wavelength of our laser. One can improve it simply by including more lasers at different wavelengths. Our proof of concept with glucose concentration also can be demonstrated with other solutions because refractive index varies with concentration. However, the calibration need to be done for each solution.

Table 1: Comparison between our sensing technique and other works using speckle patterns

Sensing technique with diffusers	Sensitivity (per RIU) or Glucose concentration	Resolution (RIU) or Glucose concentration	Controllable sensitivity
Our work	516.9 or $0.165 \text{ (mg/ml)}^{-1}$ (Glucose concentration)	3.87×10^{-6} or $1.21 \times 10^{-2} \text{ mg/ml}$ (Glucose concentration)	Yes
Ref [24]	197.3 (estimated form the graph)	No available data	Yes and simple
Ref [25]	No available data	Method 1: 51.6×10^{-4} (glass thickness 20mm) 54.5×10^{-4} (glass thickness 25mm)	No
		Method 2: 1.9×10^{-4} (glass thickness 20mm) 1.6×10^{-4} (glass thickness 25mm)	
Ref [26]	$6.43 \times 10^{-3} \text{ (mg/ml)}^{-1}$ (Glucose concentration)	1.1 mg/ml (Glucose concentration)	No
Ref [27]	No available data	3.8×10^{-4}	Possible but inconvenient

5.3 Conclusion

We have presented a simple approach to measure solution's refractive index, which can be directly correlated to other physical parameters such as concentration or temperature. The speckle patterns on an imaging sensor are the results of light scattering through ground glasses which are sensitive to the refractive index of the surrounding medium. Our experiment and simulation results demonstrate that the correlation coefficient between two speckle patterns is a good indicator for the difference between two refractive indexes with very high sensitivity. Besides the simplicity of optical configuration setup, the sensitivity of our proposed sensing technique can be enhanced simply by adding more ground glasses. Our demonstration with 3-ground glass diffusers configuration shows the detectable level of 3.87×10^{-6} RIU, comparable to some optical resonance sensing techniques which require intensive device fabrication. The current detectable level allows us to measure the change in glucose concentration at the level of 1.21×10^{-2} (mg/ml) or 12 ppm. The results also indicate that it is even possible to differentiate Oxygen (refractive index of 1.000271) from Nitrogen (refractive index of 1.000298) due to the refractive index difference of 2.7×10^{-5} . Besides the high sensitivity, and low detectable level, the demonstrated stability and repeatability suggests a simple calibration process with known reference refractive index could be done to build a refractive index measurement system for practical applications.

References

- [1] C.-Y. Tan, Y.-X. Huang, Dependence of Refractive Index on Concentration and Temperature in Electrolyte Solution, Polar Solution, Nonpolar Solution, and Protein Solution, *Journal of Chemical & Engineering Data*, 60 (2015) 2827-2833.
- [2] G.N. Tsigaridas, A study on refractive index sensors based on optical micro-ring resonators, *Photonic Sensors*, 7 (2017) 217-225.
- [3] Z. Xiao, H. Dai, X. Chen, Ultrasensitive optofluidic resonator refractive index sensor, *Opt. Lett.*, 43 (2018) 4216-4219.
- [4] W. Yang, S. Song, X. Yi, S.X. Chew, L. Li, L. Nguyen, Silicon-on-insulator microring resonator sensor based on an amplitude comparison sensing function, *Opt. Lett.*, 43 (2018) 70-73.
- [5] P. Moock, L. Kasper, M. Jäger, D. Stolarek, H. Richter, J. Bruns, K. Petermann, TDM-controlled ring resonator arrays for fast, fixed-wavelength optical biosensing, *Opt. Express*, 26 (2018) 22356-22365.
- [6] W. Wei, X. Zhang, X. Ren, Plasmonic circular resonators for refractive index sensors and filters, *Nanoscale Research Letters*, 10 (2015) 211.
- [7] H. Wang, Plasmonic refractive index sensing using strongly coupled metal nanoantennas: nonlocal limitations, *Scientific Reports*, 8 (2018) 9589.
- [8] A.A. Rifat, F. Haider, R. Ahmed, G.A. Mahdiraji, F.R. Mahamd Adikan, A.E. Miroshnichenko, Highly sensitive selectively coated photonic crystal fiber-based plasmonic sensor, *Opt. Lett.*, 43 (2018) 891-894.
- [9] A.R. Sadrolhosseini, M. Naseri, H.M. Kamari, Surface plasmon resonance sensor for detecting of arsenic in aqueous solution using polypyrrole-chitosan-cobalt ferrite nanoparticles composite layer, *Optics Communications*, 383 (2017) 132-137.

- [10] Z. Ding, K. Sun, K. Liu, J. Jiang, D. Yang, Z. Yu, J. Li, T. Liu, Distributed refractive index sensing based on tapered fibers in optical frequency domain reflectometry, *Opt. Express*, 26 (2018) 13042-13054.
- [11] J.S. Velázquez-González, D. Monzón-Hernández, D. Moreno-Hernández, F. Martínez-Piñón, I. Hernández-Romano, Simultaneous measurement of refractive index and temperature using a SPR-based fiber optic sensor, *Sensors and Actuators B: Chemical*, 242 (2017) 912-920.
- [12] S.K. Sahoo, D. Tang, C. Dang, Enhancing security of incoherent optical cryptosystem by a simple position-multiplexing technique and ultra-broadband illumination, *Scientific Reports*, 7 (2017) 17895.
- [13] Y. Choi, C. Yoon, M. Kim, W. Choi, W. Choi, Optical Imaging With the Use of a Scattering Lens, *IEEE Journal of Selected Topics in Quantum Electronics*, 20 (2014) 61-73.
- [14] X. Xu, X. Xie, H. He, H. Zhuang, J. Zhou, A. Thendiyammal, A.P. Mosk, Imaging objects through scattering layers and around corners by retrieval of the scattered point spread function, *Opt. Express*, 25 (2017) 32829-32840.
- [15] C. Park, J.-H. Park, C. Rodriguez, H. Yu, M. Kim, K. Jin, S. Han, J. Shin, S.H. Ko, K.T. Nam, Y.-H. Lee, Y.-H. Cho, Y. Park, Full-Field Subwavelength Imaging Using a Scattering Superlens, *Physical Review Letters*, 113 (2014) 113901.
- [16] S.K. Sahoo, D. Tang, C. Dang, Single-shot multispectral imaging with a monochromatic camera, *Optica*, 4 (2017) 1209-1213.
- [17] R. Won, Scattering lens power, *Nature Photonics*, 9 (2015) 418.
- [18] E. Edrei, G. Scarcelli, Memory-effect based deconvolution microscopy for super-resolution imaging through scattering media, *Scientific Reports*, 6 (2016) 33558.

- [19] H. Yilmaz, E.G. van Putten, J. Bertolotti, A. Lagendijk, W.L. Vos, A.P. Mosk, Speckle correlation resolution enhancement of wide-field fluorescence imaging, *Optica*, 2 (2015) 424-429.
- [20] E.G. van Putten, D. Akbulut, J. Bertolotti, W.L. Vos, A. Lagendijk, A.P. Mosk, Scattering Lens Resolves Sub-100 nm Structures with Visible Light, *Physical Review Letters*, 106 (2011) 193905.
- [21] M. Mazilu, T. Vettenburg, A. Di Falco, K. Dholakia, Random super-prism wavelength meter, *Opt. Lett.*, 39 (2014) 96-99.
- [22] B. Redding, S.F. Liew, R. Sarma, H. Cao, Compact spectrometer based on a disordered photonic chip, *Nature Photonics*, 7 (2013) 746.
- [23] H. Cao, Perspective on speckle spectrometers, *Journal of Optics*, 19 (2017) 060402.
- [24] F.P. Quintian, M.A. Rebollo, E.N. Hogert, M.R. Landau, N.G. Gaggioli, Relationship between speckle correlation and refraction index variations: applications for roughness measurements, *Optical Engineering*, 35 (1996) 1175-1178, 1174.
- [25] C. Guo, D. Li, D.P. Kelly, H. Li, J.P. Ryle, J.T. Sheridan, Measuring refractive index of glass by using speckle, *Appl. Opt.*, 57 (2018) E205-E217.
- [26] S. Mahajan, V. Trivedi, V. Chhaniwal, M. Prajapati, Z. Zalevsky, B. Javidi, A. Anand, Measurement of concentration of sugar in solutions with laser speckle decorrelation, in: *SPIE Optical Metrology*, SPIE, 2015, pp. 6.
- [27] V. Trivedi, S. Mahajan, M. Joglekar, V. Chhaniwal, Z. Zalevsky, B. Javidi, A. Anand, 3D printed hand-held refractometer based on laser speckle correlation, *Optics and Lasers in Engineering*, 118 (2019) 7-13.

[28] K. Kim, H. Yu, K. Lee, Y. Park, Universal sensitivity of speckle intensity correlations to wavefront change in light diffusers, *Scientific Reports*, 7 (2017) 44435.

Chapter 6: Conclusion and Recommendations

Throughout Chapter 3, a simple but useful technique has been introduced for making and moving focus spot behind scattering media. The outstanding advantages of this work has not been only developed from previous researches but also based on new ideas and techniques. Among well-known methods to overcome scattering effect by modulating incident light, making focus spot is basic but very practicable step. Moving spot digitally based on simple setup is a practicable property which from this work can lead to prominent applications in some specific fields such as laser cutting or laser surgery. Unlike previous researches which also rely on ME, my work introduced in this thesis is also able to extend the area of making focus spot out of ME range which is so-called enlarging FOV. In fact, introduced technique for enlarging FOV is quite straightforward as it inherits the phase pattern from the original optimization to optimize for a spot at the edge of ME range. On the other hand, ability of moving digitally or creating simultaneously focus spot allow this technique to do imaging through scattering media which can lead to remarkable applications in bio-imaging or imaging therapy. However, this technique is still obstructed because its operation is an invasive process. Indeed, the input factor for optimization process still requires capturing directly target area behind scattering media.

To solve the problem of invasive focusing technique above, I and my colleagues propose a new method called noninvasive focusing technique which has been already confirmed by simulation and also produced convince results. With this new method, both modulation part and observation part of setup can be placed on the same side of scattering medium or i.e. a focus spot can be created inside a bio-subject without inner interaction with it. In principle,

this tech still relies on a GA optimization, however the input is extracted from speckle pattern observed outside scattering medium. The experiment setup for this method is very simple as follow: incident wavefront is modulated by SLM and shined to a diffuser as a scattering medium; a mask of quantum dots (QD) is placed on the other side of scattering medium; then a camera is placed at the same side of SLM to observe incoherent speckle pattern emitted from QD mask behind scattering medium. In principle, this technique still relies on GA optimization process. Nevertheless, the input for optimization process is extracted from incoherent speckle pattern after an analyzing process. In the analyzing process, we calculate a factor of which value will increase when more light is modulated to focus into a sufficient small area on the QD mask. By using that factor as input, optimization process of this new technique operates similarly to the one described in chapter 3. The results and principle of this noninvasive focusing technique is being prepared to publish very soon.

In chapter 4, proposed imaging technique with PSF and deconvolution has shown a prominent and practical approach for imaging through scattering media. The essential requirement of this technique is to have a point source which will produce PSF for de-scattering process. In introduced work in this thesis, PSF is created manually which limits the technique to be an invasive imaging method. However, with future work above for noninvasive focusing technique, the method in chapter 4 can rely on to produce noninvasive imaging applications. With principle relied on ME, imaging technique with use of PSF here is limited by the thickness of scattering media. Therefore, future works to improve this technique is to do imaging without ME, for example using diffusive photon. With that

improvement, this imaging technique can be used for applications which deal with thicker scattering media such as human body.

In other interest subject of this thesis, there are also circumstance where we can utilize the randomness of scattering effect to serve for useful applications. One of them has been discussed during the chapter 5. With the principle and method introduced in chapter 5, a very simple and sensitive setup can be used for refractive index sensing application. The outstanding advantage of this technique is not only from its simplicity but also from the ability of increasing sensitivity. As described in chapter 5, simply adding in more scattering media in contact with target medium can increase significantly the sensitivity of setup. On the other hand, beside number of scattering media, there are also other factors which can affect the sensitivity such as: distance between scattering media, size of pinhole and so on. Therefore, from achievement in chapter 5, I and my research group will continue investigating those factor to fulfill the research of refractive index sensing technique with use of scattering media. Excitingly, from the proposed setup and its ability, making and packaging a high sensitive and competitive devices in refractive index sensors field are very prominent. However, there are also more requirements before reaching that step such as: collect more data, build up reference data, testing stability as well as precision of setup and so one. Those works are exciting targets that I will do more researches in future. Moreover, from this research of utilizing randomness of scattering medium for refractive index sensor, there should be more similar circumstance for the use of scattering media which I will investigate further to reveal them in future.

Author's Publications

- D. Tang, S.K. Sahoo, **V. Tran**, C. Dang, Single-shot large field of view imaging with scattering media by spatial demultiplexing, *Appl. Opt.*, 57 (2018) 7533-7538.
- **V. Tran**, S.K. Sahoo, D. Tang, C. Dang, Swiftly moving focus points and forming shapes through the scattering media, in: *SPIE BIOS*, SPIE, 2018, pp. 9.
- **V. Tran**, S. Sahoo, D. Wang, C. Dang, Utilizing the randomness of light propagation through scattering media for sensing application (Conference Presentation), SPIE, 2019.
- **V. Tran**, S.K. Sahoo, D. Tang, C. Dang, Utilizing optical conjugate plane to enhance 3D focusing and forming shapes behind turbid media, SPIE, 2019.
- **Tran V.**, Sahoo, S.K. & Dang, C. Fast 3D movement of a laser focusing spot behind scattering media by utilizing optical memory effect and optical conjugate planes. *Sci Rep* 9, 19507 (2019) doi:10.1038/s41598-019-56214-3
- **V. Tran**, S.K. Sahoo, D. Wang, C. Dang, Utilizing multiple scattering effect for highly sensitive optical refractive index sensing, *Sensors and Actuators A: Physical*, 301 (2020) 111776.
- D. Li, **V. Tran**, S.K. Sahoo, H.Q. Lam, D. Wang, C. Dang, “Wavefront shaping with feedback from linear fluorescence signal to non-invasively focus laser light inside scattering media”. Under preparation for publication.