Optics and Lasers in Engineering 158 (2022) 107133

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Accurate optical information transmission through thick tissues using zero-frequency modulation and single-pixel detection

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ARTICLE INFO

Keywords:
Optical wireless transmission
Thick biological tissues
Zero-frequency modulation
Single-pixel optical detection

ABSTRACT

Delivering accurate information through thick biological tissues is critical in many biomedical applications. However, it is challenging to realize accurate optical information transmission and achieve large penetration depth due to complex structures and compositions of thick biological tissues. The absorption and scattering through biotissues are inter-related, and could cause light attenuation dramatically. In this paper, a new method based on zero-frequency modulation (ZFM) is proposed to generate a series of 2D random amplitude-only patterns for accurate optical information transmission through thick tissues at low light intensities. Light source modulated by the generated 2D patterns propagates through biological tissues, and a single-pixel bucket detector is used to record light intensity with a differential detection technique. Different sample thicknesses and the light source with different wavelengths are used to experimentally verify the proposed method. The proposed method can realize accurate optical information transmission through biological tissues with a thickness of 16.0 mm, when a low laser power of only 0.08 mW/cm^2 is used to illuminate the sample at wavelength of 658.0 nm. The proposed method realizes accurate optical information transmission through thick biological tissues, and is able to overcome the challenges, e.g., penetration through small-thickness tissues and low quality of the retrieved signals. The proposed method provides a promising means for optical data transmission through deep tissues.

1. Introduction

With ever-increasing concerns on life quality, there is much fast-growing interest in developing new technologies for medical devices and applications. In recent years, wireless communication offers a reliable and portable means for medical devices [1,2]. Technological developments over the past decades have made possible not only to monitor health conditions but also to diagnose and react to numerous onsets. Novel health-related technologies allow to enhance the quality of life and save lives in critical health conditions. Nowadays, medical devices and various sensors play a significant role in medical information communication [3–6]. The communications can be conducted by using radio frequency (RF) and acoustic waves. RF technology provides an attractive solution by powering wireless devices with continuous and stable energy over the air. However, when body sensors using the same RF spectrum operate in close vicinity, safety threats exist [7,8] and interference could become a challenge. Since data integrity also plays a vital role in medical information communication, any undesired interference may lead to information impotence. Moreover, there is also a concern of vital RF signals being accessed by unintended parties. Ultrasonic communication produces a wireless connection between remote communication nodes using elastic waves. Ultrasonic waves can also be generated to propagate through biological tissues, and ultrasound techniques have been widely used to diagnose the onsets. However, penetration depth of ultrasonic communication is limited [8,9]. A major disadvantage of ultrasound methods is their incompetence to propagate in free space. The RF and ultrasounds dissipate energy while propagating through the tissues, indicating that an increased amount of energy could be absorbed and dispersed by biological tissues [10,11]. Optical wireless transmission (OWT) has emerged as a promising means in recent years, and optical light source has some remarkable advantages. For instance, the OWT is secure, private and safe. In many medical applications, it is feasible to transmit data using optical light source, and it is highly desirable that delivering accurate information through thick tissues can be fully explored by using optical light source with low illumination power.

In this paper, a new method based on zero-frequency modulation (ZFM) is proposed to realize accurate optical information transmission through thick tissues at low light intensities. To the best of our knowledge, this is the first investigation of encoding data information into 2D random amplitude-only patterns to realize accurate optical information transmission through thick tissues. In the proposed ZFM-based encoding scheme, information to be transmitted is considered as a

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https://doi.org/10.1016/j.optlaseng.2022.107133
Received 11 January 2022; Received in revised form 13 April 2022; Accepted 2 June 2022
Available online 12 June 2022

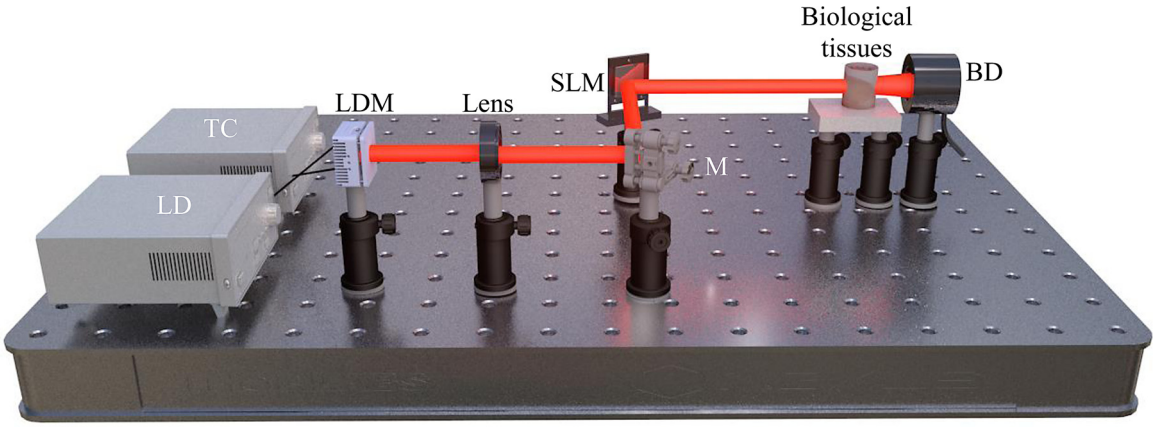

Fig. 1. A schematic experimental setup for the proposed ZFM-based optical information transmission through thick biological tissues: LD: Laser driver; TC: Temperature controller; LDM: Laser diode mount; M: Mirror; SLM: Amplitude-only spatial light modulator; BD: Single-pixel (bucket) detector. Chicken breast tissue is used as a sample in this study, and single-pixel detector is placed close to the sample.

series of independent pixel values, and each pixel value is encoded into one 2D random amplitude-only pattern. Subsequently, the generated 2D random amplitude-only patterns are sequentially embedded into spatial light modulator (SLM) to be modulated. Then, the modulated wave propagates to the tissue and propagates through biological tissues, i.e., chicken breast tissues used in this study. The optical beams are scattered and absorbed through chicken breast tissues, and a single-pixel detector [12–20] is used to record light intensity without a lens. A differential detection approach is further developed to suppress noise and enhance quality of the detected signals (e.g., peak signal-to-noise ratio (PSNR)). Accurate information is retrieved by using the collected light intensity without any complex post-processing algorithms. The proposed method is experimentally verified by using different thicknesses of chicken breast tissues and a laser beam with different wavelengths.

2. Samples and methods

2.1. Experimental preparation

A schematic optical setup is shown in Fig. 1. The laser diode current is controlled by using a laser driver (Thorlabs, LDC205C) in a range of 0–500 mA using a laser diode mount (Thorlabs, LDM56/M). The laser is stabilized at room temperature with a controller (Thorlabs, TED200C). In optical experiments, laser diodes with three different wavelengths are individually used, i.e., 658.0 nm (Thorlabs L658P040), 520.0 nm (Thorlabs L520P50) and 405.0 nm (Thorlabs DL5146–101S). The laser beam is expanded and collimated by a converging lens with a focal length of 100.0 mm. The collimated laser beam is reflected by a mirror, and then illuminates the surface of an amplitude-only spatial light modulator (Holoeye, LC-R720) with pixel size of 20.0 μm. In this study, a modulation rate of 1.25 Hz is used to conduct a proof-of-principle experiment and verify the proposed method. The angle between the incident beam and the reflected beam on the surface of SLM is 45°. Then, the modulated optical wave propagates through biological tissues. At the receiving end, a single-pixel detector (Newport, 918D-UV-OD3R) with a power meter (Newport, 1936-R) is used to record light intensity. In this study, laboratory temperature is set as 20°C for a series of optical experiments.

The sample used in this study is frozen and raw chicken breast tissues, since chicken breast has good muscle orientation whose characteristic is similar to human tissues. In our optical experiments, the samples are purchased from a local supermarket, and the skin and fat of chicken breast are removed. The chicken breast is cut to be placed into a transparent container. The container is filled with a small amount of microscope oil to avoid water evaporation in optical experiments. Optical properties of chicken breast tissues might be slightly variable due to biological variations and other conditions, e.g., the freezing and thawing period that can cause cell rupture. All optical experiments are performed within 3 days after phantom preparation. Optical powers illuminated onto the samples are monitored and measured, and are in accordance with the safety requirement.

2.2. Principle

A series of 2D random amplitude-only patterns are first generated to encode original information to be transmitted. Then, a laser diode generates spatially coherent monochromatic beam to illuminate the SLM which sequentially displays the series of generated 2D random amplitude-only patterns as schematically shown in Fig. 1.

The proposed approach to generating 2D random amplitude-only patterns for encoding original information is described as follows: A 2D random matrix with real and nonnegative values is first generated. Then, fast Fourier transform (FFT) is applied to the 2D random matrix to obtain its corresponding Fourier spectrum. Zero frequency of the generated Fourier spectrum is replaced by one pixel value of original information, and a new Fourier spectrum is correspondingly generated. Subsequently, inverse fast Fourier transform (IFFT) is applied to the new Fourier spectrum to obtain an updated 2D random amplitude-only pattern (P). The above steps are repeated until each pixel value of original information is encoded into one 2D random amplitude-only pattern. It is worth noting that size of the generated 2D random amplitude-only pattern (P) can be flexibly designed in the proposed ZFM method, e.g., 256×256 or 512×512 pixels. The process of the proposed ZFM-based encoding scheme is further shown in Fig. 2. In the optical experiments, negative values existing in the generated 2D random patterns (P) cannot be displayed by the SLM, and each generated 2D random pattern (P) is further transformed into two separate patterns, i.e., patterns (t+P) and (t-P) where t denotes a positive constant.

The interaction between the light and biological tissues is an important topic, and optical wave propagation through thick biological tissues is a complex process. When optical lightwave propagates through thick biological tissues, it generally undergoes reflection and refraction at the interface of inner tissues. The biotissues, e.g., chicken breast tissues, could be considered as high anisotropy media with strong absorption and scattering. Therefore, optical light source attenuates dramatically by the absorption and scattering, and the total light attenuation coefficient μ can be described by

$$\mu = \mu_s + \mu_a, \tag{1}$$

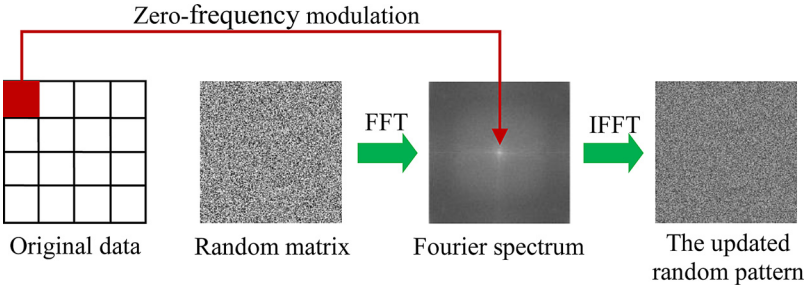

Fig. 2. A flowchart to schematically illustrate the proposed ZFM-based encoding method for accurate optical information transmission through thick biological tissues. In the proposed method, a 2D random amplitude-only pattern is generated for each pixel value of original information. FFT, fast Fourier transform; IFFT, inverse fast Fourier transform.

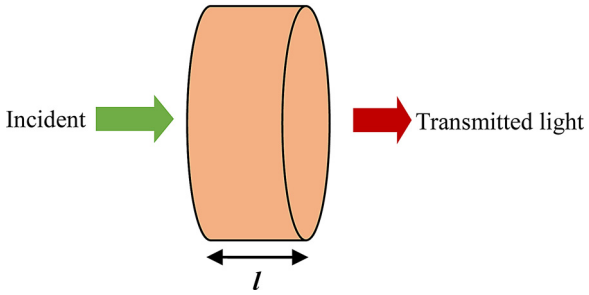

Fig. 3. A schematic of the transmittance.

where μ_s denotes scattering coefficient and μ_a denotes absorption coefficient. In the biotissues, hemoglobin, melanin, bilirubin and betacarotene are the main absorbers [21], and optical wave propagation through the biotissues can be described by Beer-Lambert law [22] as follows:

$$I = I_0 \exp(-\mu l), \tag{2}$$

where I_0 denotes the incident light intensity just before the sample, I denotes the transmitted light intensity just after the sample, and l denotes optical path length. A schematic is shown in Fig. 3 to describe the transmittance rate, and the transmittance T is described by

$$T = \frac{I}{I_0}. \tag{3}$$

Optical scattering is caused by the mismatch of refractive indices through biological tissues. Scattering coefficients and anisotropy factor can approximate the scattered light in the biotissues [23]. The light can be scattered in various directions through the biotissues, and anisotropy factor g is defined by

$$g = \langle \cos\theta \rangle, \tag{4}$$

where θ denotes photon scattering angle and $\langle\ \rangle$ denotes an ensemble average. The range of anisotropy parameter is [−1, 1]. Here, backward scattering is represented by −1, and forward scattering is represented by 1. Biotissues undergo Rayleigh scattering and Mie scattering due to the heterogeneous structures. For most biotissues, anisotropy factor g is approximately 0.9 [24], which means that forward scattering dominates over backward scattering.

After optical waves propagate through thick tissues, light intensity is recorded by using a single-pixel detector [12–20] at the receiving end as shown in Fig. 1. Single-pixel detection process is described by

$$\begin{aligned} \mathrm{B1} &= \delta \int\int [t + P(x,y)]\ \ e^{-2\pi j(x\xi+y\eta)}\mathrm{dxdy}|_{\xi=0,\eta=0}, \\ &= \delta \int\int [t + P(x,y)]\ \ \mathrm{dxdy} \end{aligned} \tag{5}$$

$$\begin{aligned} \mathrm{B2} &= \delta \int\int [t - P(x,y)]\ \ e^{-2\pi j(x\xi+y\eta)}\mathrm{dxdy}|_{\xi=0,\eta=0}, \\ &= \delta \int\int [t - P(x,y)]\ \ \mathrm{dxdy} \end{aligned} \tag{6}$$

where $j = \sqrt{-1}$, (x,y) denotes a coordinate in spatial domain, (ξ, η) denotes a coordinate in frequency domain, t+$P(x,y)$ and t-$P(x,y)$ denote

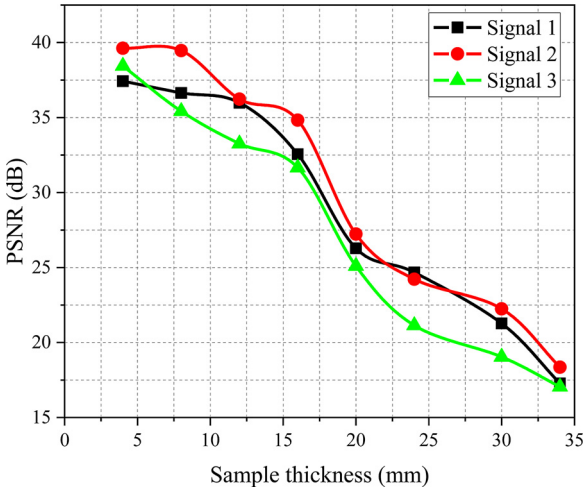

Fig. 4. A relationship between sample thickness (i.e., chicken breast tissues) and quality of the experimentally retrieved analog signals using the proposed ZFM method.

2D random patterns with 256×256 pixels embedded into the SLM, δ denotes a scaling factor related to free-space wave propagation environment, and B1 and B2 denote the recorded intensity values which are related to one pixel value of original information. The differential operation process is described by

$$\mathrm{B} = \mathrm{B1} - \mathrm{B2}. \tag{7}$$

3. Experimental results and discussion

The capabilities of light to penetrate the biotissues, interact with the biotissues and transmit through the biotissues are critical in practical applications. Therefore, the light penetration depth through biotissues is first studied at low light levels in the designed optical wireless transmission. Subsequently, optical light source with different wavelengths is investigated, and absorption and scattering through biotissues are studied to determine the transmitted light intensity. Here, a series of optical experiments are conducted, and experimental results are presented and discussed to verify feasibility and effectiveness of the proposed method.

3.1. Light penetration depth through chicken breast tissues

The penetration depth through biological tissues is important, and efficiency and fidelity of the designed optical wireless transmission setup are studied. A laser diode with wavelength of 658.0 nm is used as light source shown in Fig. 1, and a chicken breast sample with different thicknesses is prepared and placed in the optical path to investigate feasibility and effectiveness of the proposed method. Low light intensities are used for sample illumination. Experimental results are shown in Figs. 4 and 5. To quantitatively evaluate experimental results, PSNR is calculated

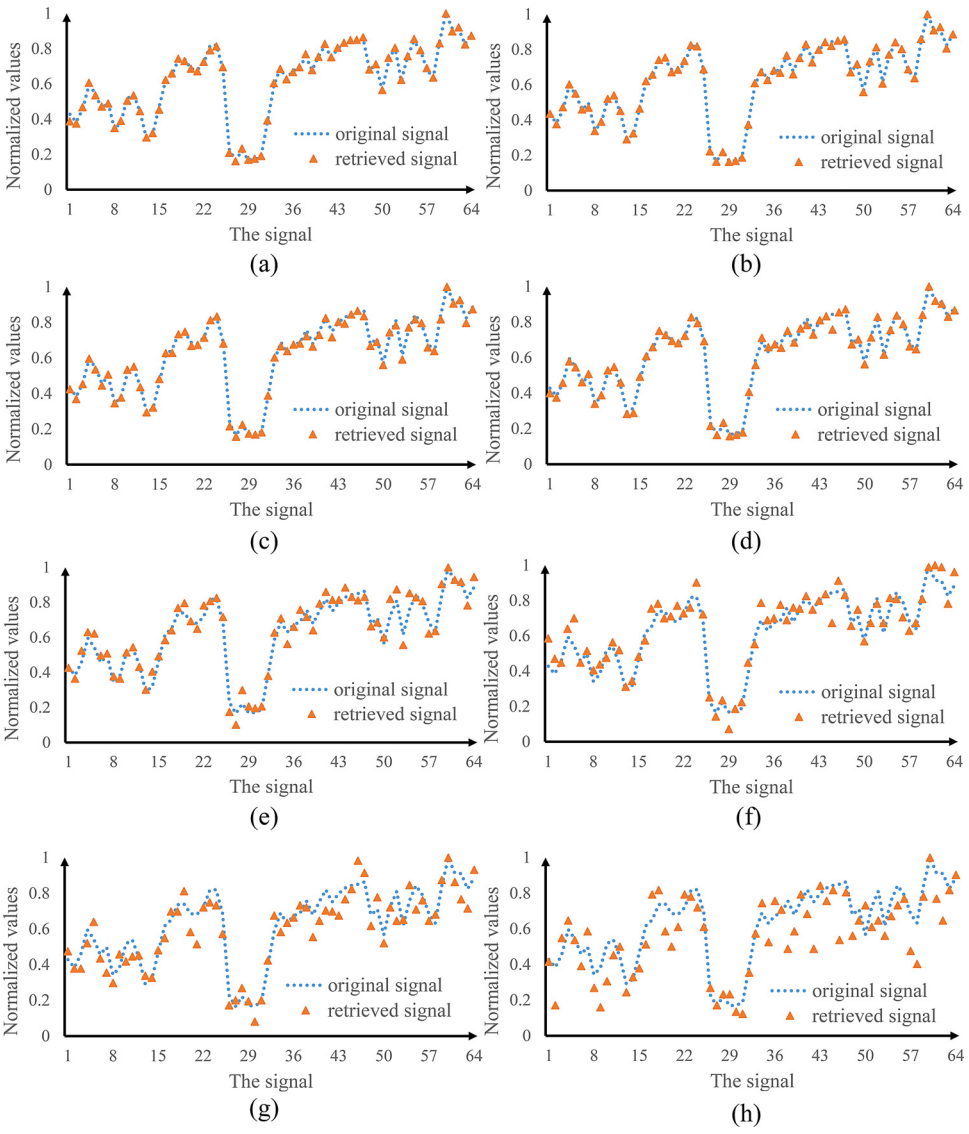

Fig. 5. Comparisons between original signal and the experimentally retrieved signals when different sample thicknesses of (a) 4.0 mm, (b) 8.0 mm, (c) 12.0 mm, (d) 16.0 mm, (e) 20.0 mm, (f) 24.0 mm, (g) 30.0 mm, and (h) 34.0 mm are respectively applied in optical experiments using the proposed ZFM method at low light illumination levels. Here, the signal 2 in Fig. 4 is tested and typically presented.

and defined by

$$\mathrm{PSNR} = 10\log_{10}\left(\frac{MAX_{ori}^2}{\mathrm{MSE}}\right), \tag{8}$$

$$\mathrm{MSE} = \frac{1}{N}\sum\left(S_{ori} - S_{re}\right)^2, \tag{9}$$

where MAX_{ori} denotes the maximum value of original information, S_{ori} denotes original information, S_{re} denotes the retrieved information, and N denotes the total number of pixels in original information.

Experimental results are shown in Fig. 4, when chicken breast tissues with different thicknesses are used as sample. Three typically irregular analog signals are tested in this case. The typically retrieved analog signals are shown in Fig. 5. It can be seen in Fig. 4 that PSNR values decrease with the increased sample thickness. When the thickness of biotissues is not larger than 16.0 mm, the retrieved signals are always of high quality as shown in Fig. 4 and Figs. 5(a)–5(d). The accurate information transmission through biological tissues is realized by using the proposed method. Here, a low laser power of only 0.08 mW/cm^2 has been used to illuminate the sample, and the transmittance rate is calculated and given in Table 1. Compared with conventional methods [25], the proposed method realizes accurate optical information transmission through biological tissues with a thickness of 16.0 mm, when a low laser power of only 0.08 mW/cm^2 is used. It is demonstrated that the proposed method is effective and robust for accurate optical information transmission through thick tissues using a low illumination power.

3.2. Laser beam with different wavelengths

In visible light spectrum, average absorption coefficients and reduced scattering coefficients through biological tissues could be different. We further investigate the proposed method using a laser beam with different wavelengths for optical information transmission through thick tissues, and experimental results are shown in Figs. 6 and 7. In this case, a low laser power of only 0.08 mW/cm^2 has been used just before the sample.

It can be seen in Fig. 6 that accurate optical information transmission through chicken breast tissues is realized by using red and green laser beams in the proposed method, but quality of the retrieved signal is low when a blue laser is used as the illumination light source. It has also been demonstrated [10,24] that two absorption peaks could exist when light source with the wavelengths of 430.0 nm and 540.0 nm is used, and a reduced scattering coefficient peak exists at the wavelength of 450.0 nm. The peaks in the measured absorption spectra are generated due to the absorbers like hemoglobin, melanin, myoglobin, bilirubin

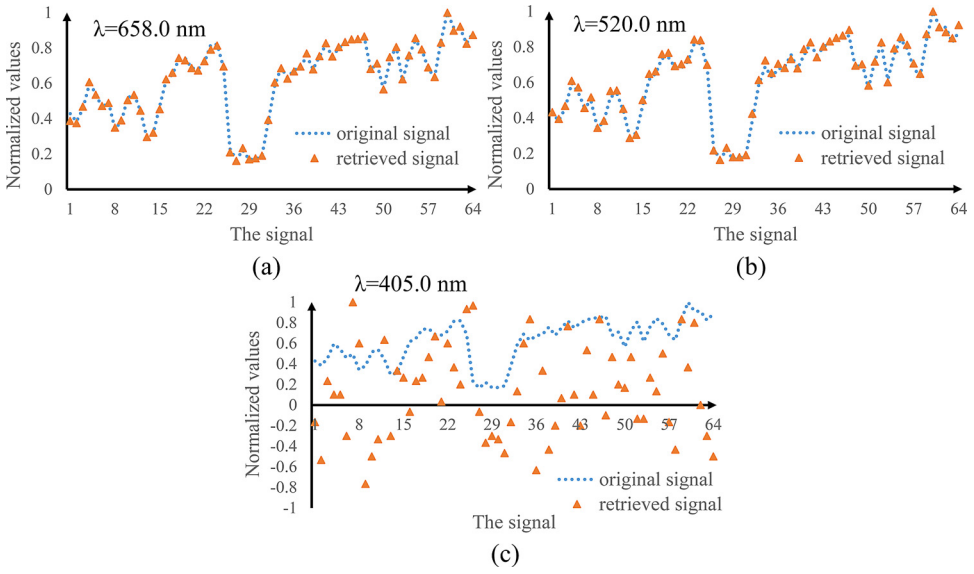

Fig. 6. Comparisons between original signal and the experimentally retrieved signals when a laser beam with different wavelengths of (a) 658.0 nm, (b) 520.0 nm and (c) 405.0 nm is respectively applied in optical experiments using the proposed ZFM method. The thickness of biological tissue is 4.0 mm in this case.

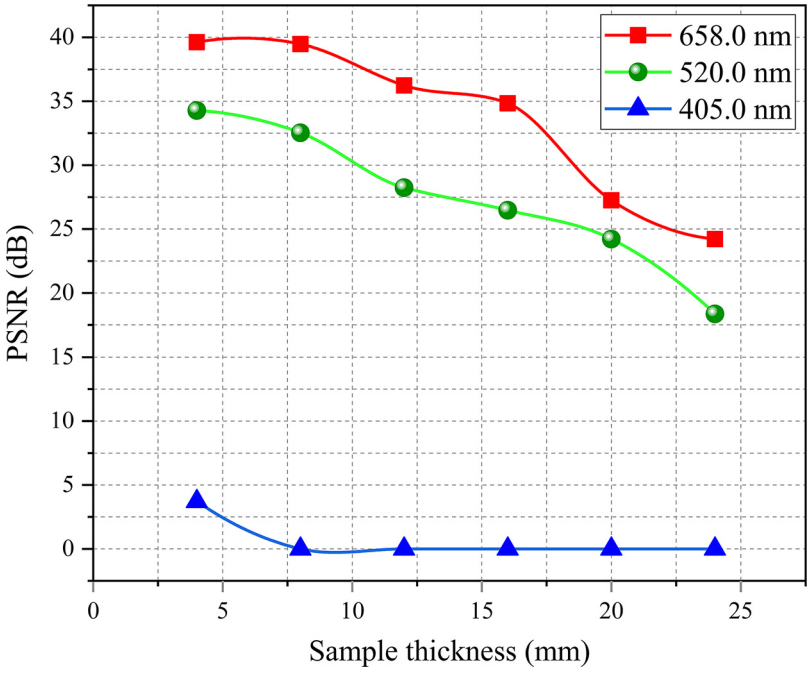

Fig. 7. Effect of light source with different wavelengths (i.e., red, green and blue) on quality of the retrieved signals when a sample with different thicknesses (i.e., 4.0 mm, 8.0 mm, 12.0 mm, 16.0 mm, 20.0 mm and 24.0 mm) is applied in optical experiments using the proposed ZFM method.

Table 1
Transmittance rate for optical information transmission through biotissues with different thicknesses using the proposed ZFM method. The light power detection area is 1.0 cm^2.

Thickness (mm)	Incident light power I_0 (mW)	Transmitted light power I (mW)	Transmittance rate (%)
4.0	0.08	4.54×10^{-3}	5.68
8.0	0.08	4.02×10^{-3}	5.03
12.0	0.08	1.58×10^{-3}	1.98
16.0	0.08	1.28×10^{-3}	1.60
20.0	0.08	1.01×10^{-3}	1.26
24.0	0.08	0.76×10^{-3}	0.95
30.0	0.08	0.64×10^{-3}	0.80
34.0	0.08	0.52×10^{-3}	0.65

and carotene in chicken breast tissues. In addition, scattering through chicken breast tissues originates from cell and cellular organelles, e.g., membranes, nuclei and mitochondria [26].

Breast chicken tissue with different thicknesses is used to further investigate performance of the proposed method using red, green and blue lasers, and quality of the retrieved signals is quantitatively evaluated and shown in Fig. 7. High transmission accuracy is always achieved at the wavelength of 658.0 nm when the thickness of chicken breast tissues is not larger than 16.0 mm, and the blue laser with wavelength of 405.0 nm is not suitable to be applied as illumination light source for accurate optical information transmission through biological tissues using the proposed method. It can be seen in Figs. 6 and 7 that when light source with the longer wavelength is used in the proposed method, there are less absorption and scattering through chicken breast tissues.

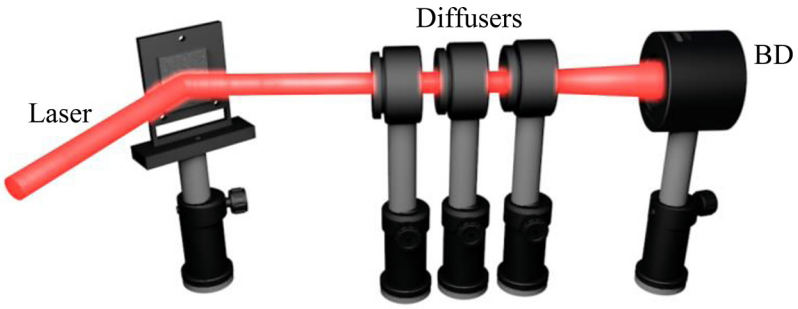

Fig. 8. A schematic experimental setup for testing the proposed method against scattering using three cascaded diffusers.

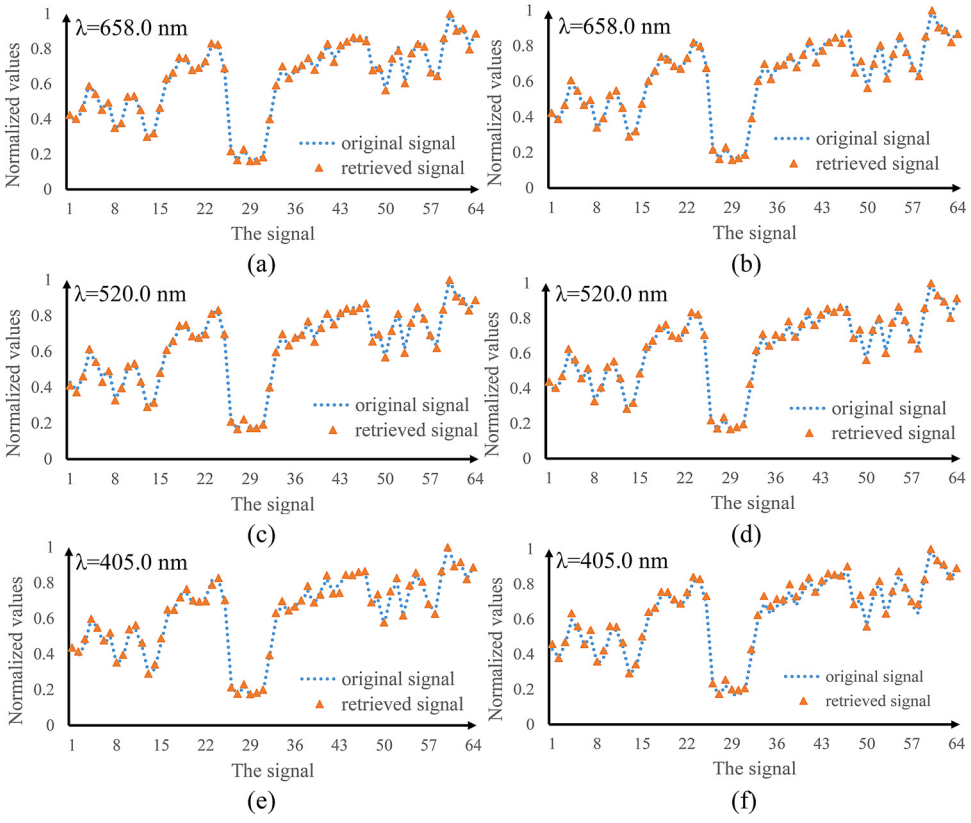

Fig. 9. The effect of scattering on quality of the experimentally retrieved signals when a laser beam with wavelengths of 658.0 nm, 520.0 nm and 405.0 nm is respectively applied in optical experiments using the proposed ZFM method. (a), (c), (e) Comparison between original analog signal and the experimentally retrieved analog signals when free space environment without scattering media is used; (b), (d), (f) comparison between original analog signal and the experimentally retrieved analog signals when a scattering medium with three cascaded diffusers is used in free space.

3.3. Scattering effect

The attenuation of light depends on scattering and absorption when traversing chicken breast tissues, and we further uncouple the effect of scattering and absorption in order to explain the findings in Section 3.2 using the proposed ZFM method. Here, a ratio (r) between scattering and absorption is described by

$$r = \frac{\mu_s}{\mu_s + \mu_a}, \tag{10}$$

where scattering dominates when $r = 1$ and absorption dominates when $r = 0$.

To quantitatively evaluate the proposed method, three cascaded diffusers (Thorlabs, DG10–1500-MD) are used to emulate only the scattering (i.e., $r = 1$) as shown in Fig. 8, and each diffuser has a diameter of 25.4 mm and a thickness of 2.0 mm. It has been well recognized that through the biotissues, Mie scattering dominates over Rayleigh scattering [27–30]. In our optical experiments, a laser beam with different wavelengths is applied, and free space without and with scattering media is studied. Experimental results are shown in Figs. 9(a)–9(f), and quality of the experimentally retrieved signals is quantitatively evaluated and given in Table 2.

Table 2
Optical information transmission accuracy in free space without and with scattering media using the proposed ZFM method with a laser beam of different wavelengths corresponding to those in Figs. 9(a)–(f).

Wavelength (nm)	PSNR (dB)	
	Without scattering	With scattering
405.0	34.63	31.46
520.0	38.63	35.32
658.0	38.08	37.51

It can be seen in Table 2 and Fig. 9 that high-fidelity analog signal is always obtained at the receiving end using the proposed method. It is demonstrated that the proposed method has high robustness against scattering, and the low quality of the retrieved signals, i.e., the finding described in Section 3.2, is mainly due to absorption through chicken

breast tissues rather than scattering when the blue laser with wavelength of 405.0 nm is used as illumination light source.

4. Conclusion

A new method using ZFM-based optical data encoding scheme has been proposed to realize accurate optical information transmission through thick tissues at low light intensities. Optical experiments have been conducted to verify the proposed method using different thicknesses of chicken breast tissues and the laser beam with different wavelengths. Experimental results demonstrate that the proposed method can realize accurate optical information transmission through thick biological tissues, and is able to overcome the existing challenges (i.e., small penetration depth and low transmission accuracy). It is illustrated that the proposed method can realize accurate optical information (i.e., analog signals rather than only binary signals) transmission through biological tissues with a thickness of 16.0 mm, when a low laser power of only 0.08 mW/cm^2 is used to illuminate the biological sample at wavelength of 658.0 nm. The proposed method provides a promising means for accurate optical information transmission through deep biological tissues.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was financially supported by Hong Kong Research Grants Council (15224921) and The Hong Kong Polytechnic University (1-W167, 1-W19E).

References

[1] Yuce MR. Implementation of wireless body area networks for healthcare systems. Sens. Actuators A Phys. 2010;162(1):116–29.
[2] Abbasi QH, Rehman MU, Qaraqe K, Alomainy A. Advances in body centric wireless communication: applications and state-of-the-art. London: IET; 2016.
[3] Mujeeb-U-Rahman M, et al. Optical power transfer and communication methods for wireless implantable sensing platforms. J Biomed Opt 2015;20(9):095012.
[4] Abou-Elnour A, Safi A, Alaalu A.N A reliable wireless monitoring network for healthcare applications. Health Monitoring of Structural and Biological Systems. In: Proc. of SPIE 7984. San Diego, California, United States: SPIE; 2011. p. 79841C-1. doi:10.1117/12.880997.
[5] Kiourti A, Nikita KS. A review of in-body biotelemetry devices: implantables, ingestibles, and injectables. IEEE Trans Biomed Eng 2017;64(7):1422–30.
[6] Camara C, Peris-Lopeza P, Tapiadora JE. Security and privacy issues in implantable medical devices: a comprehensive survey. J Biomed Inform 2015;55:272–89.
[7] Mucchi L, Jayousi S, Martinelli A, Caputo S, Marcocci P. An overview of security threats, solutions and challenges in WBANs for healthcare. In: Proc. 13th Int. Symp. Med. Inf. Commun. Technol. Oslo, Norway: IEEE; 2019. p. 1–6. doi:10.1109/ISMICT.2019.8743798.
[8] Bos T, Dehaene W, Verhelst M. Ultrasound in-body communication with OFDM through multipath realistic channels. In: Proc. IEEE Biomed. Circuits Syst. Conf. Nara, Japan: IEEE; 2019. p. 1–4. doi:10.1109/BIOCAS.2019.8918755.
[9] Mazzilli F, Peisino M, Mitouassiwou R, Cotté B, Thoppay P, Lafon C, Favre P, Meurville E, Dehollain C. In-vitro platform to study ultrasound as source for wireless energy transfer and communication for implanted medical devices. In: Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Buenos Aires, Argentina: IEEE; 2010. p. 3751–4. doi:10.1109/IEMBS.2010.5627541.
[10] Marquez G, et al. Anisotropy in the absorption and scattering spectra of chicken breast tissue. Appl Opt 1998;37(4):798–804.
[11] Taroni P, et al. In vivo absorption and scattering spectroscopy of biological tissues. Photochem Photobiol Sci 2003;2(2):124–9.
[12] Tajahuerce E, et al. Image transmission through dynamic scattering media by single-pixel photodetection. Opt Express 2014;22(14):16945–55.
[13] Dutta R, et al. Single-pixel imaging of the retina through scattering media. Biomed. Opt. Express 2019;10(8):4159–67.
[14] Xiao Y, Zhou L, Chen W. Experimental demonstration of ghost-imaging-based authentication in scattering media. Opt Express 2019;27(15):20558–66.
[15] Edgar MP, Gibson GM, Padgett MJ. Principles and prospects for single-pixel imaging. Nat Photonics 2019;13(1):13–20.
[16] Xiao Y, Zhou L, Chen W. High-fidelity ghost diffraction and transmission in free space through scattering media. Appl Phys Lett 2021;118(10):104001.
[17] Xiao Y, Chen W. High-fidelity optical transmission around the corner. IEEE Photon. Tech. Lett. 2021;33(1):3–6.
[18] Xiao Y, Zhou L, Chen W. Wavefront control through multi-layer scattering media using single-pixel detector for high-PSNR optical transmission. Opt Lasers Eng 2021;139:106453.
[19] Pan Z, Xiao Y, Zhou L, Cao Y, Yang M, Chen W. Non-line-of-sight optical information transmission through turbid water. Opt Express 2021;29(24):39498–510.
[20] Pan Z, Xiao Y, Cao Y, Zhou L, Chen W. Optical analog-signal transmission and retrieval through turbid water. Appl Opt 2021;60(34):10704–13.
[21] Jacques SL. Optical properties of biological tissues: a review. Phys Med Biol 2013;58(11):R37–61.
[22] Kim D-H. Fundamentals of propagation of light in tissue. Theory Appl. Heat Transf. Humans 2018;1:153–66.
[23] Key H, et al. Optical attenuation characteristics of breast tissues at visible and near-infrared wavelengths. Phys Med Biol 1991;36(5):579–90.
[24] Trevlakis S.E, Boulogeorgos A.A.A, Chatzidiamantis N.D Pathloss modeling for in-body optical wireless communications. 10th International Conference on Modern Circuits and Systems Technologies (MOCAST). Thessaloniki, Greece: IEEE; 2021. p. 1–6.
[25] Jin P, Fu J, Wang F, Zhang Y, Wang P, Liu X, et al. A flexible, stretchable system for simultaneous acoustic energy transfer and communication. Sci Adv 2021;7:eabg2507.
[26] Tuchin VV. Tissue optics: light scattering methods and instruments for medical diagnostics. 2nd ed. Bellingham, WA: SPIE Press; 2009.
[27] Senjuti H. Measurements and characterization of optical wireless communications through biological tissues. University of Oulu; 2020. Master Thesis.
[28] Welch AJ, van Gemert MJC. Optical-Thermal response of laser-irradiated tissue. New York: Plenum Press; 1995.
[29] Ripoll J, Yessayan D, Zacharakis G, Ntziachristos V. Experimental determination of photon propagation in highly absorbing and scattering media. J Opt Soc Am A 2005;22(3):546–51.
[30] Nolte DD. Optical interferometry for biology and medicine. New York: Springer; 2012.