The measurement of optical properties of a multiple scattering medium based on diffused photon pair density wave

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ABSTRACT

A photon pair density wave (PPDW) is initiated and compared with the conventional defused photon density wave (DPDW) to verify its optical properties generated by correlated parallel polarized pair photons propagating in a scattering medium. An optical heterodyne signal is generated by the scattered correlated pair photons in the scattering medium. However, the phase delay of the signal depends upon the beat frequency and the distance between source and detector. This is similar to DPDW at the lower modulated frequency of laser source in frequency domain. Spherical wave fronts of constant attenuated intensity and the phase delay of PPDW are observed in a homogenous scattering medium by using a lock-in amplifier. The assumption that polarized photon pairs propagating as photon density wave in a multiple scattering medium is verified experimentally. Optical properties of PPDW in the scattering medium are demonstrated successfully.

Keywords: photon density wave, polarization, optical heterodyne, diffusion equation

1. INTRODUCTION

Conventionally, to image an object in a scattering medium is mainly based on measurements of absorption coefficient such as the x-ray imaging using Beer-Lambert law.(1) Such measurements result in a blurred image in a highly scattering medium where scattering effect is determined by a scattering coefficient. It is absorbed into an effective absorption coefficient in order to fit Beer-Lambert law. Therefore, the optical properties of the scattering medium can not be identified quantitatively.(2) In contrast, a diffused photon density wave (DPDW), which satisfies diffusion equation, provides the phase and the amplitude information of DPDW propagating in a multiple scattering medium. Then the absorption coefficient and the scattering coefficient of the medium can be determined quantitatively at the same time.(3, 4) Recently, an intensity-modulated laser beam being used to generate DPDW in the scattering medium has been widely studied. A DPDW-based imaging system was successfully demonstrated in clinical applications,(5) where the absorption and the scattering coefficients of the scattering medium can be determined in terms of the attenuated intensity of the modulated laser beam and the phase delay of DPDW. Therefore, the scatter and the absorber in a homogeneous multiple scattering medium can be imaged by scanning the scattering object in 2-dimension. This results in the imaging ability of DPDW in the scattering medium.(1)

In this paper, a diffused photon pair density wave (PPDW) is introduced and compared with DPDW on their optical properties in a scattering medium. Theoretically, PPDW emphasizes coherence properties of photon pairs propagating in a scattering medium, which retrieves the information of phase and amplitude based on optical heterodyne interferometry.(6,7) In contrast, laser intensity modulation technique of DPDW in frequency domain is able to retrieve the information of phase and amplitude by photometric means.(3, 4) In this study, the attenuated intensity and the phase delay of the optical heterodyne signal versus the distance between source and detector are measured at different concentrations of the scattering medium. Through the experiment, the assumption that photon pairs propagating in a multiple scattering medium behave like a photon density wave which satisfies diffusion equation is verified. In the meantime, the scattering and the absorption coefficients of the scattering medium are successfully calculated in terms of the phase delay and the attenuated intensity of the optical heterodyne signal.

2. THEORY OF PPDW

A Zeeman laser outputs a pair of correlated linear polarized light waves which are P and S waves of different temporal frequencies (ω_1, ω_2), respectively. When both P and S waves pass a polarizer, they convert into a pair of parallel polarized photons. When these correlated linear polarized photon pairs propagate in a multiple scattering medium are detected and heterodyned by a photodetector. The degree of spatial coherence and the degree of polarized pair photons are degraded due to multiple scattering. Then the output voltage, which is filtered by a band pass filter whose central frequency is at $\Delta\omega$, becomes

$$V_{ac}(\Delta\omega t) = A_p A_s \gamma \sin 2\theta \cos(\Delta\omega t + \Delta\Phi) \quad \text{.......................................} (1)$$

(A_p, A_s) means the amplitude of P and S polarized light waves. $\Delta\omega = \omega_1 - \omega_2$ is the beat frequency of pair photons[6,7]. $\Delta\Phi$ is the phase difference between parallel polarized pair photons propagating in the multiple scattering medium. In addition, γ means the optical heterodyne efficiency which is characterized by $J_0(\alpha)$ of Bessel function of the first kind. α is the misaligned angle between two correlated polarized photons.(8) In a multiple scattering medium, the photon pairs as a whole are scattered into a distributed angle in the medium; therefore, the photon pairs which are scattered in a larger scattering angle induce lower heterodyne efficiency γ of the heterodyne signal. This is caused by the degradation of spatial coherence of pair photons.[8] To assume that the polarized pair photons propagating in a homogenous multiple scattering medium is a photon density wave which satisfies diffusion equation,[3,4] then the time dependent harmonic wave function $\tilde{\varphi}_j(r,t)$ of *j*th polarized photon of photon pair in a multiple scattering medium can be described by

$$\tilde{\varphi}_j(r,t) = \beta\left(\frac{e^{-k_r^j r}}{r}\right)^{1/2} e^{i(k_i^j r - \omega_j t)} \quad (\mathrm{j} = 1.2) \text{...} (2)$$

ω_j means the angular frequency of *j*th polarized photon. (k_r^j, k_i^j) is defined as the real and imaginary parts of the complex angular wave number of the time dependent harmonic wave of *j*th polarized photon. r is the distance between the source and the detector in the scattering medium. Therefore, the output intensity of the optical heterodyne signal of scattered polarized photon pairs becomes

$$\begin{aligned} I(\Delta\omega t) &= \left|\tilde{\varphi}_1(r,t) + \tilde{\varphi}_2(r,t)\right|^2 \\ &= \beta^2 \frac{e^{-k_{2r} r}}{r} \cos(\Delta\omega t - \Delta\Phi) \\ &= \beta^2 \frac{e^{-k_{2r} r}}{r} \mathrm{Re}\left\{e^{i(\Delta\omega t - \Delta\Phi)}\right\} \text{...} (3) \end{aligned}$$

where $\Delta\omega$ is the beat frequency of pair photons. β^2 is the radiant energy fluence rate of PPDW. And

$$\Delta\Phi = (k_i^1(\omega_1) - k_i^2(\omega_2)) \cdot r \text{...} (4)$$

$\Delta\Phi$ is the phase delay between pair photons propagation in the scattering medium. Then Eq. (3) represents the PPDW which satisfies the diffusion equation. In order to confirm the similarity between PPDW and the CW light wave propagating in a multiple scattering medium, a linear polarized single frequency laser replaces the Zeeman laser so that the conditions of $\omega_1 = \omega_2$, $k_i^1 = k_i^2$, and $k_r^1 = k_r^2 = k_r$ are satisfied simultaneously. Therefore, the output intensity from Eq. (3) of the CW light wave in a scattering medium becomes $I_s = \beta^2\left(\frac{e^{-k_r r}}{r}\right)$. This is identical to the DC part of diffused photon density wave of the diffusion equation.[4] In the mean time,

$$k_r^1 \cong k_r^2 = k_{2r} = (3\mu_{2a}(\mu'_{2s} + \mu_{2a}))^{1/2} \text{...} (5)$$

where k_{2r} is defined as the real part of complex wave number of PPDW due to the reason that PPDW propagating in the scattering medium behaves like a continuous wave.[3,4] Therefore, the attenuation of the measured intensity of the optical heterodyne signal from Eq. (3) becomes

$$\ln\left(\frac{I}{I}\right) = \left[\ln\left(\frac{r_0}{r}\right) - k_{2r}\Delta r\right] \text{...} (6)$$

where I_0 and I are the detected intensities with respect to different distances r_0 and r from the detector to the source, respectively. Then

$$k_{2r} = \frac{-1}{\Delta r}\left[\ln\left(\frac{I}{I_0}\right) - \ln\left(\frac{r_0}{r}\right)\right] \quad (7)$$

where $\Delta r = r - r_0$ means the distance of the detector translated in the measurement.

According to Eq. (4), $\Delta\Phi$ is defined as the phase delay between pair photons propagating in the scattering medium. This is because two parallel polarized pair photons behave similarly and propagate in a common path in the scattering medium; therefore, the distance r in Eq (4) is required to be changed to an average photon path length $\tilde{r}$ of the scattered photon pairs in the multiple scattering medium.[9,10] Then Eq (4) becomes

$$\Delta\Phi \cong (k_i^1(\omega_1) - k_i^2(\omega_2)) \cdot \tilde{r}$$

$$= \frac{n\Delta\omega}{c}\left(\frac{3\mu_{2s}^{'}}{4\mu_{2a}}\right)^{1/2} \cdot r$$

$$= k_{2i} \cdot r \quad (8)$$

and

$$\tilde{r} = \left(\frac{3\mu_{2s}^{'}}{4\mu_{2a}}\right)^{1/2} r \quad (9)$$

k_{2i} is defined as the imaginary part of the complex wave number of PPDW.

$$k_{2i} = \frac{n\Delta\omega}{c}\left(\frac{3\mu_{2s}'}{4\mu_{2a}}\right)^{1/2} \quad (10)$$

Thus, the phase velocity of PPDW is

$$V_{pp} = \frac{\Delta\omega}{k_{2i}} = \frac{c}{n}\left(\frac{4\mu_{2a}}{3\mu_{2s}'}\right)^{1/2} \quad (11)$$

This means the phase velocity of PPDW in a multiple scattering medium is constant. This is the same as DPDW at lower modulation frequency.[4] Therefore, Eq. (3) is the mathematical representation of PPDW which satisfies the diffusion equation.[4] The complex wave number of PPDW in a multiple scattering medium is defined as (k_{2r} , k_{2i}). Then the beat frequency of PPDW is indeed equivalent to the modulation frequency of DPDW.[4] In fact, the increase of the reduced scattering coefficient enlarges the average photon pair propagation length and the phase delay of PPDW according to Eqs. (8) and (9) where n is the refractive index of the scattering medium, and c is the speed of light in vacuum. In contrast, the decrease of the absorption coefficient reduces the average photon pair propagation length and the phase delay of PPDW.

From Eqs. (5) and (10), μ_{2a} and μ_{2s}' can be represented in terms of k_{2r} and k_{2i} by

$$\mu'_{2s} = \frac{2ck_{2r}k_{2i}}{3n\Delta\omega} \qquad (12)$$

and

$$\mu_{2a} = \frac{n\Delta\omega}{2c}\left(\frac{k_{2r}}{k_{2i}}\right) \qquad (13)$$

Therefore, in a multiple scattering medium, μ_{2a} and μ'_{2s} can be obtained simultaneously by measuring the phase delay and the attenuated intensity of the optical heterodyne signal with a lock-in amplifier.

From the theory derived above, the optical properties of PPDW in a multiple scattering medium, where $\mu'_{2s} >> \mu_{2a}$, is studied. k_{2r} is independent of the beat frequency of pair photons while k_{2i} is linearly dependent of the beat frequency at the same time. This is similar to the optical properties of DPDW in a multiple scattering medium where the modulation frequency of the laser source is at lower frequency.[(4)] Therefore, PPDW is indeed a photon density wave which satisfies the diffusion equation in a multiple scattering medium.

3. THE EXPERIMENTAL SETUP AND RESULTS

The optical setup of this experiment is shown in Fig. 1 where a Zeeman laser (HP 5519A, Santa Clara CA) outputs two orthogonal laser polarized light waves, p wave and s wave, with different temporal frequencies at ω_1 and ω_2, respectively. The output power of this Zeeman laser is 0.245 mw. And the wavelength is 632.8nm. In this experimental setup, a Glan-Thompson polarizer (GTP) of which the azimuth angle is set at 45^o to x-axis is used. GTP is able to project both p and s waves onto its polarization direction and generate two parallel linear polarized light waves of different temporal frequencies. An objective (20X) focuses the laser beam onto a plastic fiber (Mitzubishi Ryan, Japan) that guides the laser beam into a scattering medium. In the mean time, another identical plastic fiber, which is paralleled to the source fiber at a lateral distance away, is deployed in order to collect the scattering photons. Both fibers are 120 cm long and 1000 μm in diameter. The elliptical polarization of the laser beam is ignored in this setup. Among the scattering photons, only correlated polarized photon pairs are able to generate an optical heterodyne signal by making use of a photomultiplier tube (PMT) (Oriel 77348, Stratford CT). There are three Zeeman lasers used in this setup. The beat frequencies of the heterodyne signals are 1.801MHz, 2.611MHz and 20MHz, respectively. The signal is then amplified by a linear amplifier and filtered by a band pass filter. During the measurement, the distance between the source fiber and the detector fiber is scanned within a range from 24mm to 54mm in order to satisfy the requirement of diffusion approximation.[(3)] A beam splitter (BS) divides the laser beam into a reference beam and a signal beam. The reference beam is focused by a lens onto photodetector D_r to generate a reference heterodyne signal of the same carrier frequency. Then the output intensity and the phase delay of the heterodyne signal versus distance are measured with a lock-in amplifier (SR844, Stanford CA). Therefore, μ_{2a} and μ'_{2s} are able to be obtained in terms of the measured phase delay and the output intensity of the heterodyne signal according to Eqs (11) and (12). All the scattering measurements are conducted in a 20x20x10 (cm^3) tank filled with 3.6 liters of an emulsified Intralipid solution (Fresenius Kabi AB, Sweden). Two plastic fibers are positioned at the center of the tank and are located below the liquid level by 4 cm. Therefore, we can treat the medium as an infinite scattering medium. There are two kinds of absorber (Methyl-Blue and Black ink) added into the intralipid solution in order to determine μ_{2a} of the scattering medium versus absorber concentrations. Besides, by varying the concentrations of intralipid solution, μ'_{2s} of the scattering medium versus scatter concentrations can be determined as well.

In this setup, a band pass filter that filters out background noise and DC bias of the intensity enhances the SNR of the heterodyne signal. Figure 2 shows the contours of constant amplitude and constant phase of PPDW in a homogeneous intralipid-20% solution at 7.5% volume concentration. The light source of this measurement is a Zeeman laser at 1.801MHz of beat frequency. Those contours indicate that PPDW propagates in a homogenous scattering medium in a 3-dimensional spherical wave front which is similar to the conventional DPDW propagating in a turbid medium. In addition, the experimental results of Fig. 5 show the linear dependence of the attenuated intensity (logarithm scale) and the phase delay versus source/detector distance r at different vol. % (7.5% and 14%) of intralipid-20% solutions, respectively. In order to assure that the detected photons are diffused photons in this setup, the distance r>24mm is required; otherwise, the ballistic photons which are non-scattering photons are detected by PMT in the measurement.

According to Eqs. (5), (6) and (8), the increasing of the concentration of intralipid implies that μ'_{2s} becomes larger and the intensity is attenuated faster. In the meantime, the phase delay is enlarged, too. These results are observed in the experiment shown in Fig. 5. In contrast, when a 5 $\mu\ell$ black ink as the absorber is mixed into intralipid-20% solution at 14% volume concentrations. The experimental results (shown in Fig. 4) present the attenuated intensity and the phase delay to distance r. The deviations of the attenuated intensity and the phase delay with and without the absorber are clearly observed. When the scattering medium is mixed with the absorber, the average photon path from source to detector becomes shorter according to Eq. (9). This indicates that the photon pairs propagate in a longer photon path are absorbed by the absorber. Then the phase delay becomes smaller. Meanwhile, the absorption of the photon pairs results in further attenuation of output intensity. The experimental results in Fig. 4 show the correctness of the theory. In addition, the attenuation of the intensity, which is independent of the beat frequency $\Delta\omega$ according to Eq (5), is observed and shown in Fig. 5(a) at $\Delta\omega = 1.8$ MHz and 20 MHz, respectively. In contrast, the dependence of the phase delay on $\Delta\omega$ is shown in Fig. 5(b). In this experiment, a Zygo Axiom 2/20 laser ($\Delta\omega \cong$20MHz) is used in the measurement. To compare these experimental results shown in Figs. 2-5 with Eqs. (6) and (8), PPDW belonging to a photon density wave is then verified.

All the above experiments emphasize r dependence of the attenuation intensity and phase delay of the heterodyne signal of PPDW in the Intralipid solution. It is important to calculate μ_{2a} and μ'_{2s} in terms of the above two measurements of optical heterodyne signal at different r. Figure 6 presents the experimental results of μ_{2a} and μ'_{2s} in cm^{-1} at different volume concentrations of Intralipid-10% solution by adopting $\Delta\omega$=1.8MHz Zeeman laser. The linear relationship between μ'_{2s} versus concentration is shown in Fig. 6 where μ_{2a} remains unchanged because the scattering effect is dominated in this experiment. Furthermore, $\delta(\mu'_{2s}) \approx 0.1cm^{-1}$ is able to be detected according Eq.(8) using Zygo Axiom 2/20 laser. μ_{2a} and μ'_{2s} are determined by averaging values taken at five different fiber distances within $28 \le r \le 53$ (mm). $5\,\mu\ell$ black ink mixed with intralipid -10% solution enlarges the absorption coefficient of the scattering medium significantly; however, the scattering coefficient remain the same. Table 1 gives the data of μ_{2a} and μ'_{2s} of PPDW in response to different concentrations. Similar results are obtained at different concentrations of the Intralipid solution based on DPDW.(4)

In addition to the above experiment, an experiment of mixing Methy Blue (MB) into a 14% Intralipid-10% solution as an absorber is done as well, in which μ_{2a} is proportional to the concentration of MB while μ'_{2s} remains unchanged in the measurement (as shown in Fig. 7). The same response is also observed by mixing $TPPS_4$ absorber in the Intralipid solution based on DPDW.(4) As a result, the linear dependence of Fig. 7 indicates that a small variation of μ_{2a}, $\delta(\mu_{2a}) \cong 0.00027cm^{-1}$, is can still be determined in the presence of a substantial scattering medium. In consequence, PPDW is able to determine μ_{2a} and μ'_{2s} of a multiple scattering medium successfully.

4. DISCUSSION AND CONCLUSION

In this paper, a novel photon pair density wave in a multiple scattering medium is proposed. It is based on correlated polarized pair photons propagating in a multiple scattering medium where an optical heterodyne signal is detected. The attenuated intensity and the phase delay of the optical heterodyne signal are measured in real time so that the optical properties of the scattering medium can be determined. In addition, PPDW which satisfies diffusion equation is verified experimentally. The complex wave number of PPDW is defined and the phase velocity of PPDW is analyzed. Besides, the beat frequency of PPDW is equivalent to the modulation frequency of laser intensity of DPDW in frequency domain. The intensity of PPDW is attenuated following CW light wave in the multiple scattering medium, that the attenuated intensity is beat frequency independent. This result is similar to DPDW when modulation frequency is at lower frequency. In contrast, the phase delay of PPDW is linearly dependent of the beat frequency of heterodyne signal. This is similar to DPDW at lower frequency, too.

PPDW bases on interferometric technique while DPDW belongs to photometric technique. Therefore, the sensitivity on amplitude and phase measurements of output signals of these two methods is different. PPDW depends on coherence properties of pair photons in the medium so that the degree of spatial coherence and degree of polarization are sensitive to the scattering. Thereby, the scattered photon pairs at a larger scattering angle or a longer photon pair propagation length reduce the heterodyne efficiency of the optical heterodyne signal. This implies that a smaller scattering angle or a shorter photon path of scattered polarized photon pairs is detected in order to generate the optical heterodyne signal of PPDW. In this study, PPDW which satisfies the diffusion equation is verified experimentally. However, the attenuation of the intensity is similar to CW light wave where the real part of complex wave number of PPDW is independent of the beat frequency of pair photons. In contrast, the imaginary part of the wave number is linearly dependent of the beat frequency at the same time. In fact, higher beat frequency of photon pairs can be generated by using an electro-optic modulator[11] in this setup. the optical properties of PPDW is then expected to remain the same result. Therefore, PPDW behaves similarly to DPDW only at lower modulation frequency of the laser source. Moreover, the $e^{-k_2 r}/r$ dependence on the intensity attenuation of PPDW is analyzed. Figures 8 shows the linear relationship of ln(rI) versus r in a range of $28 \le r \le 48$ that Eq. (6) is satisfied at different beat frequencies ($\Delta\omega$=2.6MHz and 20MHz). On the other hand, the phase delay of PPDW is similar to DPDW, and the average photon pair propagating length of PPDW in scattering medium is proportional to $\left(\frac{\mu'_{2s}}{\mu_{2a}}\right)^{1/2}$ as well.

In conclusion, photon pairs' feature as a photon density wave is verified experimentally. The optical properties of PPDW in a multiple scattering medium are similar to DPDW based on the attenuation of the intensity and the phase delay of the optical heterodyne signal of PPDW. A three-dimensional contour of the constant attenuated intensity and the phase delay of PPDW has been verified by experiments as well.

Since high beat frequency of photon pairs is obtainable in different methods, PPDW can be compared with DPDW in a range of higher modulation frequency. From the above theory, attenuated intensity of PPDW is beat frequency independent; therefore, unlike DPDW that requires higher modulation frequency, PPDW is easier to be setup. However, the sensitivity of measurements on phase delay, which is beat frequency dependent, is maximized by optimizing the beat frequency of photon pairs that is dependent on the optical properties of the multiple scattering medium. Hence, PPDW provides not only simple configuration of experimental setup with lower beat frequency of photon pairs but also higher detection sensitivity on μ_{2a} and μ'_{2s} of the scattering medium according to the experiments. Except verifying that photon pairs propagate as a photon density wave in a multiple scattering medium, the diffraction and the interference phenomena will be further studied in the near future. The capability of using PPDW to image the absorber and the scatter in a multiple scattering medium will be evaluated in subsequent research.

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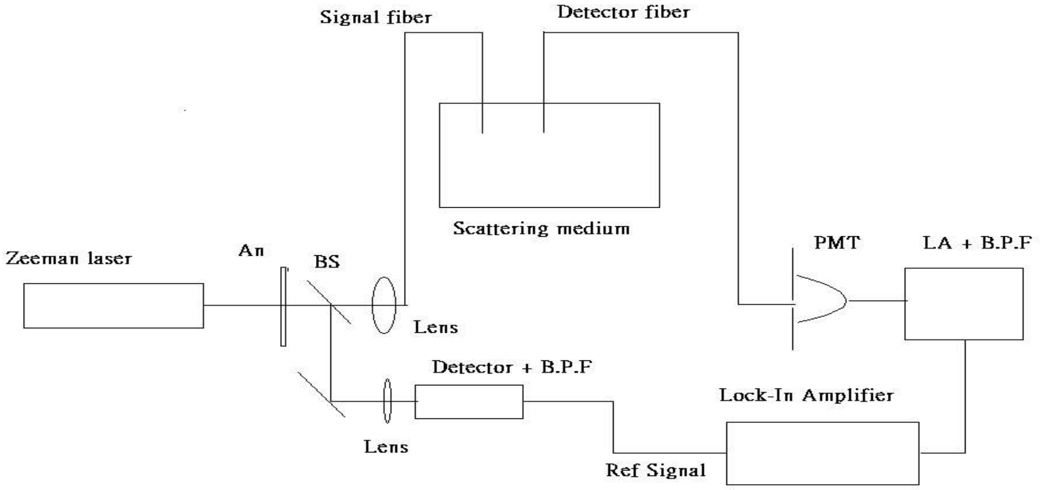
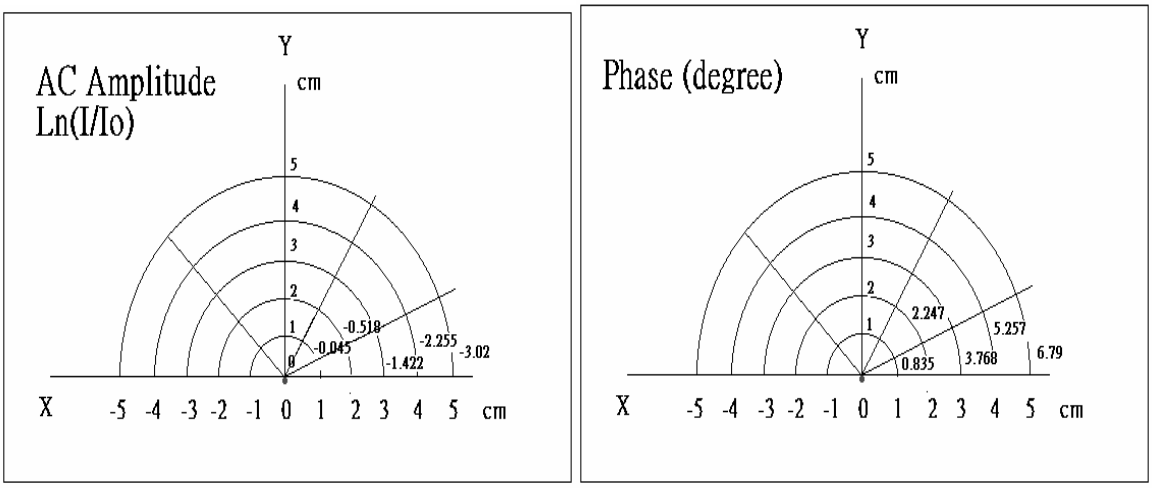


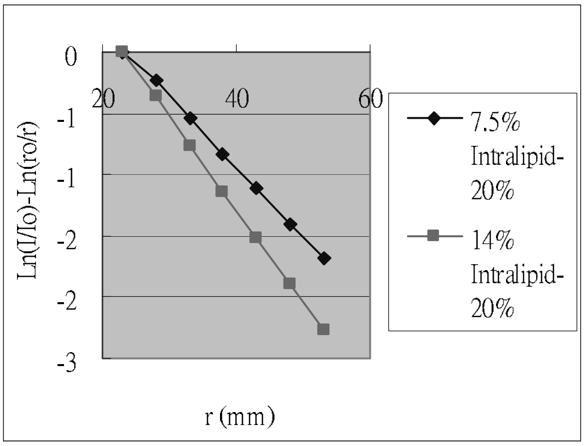
Fig. 1

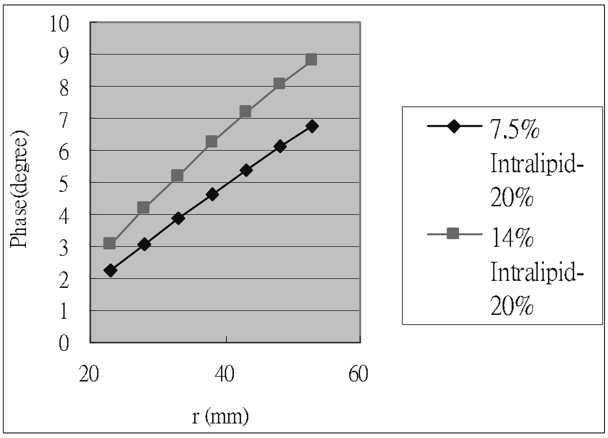
The optical setup



(a) Fig. 2 (b)

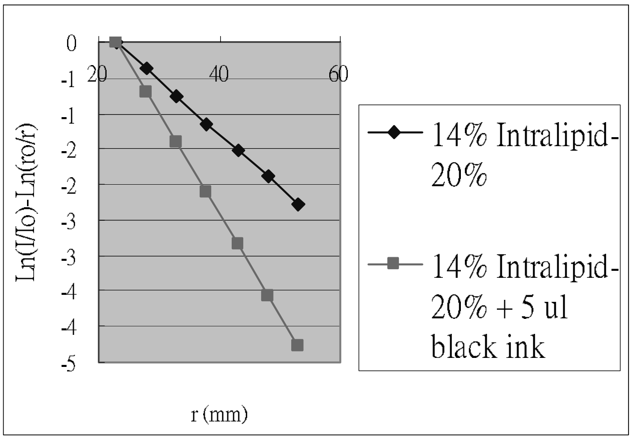
The spherical wavefront of attenuated intensity (a) and phase delay (b) of PPDW

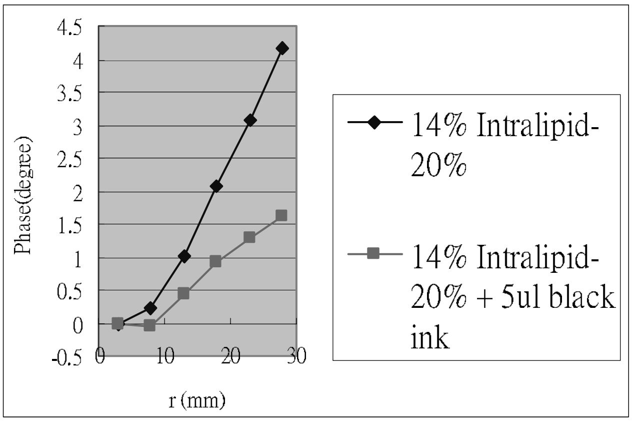




(a) Fig. 3 (b)

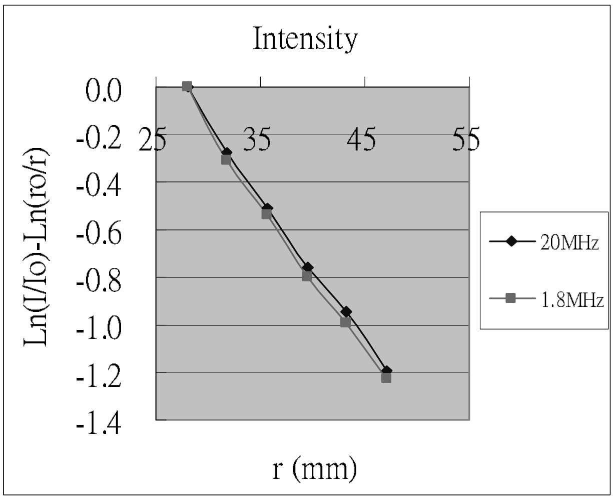
The linear dependence of attenuated intensity (a) and phase delay (b) of PPDW versus r in different concentrations of intralipid solutions.

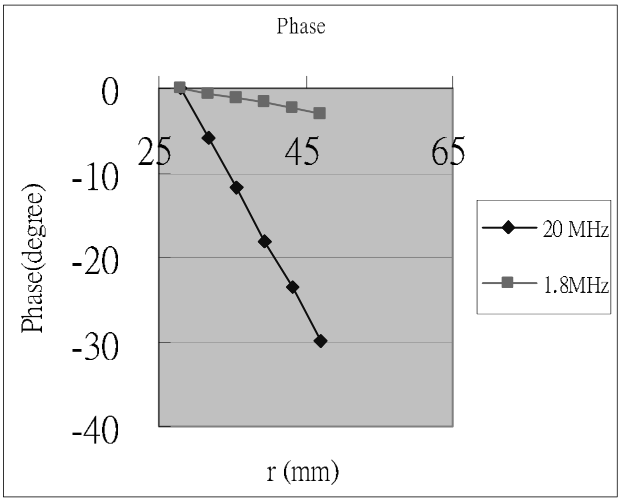




(a) Fig. 4 (b)

The linear dependence of attenuated intensity (a) and phase delay (b) of PPDW versus r in intralipid solution where black ink is mixed into the solution.





(a) Fig. 5 (b)

The linear dependence of attenuated intensity (a) and phase delay (b) versus r of intralipid solution with different beat frequency.

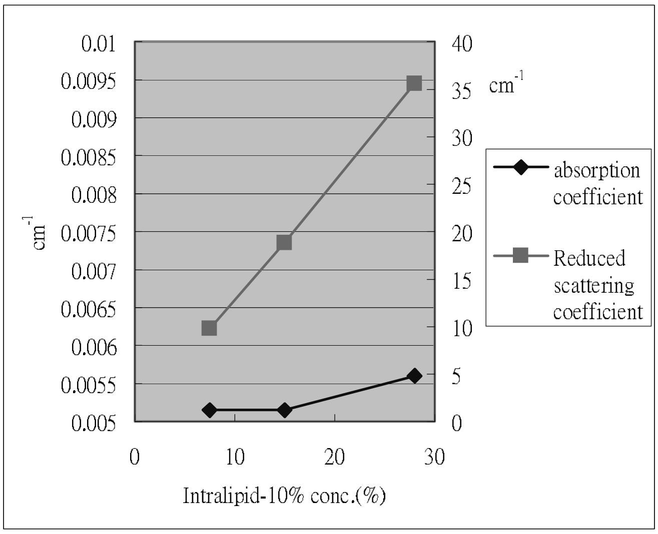


Fig. 6

The linear dependence of reduced scattering coefficient on different concentration of intralipid solution.

Table 1

Intralipid-10%(%)	μa(cm-1)	μs'(cm-1)
7.5	0.005152	9.81
15	0.00516	18.86
28	0.0056	35.61
28 (+ 5ul ink)	0.0291	35.63

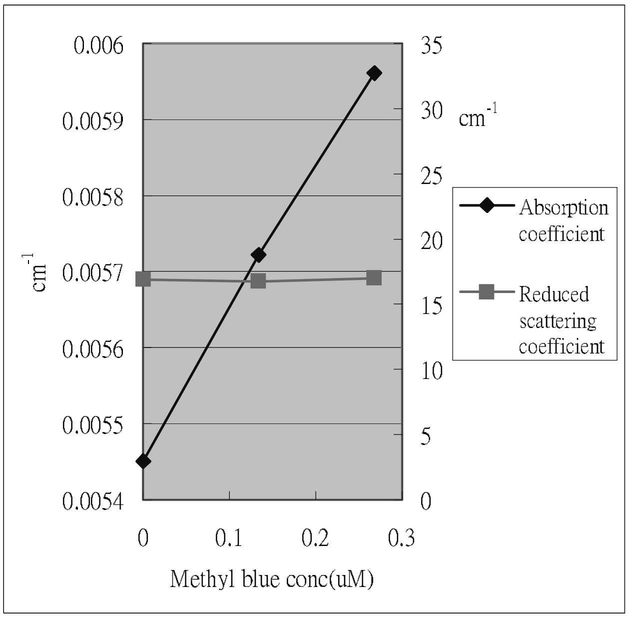


Fig. 7

The linear dependence of absorption coefficient on different concentration of MB in intralipid solution.

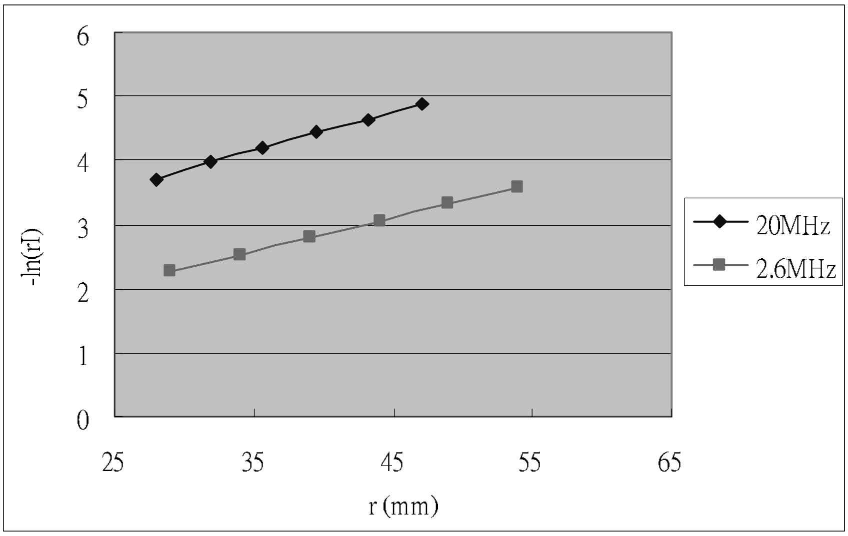


Fig. 8:

The linear dependence of ln(rI) of attenuated intensity of PPDW versus r at different beat frequency. This result verifies that the intensity of PPDW is $[\exp(-k_{2r}r)]/r$ dependent.