Low-Frequency Noise Reduction in Dual-Fiber Optical Trap Using Normalized Differential Signal of Transmission Lights

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Abstract: The accuracy of long-term position detection in dual-fiber optical trap is limited by low-frequency noise. We propose a technique that can reduce such noise. A position detection system for dual-fiber optical trap using a quadrant photodiode is built. The transmission light from the trapped particle is detected by two photodiodes. The normalized differential signal of transmission lights is demonstrated to carry the noise caused by asymmetric laser power fluctuation irradiating the microsphere, which is proved to dominate low-frequency noise. By subtracting this normalized difference from the position signal, the noise-reduction capability of this technique is remarkably 67% depending on detection bandwidth. It is expected to be applied to integrated and microfluidic fiber-optic trap system.

Index Terms: Dual-fiber optical trap, optical manipulation, optical instruments, noise reduction.

1. Introduction
Optical trap is based on the force of radiation pressure. The first optical tweezer (OT) was reported by Ashkin who utilized a high numerical aperture objective to focus laser beams to a microsphere [1]. In the past two decades, highly integrated dual-fiber optical trap (DFOT) system became increasingly popular due to the features of low required laser power, easy for lab-on-chip integrations, and so on [2]–[5]. These experimental methods have played a remarkable role in areas of biological sciences [6]–[10], and physical sciences [11]–[14]. Accurate position detection contributes significantly to the understanding of particles of interest. Theoretically, the position detection accuracy of optical trap is limited by Brownian thermal motion of the particles [15]. However, for long-term measurement (detection time above seconds, even minutes), low-frequency noise is generally critical in frequency region lower than approximately 1 hertz. Mechanical vibrations, thermal noise, laser power instabilities give rise to various kinds of noise and drifts that are the dominating noise in low-frequency region [16]–[18]. High pass filters are not good choices as they will suppress the detected signal in low-frequency ranges as well. It’s desirable to explore techniques to reduce low-frequency noise of optical traps.
There have been several reports on noise reduction for optical tweezers. M. Klein et al. presented a dual-trap technique for low-frequency noise reduction through subtracting noise from a well correlated reference bead [19]. A. R. Carter et al. achieved drift compensation in research of DNA basepair by subtracting the motion of a marker [20]. Y. Seol et al. realized suppressing intrinsic noise in bead position by adding fluctuation in the trap position [21]. These noise reduction methods significantly enhanced the detection accuracy for OT. However, little similar research for DFOT has been reported. Apart from methods above, it is also desirable to explore a noise reduction technique for DFOT system.

In this paper, a novel technique is proposed for noise reduction for DFOT system. The normalized differential signal of transmission lights is demonstrated to carry the dominating low-frequency noise. A subtraction of low-frequency components of reference noise from position signal is expected to yield a corrected signal that is less influenced by low-frequency noise. It is found that this noise-reduction technique removes the major component of low-frequency noise without significant impact on the detected signal. Moreover, the detection bandwidth is not affected.

2. Experimental Setup and Principles

2.1 Experimental Setup

The optical layout for the experiment is illustrated in Fig. 1. The optical trapping device is made up of a polydimethylsiloxane chip, housing two axial aligned single-mode fibers across a microcavity. The fiber end faces have been coated films to enhance the transmittance. Each fiber is coupled with separated laser source (1550 nm, TOP photonics) to avoid the generation of coherent interference. The distance between two fiber ends is 200 μm and the laser powers emitted from two fibers are both 100 mW. A polystyrene microsphere is trapped by optical force in the microcavity. The radius of the microsphere is 5 μm, and the refractive index is 1.59. The transmitted light from the microsphere is coupled to the 90/10 fiber coupler and then monitored by two photodiode detectors (PDA-50B, Thorlabs). A condenser is assembled perpendicular to the propagating beam to collect the side-scattered light from the captured microsphere. A quadrant photodiode detector (PDQ-30C, Thorlabs) is then placed in the back focal plane of the condenser to probe the axial displacement of microsphere [22]. In calibrating procedure, another laser (980 nm, XMT) is coupled into the chip to move the microsphere. The quadrant photodiode detector (QPD) is calibrated by using the CCD camera to record the position change that caused by this laser. The band-pass filter (FB1550-12, Thorlabs) is inserted to prevent the irrelative light from entering detectors. Data sets from quadrant...
photodiode detector (QPD) and photodiode detector (PD) are sampled by a multichannel acquisition card.

2.2 Principles

In most cases, the trapping laser experience numbers of optical devices before acting on the microsphere [12], [17]. The resultant force exerted on the microparticle is not always null, due to the power instability of the laser sources and all kinds of noises of separated light paths. The time-dependent optical forces would undulate the microsphere and produce noise. It’s expected to be the dominating source of noise in DFOT. We used the transmission light from the microsphere to monitor such noise. The light paths of the experiment are analyzed in Fig. 2. The signals in PDs are transmission light from the trapped microsphere. The reflection on the trapped microsphere can be ignored according to Mie scattering theory [23]. The trapping powers irradiating the microsphere can be expressed as

\[ P_1 = P_0 + \delta P_1 \] \[ P_2 = P_0 + \delta P_2, \]

where \( \delta P_1 \) and \( \delta P_2 \) are laser power noise from two separated light paths and laser sources. The signals in PDs can be expressed as:

\[ P_{PD1} = P_0 T_0 + P_0 \delta T_1 + \delta P_1 T_0 + \delta P_1 \delta T_1 \]
\[ P_{PD2} = P_0 T_0 + P_0 \delta T_2 + \delta P_2 T_0 + \delta P_2 \delta T_2. \] (1)

where \( T_0 \) is the coupling efficiency, \( \delta T_1 \) and \( \delta T_2 \) are the coupling efficiency change that caused by the position change of the microsphere. \( \delta P_1 \) and \( \delta P_2 \) can be ignored as they are much smaller than others.

The power fluctuation of transmission light that caused by position change \( (P_0 \delta T_1 \) and \( P_0 \delta T_2) \) can be analyzed by the geometrical optics theory [25]. The captured microsphere can be treated as a spherical thin lens. The emitting laser illuminates the microsphere and the transmitted light beams then couple into the opposite fiber through the fiber end. The coupling efficiency is depended on the position of the microsphere. When the microsphere fluctuates within a finite region, the coupling efficiency fluctuation of both transmission lights that caused by position change \( (P_0 \delta T_1 \) and \( P_0 \delta T_2) \) are always small and nearly identical. By subtracting normalized power of two transmission lights, \( \delta P_1 T_0 \) and \( \delta P_2 T_0 \) are extracted while \( P_0 \delta T_1 \) and \( P_0 \delta T_2 \) are counteracted. Thus, the normalized differential data of two PDs can be used to monitor the asymmetric trapping power fluctuation \( \delta P_1 \) and \( \delta P_2 \).

The position noise \( (N = (s_1 - s_2)/2) \) that caused by \( \delta P_1 \) and \( \delta P_2 \) can be quantified by detecting normalized difference of two PDs. It can be calculated as follows. When the power changes, the microsphere will be held at a new equilibrium position. The axial optical forces of two counter-propagating beams can be expressed as:

\[ F_1 = Q(s_1)P_1 \]
\[ F_2 = Q(s_2)P_2. \] (2)
where \( Q(s_1) \) and \( Q(s_2) \) are the trapping efficiency factors, \( F_1 \) and \( F_2 \) are forces of radiation pressure, \( s_1 \) and \( s_2 \) are distances between microsphere and two fiber ends. The microsphere is trapped in center \( (F_1 = F_2) \). The microsphere always fluctuates within a finite region. The trapping efficiency factor is proportional to the offset from trap position \([24]\). Thus obtaining:

\[
\frac{Q(s_2)}{Q(s_1)} = \frac{s_1}{s_2} = \frac{P_0 + \delta P_1}{P_0 + \delta P_2},
\]

The distance between two fiber ends is \( L = s_1 + s_2 \). According to (3), for a long-term detection, the position noise \( (N = (s_1 - s_2)/2) \) that caused by \( \delta P_1 \) and \( \delta P_2 \) can be quantified as:

\[
(s_1 - s_2)/2 = \frac{L}{4} \left( \frac{\delta P_1}{P_0} - \frac{\delta P_2}{P_0} \right).
\]

### 2.3 Details for Data Processing

To eliminate the internal difference of two PDs, we use the normalized differential data \( \delta RF = (S_{PD1} - S_{PD1})/S_{PD1} - (S_{PD2} - S_{PD2})/S_{PD2} \) to monitor the asymmetric laser power fluctuation \( (\delta P_1/P_0 - \delta P_2/P_0) \). Where \( S_{PD1} \) and \( S_{PD2} \) are data sets from two separated PDs. \( S_{PD1} \) and \( S_{PD2} \) are the mean values of \( S_{PD1} \) and \( S_{PD2} \), respectively. The zero-mean data \( \delta RF \) is converted to reference position noise \( \delta n_{ref} \) according to (4). The reference noise is then filtered with a low-pass digital filter to extract the low-frequency component \( \delta n_{ref}^* \). All frequency components above the cutoff frequency \( f_c \) are removed from \( \delta n_{ref}^* \), since the high-frequency components are expected to contain less amount of signal that is correlated to noise of position signal \( s_{QPD} \). The Pearson’s linear correlation coefficient function is applied to analyze the correlation between \( \delta n_{ref}^* \) and \( s_{QPD} \) \([26]\). The optimum cutoff frequency \( f_c^{opt} \) is selected correspond to the peak correlation coefficient. The well correlated data \( \delta n_{ref}^* \) is then subtracted from the position signal to produce corrected signal that is less influenced by low-frequency noise.

### 3. Results

#### 3.1 Correlation Between QPD Signal and Reference Noise

For the idealized case, the detection accuracy of optical trap is limited by Brownian thermal motion of the particles \([15]\). The power spectrum of the thermal motion can be expressed as:

\[
S(f) = \frac{k_B T}{\gamma^2 f_d^2 (f_d^2 + f^2)},
\]

where \( k_B \) is the Boltzmann’s constant; \( T \) is the absolute temperature; \( \gamma \) is the hydrodynamic drag coefficient; \( f_d \) is the corner frequency of the power spectrum of the Brownian motion given by \( \kappa/2\pi\gamma \), where \( \kappa \) is the trapping stiffness. This statistical effect can be suppressed by reducing the sampling frequency.

The power spectrums of a trapped microsphere for a period of 5 min are illustrated Fig. 3(a) and (b) represent original position signal \( s_{QPD} \) and reference noise \( \delta n_{ref} \), respectively. The solid curves in both figures are the best fits for Brownian motion of the microsphere \([15]\). It shows that low-frequency noise is the dominating noise in QPD signal, represented by the low-frequency component of the power spectrum that is marked by the red frame in Fig. 3(a). In high frequency regions above approximately 1 hertz, Brownian motion dominates the power spectrum. It’s expected that low-frequency components of \( s_{QPD} \) and \( \delta n_{ref} \) are correlated. The threshold frequency in this experiment is approximately 4 Hz.

A low-pass digital filter is applied to extract the low-frequency component \( \delta n_{ref}^* \) from the reference noise. The optimum cutoff frequency \( f_c^{opt} \) is selected correspond to the peak correlation coefficient. The correlation coefficient \( R \) between \( s_{QPD} \) and \( \delta n_{ref}^* \) is analyzed with Pearson’s linear correlation.
Fig. 3. Power spectrums of data $s_{QPD}$ and reference noise $\delta n_{\text{ref}}$. (a) Represents original position signal $s_{QPD}$. (b) Represents reference noise $\delta n_{\text{ref}}$. The solid curves represent the best fits to the data of the expression for the Brownian motion of the microsphere in a trap.

Fig. 4. Correlation coefficient $R$ between position signal $s_{QPD}$ and reference noise $\delta n_{\text{ref}}^*$, as a function of cutoff frequency $f_c$.

function [26]:

$$R = \frac{\sum (s_{QPD} - \bar{s}_{QPD})(\delta n_{\text{ref}}^* - \bar{\delta n}_{\text{ref}}^*)}{\sqrt{\sum (s_{QPD} - \bar{s}_{QPD})^2} \sqrt{\sum (\delta n_{\text{ref}}^* - \bar{\delta n}_{\text{ref}}^*)^2}},$$

(6)

where $\bar{s}_{QPD}$ and $\bar{\delta n}_{\text{ref}}^*$ are the mean values of $s_{QPD}$ and $\delta n_{\text{ref}}^*$, respectively. The correlation coefficient as a function of cutoff frequency of low-pass digital filter is illustrated in Fig. 4. It shows that the correlation coefficient is greater than 50% for most frequencies in plot. The optimum cutoff frequency $f_{c}^{\text{opt}}$ for this experiment condition is 3.9 Hz, which is in agreement with the threshold frequency in Fig. 3. The resulting peak correlation coefficient takes a value of 76%. As a result, we can conclude that the low-frequency noise in $s_{QPD}$ mainly originates from the asymmetric laser power fluctuation illuminating the sphere, which is represented by $\delta n_{\text{ref}}$.

3.2 Basic Properties of the Technique

The noise-reduction capability of this technique is illustrated in time domain in Fig. 5(a). The zero-mean reference noise $\delta n_{\text{ref}}$ is shown in curve 1 and the solid curve inside curve 1 is the low-pass filtered data $\delta n_{\text{ref}}^*$, which has been filtered with a cutoff frequency of 3.9 Hz. Curve 2 represents
the original position signal $s_{\text{QPD}}$. The corrected data created by the subtraction of $\delta n_{\text{ref}}$ from $s_{\text{QPD}}$ is shown in curve 3. The sampling frequency of the curves is 1 KHz. It clearly shows that low-frequency noise is significantly reduced in corrected data. The remaining signals in corrected data originates from Brownian motion and other un-correlated noise. This kind of uncorrelated signals can be reduced by decreasing the detection bandwidth [15]. Therefore, the noise-reduction capability of this technique can be enhanced by lowering the detection bandwidth.

A statistics distribution of original data and correlated data is made, as illustrated in Fig. 5(b). The standard deviations of original data are 1.10 $\mu$m and 1.06 $\mu$m for sampling frequency of 1 KHz and 1 Hz, respectively. The standard deviation of original data in sampling frequency of 1 KHz surpasses that of 1 Hz, because more uncorrelated noise is collected with the sampling frequency increase.
A stronger noise reduction capacity is expected to present in sampling frequency lower than the threshold frequency in Fig. 3. It shows that the standard deviations of correlated data for sampling frequency of 1 KHz and 1 Hz develop into 0.57 μm and 0.35 μm, respectively. 48% of low-frequency noise is counteracted for detection bandwidth of 1 KHz, while 67% for 1 Hz remarkably. Thus, more noise can be suppressed when the detection bandwidth decreases.

To demonstrate that the external signal input is not influenced by this noise-reduction technique, an experiment was also made when an external force was executing the microsphere. Another laser (980 nm) was coupled to one side of the chip. Both QPD and PD were configured with wavelength filter to remove the power from this laser. The microsphere was pushed approximately 15 μm by this laser. The data is illustrated in Fig. 6. It can clearly be seen that this noise-suppression technique removes the chief component of low-frequency noise without effective impact on the detected signal.

4. Conclusions

Low-frequency noise is the dominating noise in long-term measurement for optical trap. We present a technique to diminish the low-frequency noise for DFOT system. The separated fluctuation of laser power irradiating the microsphere is demonstrated to be responsible for low-frequency noise in DFOT. The normalized differential signal of transmission lights is monitored as reference noise. Experiment shows that the correlation coefficient between position signal and low-frequency part of reference noise is up to 76%. Subtracting the well correlated noise from original signal, this technique works effectively in practice. The noise-reduction capability of this technique is remarkable. It shows that 48% of low-frequency noise is eliminated for detection bandwidth of 1 KHz. We find that the noise-reduction capacity of this technique gets stronger with the detection bandwidth decreases, since less uncorrelated noise is collected. Experiment shows that this technique removes 67% of low-frequency noise for detection bandwidth of 1 Hz. A better result could be presented if the trapping time is long enough and stable trap in vacuum microcavity is achieved. Experiment also demonstrates that this noise reduction technique removes the major part of low-frequency noise without effective impact on detected signal. It can be widely used in DFOT system.

A novel noise suppression technique is proposed for dual-fiber optical trap system for the first time. We realize noise reduction using the difference of different kinds of data. This technique makes it possible to achieve high-precision measurement in the integrated and microfluidic fiber-optic trap system. It can also be applied in many other fields of optical measurements.

References


