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A chromatic confocal probe with a mode-locked femtosecond laser source

Xiuguo Chen [a,b], Taku Nakamura [a], Yuki Shimizu [a,*], Chong Chen [a], Yuan-Liu Chen [a], Hiraku Matsukuma [a], Wei Gao [a]

[a] Department of Finemechanics, Tohoku University, Sendai 980-8579, Japan
[b] School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China

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ABSTRACT

The high spatial coherence and high stability of a mode-locked femtosecond laser source make it ideal for chromatic confocal imaging. Nevertheless, the high non-smoothness of spectrum of the mode-locked laser source often restricts its application in chromatic confocal probes for a wide range of depth measurement. To eliminate the spectral non-smoothness of the mode-locked laser source, we propose a new chromatic confocal setup in such a way that the reflected laser beam is divided into two sub-beams which are then made to pass through two optical paths with different confocal settings where two identical fiber detectors are placed at the focal position and a defocus position, respectively, for acquiring two confocal signals. An axial response is then obtained from the intensity ratio of the two confocal signals for depth measurement. With the proposed confocal setup, we can expand the working spectral range of a mode-locked laser source to its whole spectrum. Theoretical and experimental investigation have revealed that the developed chromatic confocal probe with the specific mode-locked laser source employed in experiments has a measurement sensitivity of about -4 nm/μm, a depth measurement range of about 40 μm, and a depth resolution of better than 30 nm, respectively.

1. Introduction

Confocal microscopy [1,2] is a powerful and also widely used technique for the visualization of three-dimensional (3D) structures due to its unique depth-sectioning property compared to conventional optical microscopy. The typical type of confocal microscopy is the so-called laser scanning confocal microscopy (LSCM) [3] that employs a traditional single-wavelength laser source for illumination. In order to obtain the depth information, the object or the measuring head needs to be scanned along the optical axis with high precision and high resolution so that the target region on the object can be in focus, which poses high requirements on the scanning device and also significantly limits the measurement throughput of LSCM. Aiming at the deficiency of LSCM, the chromatic confocal microscopy [4–13] has been developed by taking advantage of the chromatic aberration of the objective lens [4–9] or the diffractive Fresnel lens [10–13]. Compared with LSCM, broadband light sources are often employed in chromatic confocal systems. Since different spectral components of a broadband light source will be focused onto different axial positions, the depth information can be effectively obtained by measuring the peak wavelength on the spectrum of the light reflected from the object without axially scanning the object or the measuring head anymore.

The axial measurement range of a chromatic confocal probe depends on the chromatic aberration of the optical system and the spectral range of the employed light source. White light sources such as Xenon lamps that have wide spectral ranges are commonly used in chromatic confocal probes to achieve wide measurement ranges. However, the low spatial coherence of white light sources often results in low illumination efficiency and limits measurement accuracy of the chromatic confocal probes. The instability of spectra of white light sources is another deficiency that degrades the performance of chromatic confocal probes. The mode-locked femtosecond laser source [14–16], which consists of a series of specific modes with optical frequencies equally spaced by a certain mode spacing, has a highly stable optical spectrum with high spatial coherence, and is expected to overcome the above drawbacks of conventional white light sources and is intuitively ideal for chromatic confocal imaging. Moreover, the high power per mode of the mode-locked laser source is beneficial to

* Corresponding author.
E-mail address: yuki.shimizu@nano.mech.tohoku.ac.jp (Y. Shimizu).

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chromatic confocal imaging from the point of view of finding the peak wavelength. There is also a promising potential of applying the femtosecond laser frequency comb technology [14] to identify the absolute optical frequencies/wavelengths, which is important for traceable measurement in chromatic confocal microscopy. Nevertheless, a mode-locked laser source often has a highly non-smooth spectrum with multiple peaks induced by nonlinear effects in the pulse formation such as the Kelly sideband peaks [17]. The spectral range is also relatively narrow. These limit the application of a mode-locked laser source in chromatic confocal probes for a wide range of depth measurement. As an improved variant of the mode-locked laser source, the supercontinuum laser source, which is typically generated by coupling femtosecond laser pulses into a nonlinear photonic crystal fiber, can broaden the spectral range of the mode-locked laser source and has been successfully introduced for chromatic confocal imaging [8,9]. Even so, the spectral non-smoothness still restricts the full exploration of the whole spectrum of the supercontinuum laser source for a wider axial measurement range in chromatic confocal systems [9].

In this paper, we develop a chromatic confocal probe that employs a mode-locked femtosecond laser source. To eliminate the spectral non-smoothness of the mode-locked laser source, we design a fiber-based dual-detector chromatic confocal configuration in such a way that the reflected beam is divided into two sub-beams which are then made to pass through two optical paths with different confocal settings where two identical fiber detectors are placed at the focal position and a defocus position, respectively, for acquiring two confocal signals. An axial response defined as the intensity ratio of the two confocal signals is then introduced for axial displacement measurement. The depth information is finally obtained by measuring the peak position on the axial response. Compared with the signal processing approach in a chromatic confocal setup using a supercontinuum laser source [9], where the axial response is defined as the ratio of the intensity collected by a detector and the intensity of a reference beam obtained by removing the chromatic objective form the setup, the introduced axial response in this paper is found to be more robust in eliminating the spectral non-smoothness. Moreover, the introduced axial response is effective in removing the object reflection, which makes our developed chromatic confocal probe feasible for imaging samples with inhomogeneous reflectivity. It would be difficult for the chromatic setup in Ref. [9] to deal with samples with inhomogeneous reflectivity to our knowledge. With the designed confocal configuration and the introduced axial response, we successfully expand the working spectral range of the employed mode-locked laser source to its whole spectrum.

The introduced axial response in this paper is actually inspired by the signal processing approach in the so-called differential confocal systems [18–23]. However, we should note the difference between the introduced axial response and its counterparts in Refs. [18–23]. According to the specific axial responses, the existing differential confocal setups can be basically categorized into three types. The axial response in the first type is defined as the ratio of the difference of the intensities collected by two pinhole detectors and the sum [18–20] or maximum [21] of the collected two intensities, where the two pinhole detectors are placed at two symmetrical defocus positions with respect to the focal plane. The axial response in the second type is defined as the ratio of the intensities collected by two pinhole detectors that are both placed at the focal positions but with different pinhole sizes [22]. The differential confocal setups of the first and second types were developed for LSCM to avoid the traditional axial scanning. However, the depth measurement range for these two types of differential confocal setups is typically very small (about several micrometers). The third type [23] is a combination of the signal processing approaches in the first two types and the chromatic confocal microscopy to expand the depth measurement range, where the axial response is defined as the ratio of the difference of the intensities collected by two pinhole detectors placed both the focal positions but with different pinhole sizes and the sum of the collected two intensities. It should also be pointed out that the depth information in the above three types of differential confocal setups is not obtained by measuring the peak position on the axial response anymore, but from a monotone curve intercepted away from the peak position of the axial response. The range of the monotone curve determines the final depth measurement range, and the linearity of the monotone curve determines the final measurement accuracy. The monotone curve with a long range usually has poor linearity and thus yields low measurement accuracy. In addition, the differential confocal setups often have inconsistent signal-to-noise ratios and measurement precision for the points on the monotone curve that are near to and far away from the peak position of the axial response, especially for the differential confocal setups of the second and third types. In comparison, the introduced axial response in this paper is defined as the ratio of confocal signals acquired by two identical fiber detectors placed at the focal position and a defocus position, respectively, which is a new differential confocal setup. Moreover, the depth information is obtained by measuring the peak position of the axial response, which would be more robust than the depth measuring approach based on an intercepted monotone curve from the axial response in the above differential confocal setups.

2. Imaging principle

Fig. 1 presents a schematic of the optical configuration for the chromatic confocal probe. As shown in Fig. 1, a mode-locked laser is employed as the light source and single-mode fibers are employed to transfer the detected electric fields to the detectors (namely spectrometers). Each mode in the mode-locked laser has a deterministic frequency. The frequency υ_i and wavelength λ_i of the ith optical mode can be expressed by using a pulse repetition rate υ_{rep} and a carrier envelope offset frequency υ_{CEO} as follows [14–16]:

$$\upsilon_i = \upsilon_{\text{CEO}} + i \cdot \upsilon_{\text{rep}}, \tag{1}$$

$$\lambda_i = \frac{c}{\upsilon_i} = \frac{c}{\upsilon_{\text{CEO}} + i \cdot \upsilon_{\text{rep}}}, \tag{2}$$

where c is the speed of light. The use of an optical fiber in confocal microscopy, instead of a traditional pinhole, for signal detection is convenient for transferring the detected field to the spectrometer, and also ensures that the imaging is always coherent irrespective of the fiber dimensions [24]. The image in this case can be written as [24]

$$I(u,\ v) = |h_1(u,\ v)h_{2\text{eff}}(u,\ v) \otimes \tau(v)|^2, \tag{3}$$

where $\otimes$ denotes the convolution operation, $\tau(v)$ represents the amplitude reflection or transmittance of the object, and

$$h_{2\text{eff}}(u,\ v) = h_2(u,\ v) \otimes e(v), \tag{4}$$

$$h_m(u,\ v) = \int_0^1 P_m(u,\ \rho)J_0(\rho v)\rho d\rho, \quad m = 1,\ 2, \tag{5}$$

with $h_1(u,\ v)$ and $h_2(u,\ v)$ standing for the point spread functions for the objective and the collector, respectively, $P_m(u,\ \rho)$ standing for the pupil function of the corresponding lens, $e(v)$ being the eigenfunction of the fundamental mode of the fiber [25], $J_0(\cdot)$ being the zero-order Bessel function of the first kind, and v and u being the optical coordinates [26] that are related with the real radial and axial coordinates, r and z, by