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# Fiber-based chromatic confocal microscope with Gaussian fitting method

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ABSTRACT

The chromatic confocal microscopy is an effective method for displacement measurement. However, with relatively low detection efficiency, chromatic confocal systems from previous studies suffer from either a limited measuring range or an unsatisfying resolution. In this paper, a novel chromatic confocal system is proposed based on optical fiber with large diameter that is specifically chosen to allow more light to be detected, thus greatly improving the detection efficiency of the system. To accurately locate the peak wavelength of the recorded spectrum, four data processing methods are proposed and compared, within which the Gaussian fitting model is considered best for the system. A series of experiments are done to verify the feasibility, resolution and stability of the system. An applicable measuring range of 600 μm is discovered with a highly linear range of 400 μm. The system has a high resolution close to 0.10 μm with satisfying stability shown by a long-term displacement standard deviation of 0.16 μm.



## 1. Introduction

Invented by Marvin [1] in the early 1960s, confocal microscopy has become a powerful tool for a wide range of applications for its superior resolution [2] and capability of displacement discerning [3]. Such properties have made this technique especially attractive in biology and semi-conductor engineering where both transverse and longitudinal resolutions are required. In order to utilize its capability of displacement discrimination, the sample needs to be scanned transversely and longitudinally so that the target region can be focused [4]. The precision of the displacement measurement depends on the point spread function (PSF) along the longitudinal axis of the confocal system as well as the displacement precision of the scanning device. To achieve higher resolution, most of the confocal microscope systems require an extremely stable mechanic scanning device with high resolution, which largely limits its application in certain situations.

To alleviate the influence of longitudinal scanning device, Molesini et al. [5] developed an optical profilometer based on the principle of chromatic displacement, which uses the chromatic dispersion of the optical system to provide wavelength–displacement encoding for displacement measurement. Such system requires a broadband light source and a dispersive lens that allows different spectral component of the light source to be focused to different depth of the sample. Multiple methods have been proposed to further improve this technique. Lin and his colleagues used a diffractive zone plate to provide highly linear wavelength-to-displacement coding, achieving a resolution of 2.520 μm (obtained from FHWM of PSF) [6]. In 2000, this team constructed a non-translational three-dimensional profilometry system using digital micromirror device (DMD) as the scanning unit [7]. Shi et al. adopted supercontinuum light as the light source of the chromatic confocal system to achieve a displacement scanning range of 7 μm [8]. Based on supercontinuum light, Garzon et al. used Fresnel lens to further improve the wavelength-displacement encoding ability [9,10]. Meanwhile, various authors have investigated the applications of chromatic confocal technique, such as layer thickness measurement [11].

Nevertheless, current chromatic confocal systems still suffer from several technological limitations. To begin with, in order to achieve a bigger displacement measuring range, chromatic confocal system normally requires a light source with a wavelength band as broad as possible. Therefore, supercontinuum light sources are frequently used in recent studies of chromatic confocal system. Unfortunately, the high price and huge size of supercontinuum light source severely limit the applications of such chromatic confocal systems. Moreover, to satisfy the confocal conditions, light of off-focus wavelength must be spatially filtered to acquire spectral image of the focused wavelength peak. This would block most of the light energy, resulting in relatively low detection efficiency. Last but not least, to increase the linearity of the wavelength–displacement decoding, diffractive optical element (e.g. Fresnel lens), which has larger chromatic aberration is adopted. However, since the number of phase levels of diffractive element is limited by the resolution of the lithographic fabrication process, the diffraction efficiency decreases

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rapidly for small grating periods if only four or two phase levels are feasible [12]. In order of solve the problems discussed above, we proposed a novel chromatic confocal system based on optical fiber as both transmitting media and a large spatial filter with a specifically chosen diameter of 62.5 μm. Although it still carries the name of chromatic confocal microscope, it is obvious that the system deliberately give up the confocal conditions so that it can embrace higher detection efficiency. Several data processing models to locate peak wavelength in the spectrum are presented and discussed, based on which we have proposed an efficient method that can achieve a displacement measuring range of 600 μm and a resolution of 0.10 μm without sacrificing the detection efficiency.

## 2. Chromatic dispersion and measurement principle

Chromatic aberration is the deformation of the image due to the dispersion phenomenon of non-monochromatic light through optical system. In other words, the position of the focus varies with the wavelength. For a singlet lens, the focal length $f$ can be expressed as [13]

$$f(\lambda)=\frac{1}{(n(\lambda)-1)((1/R_1)-(1/R_2))} \tag{1}$$

where $n(\lambda)$ can defined by Cauchy's equation [14]

$$n(\lambda)=A+\frac{B}{\lambda^2} \tag{2}$$

By combining Eqs. (1) and (2) we can get

$$f(\lambda)=\frac{1}{(A+(B/\lambda^2)-1)((1/R_1)-(1/R_2))} \tag{3}$$

From Eq. (3) we can see that the focal length $f$ and wavelength $\lambda$ are directly related to each other and thus can be used as a displacement–wavelength encoding system. Meanwhile, in a classical confocal system, by axially scanning a target along the $z$-axis, the detected intensity as a function of the target's position can be approximated as [15]

$$\begin{cases} I(u)=\left(\frac{\sin(u/2)}{u/2}\right)^2 \\ u=\frac{8\pi}{\lambda_s}z\sin^2\left(\frac{1}{2}\alpha\right) \end{cases} \tag{4}$$

where $u$ is a normalized axial coordinate related to axial position $z$, light source wavelength $\lambda_s$ and numerical aperture $n\sin(\alpha)$. The maximum intensity can be detected when the sample is exactly in focus ($u=0$, that is $z=0$). It should be noted that the axial position $z$ from Eq. (4) is measured from the focal plane of wavelength $\lambda_s$. In a chromatic confocal system, since the position of focal plane is related to certain spectral component of the light source, maximum intensities of different wavelengths are detected on different axial position. Supposing that the focal position of wavelength $\lambda$ is expressed as $z_\lambda$ and the position of the mirror is expressed as $z_m$, both measured from a fixed position, we can calculate the detected intensity of a certain wavelength by

$$I(\lambda)=\int I(x,y,z_m-z_\lambda)\,dx\,dy \tag{5}$$

Therefore, the information of the target's position is encoded into the detected intensity spectrum, where the position of the peak intensity represents the position of the target. The displacement can thus be measured by a spectrometer.

The light detected at the spectrometer can be seen as the image of the light reflected be the target. The diameter of the Airy disk is expressed as

$$d=\frac{1.22\lambda}{\mathrm{NA}} \tag{6}$$

where NA is the numerical aperture of the lens. To satisfy the confocal conditions, spatial filter has to be used to block the light of off-focus wavelengths. Thus the spatial filter should be a small hole with a diameter similar to that of the Airy disk in order to have higher resolution [16,17].

## 3. System description

Our chromatic confocal system mainly consists of three parts: illumination, wavelength–displacement codification and detection (Fig. 1).

As is shown in Fig. 1, the light coming from the light source (1) is coupled into a multimode optical fiber of 200 μm (3) by a 10× microscope objective lens with a NA of 0.25 (2). The other end of the fiber can be seen as a point light source where the light immediately passes through a configurable spatial filter (4) and is then collimated by an achromatic collimating lens (5). After passing through the beam splitter (6), the light is focused to the scanning mirror (8) by a singlet lens with chromatic aberration (7). The light then comes back and is reflected by the beam splitter to the 5× microscope objective lens with a NA of 0.15 where it is coupled into a multimode optical fiber of 62.5 μm that

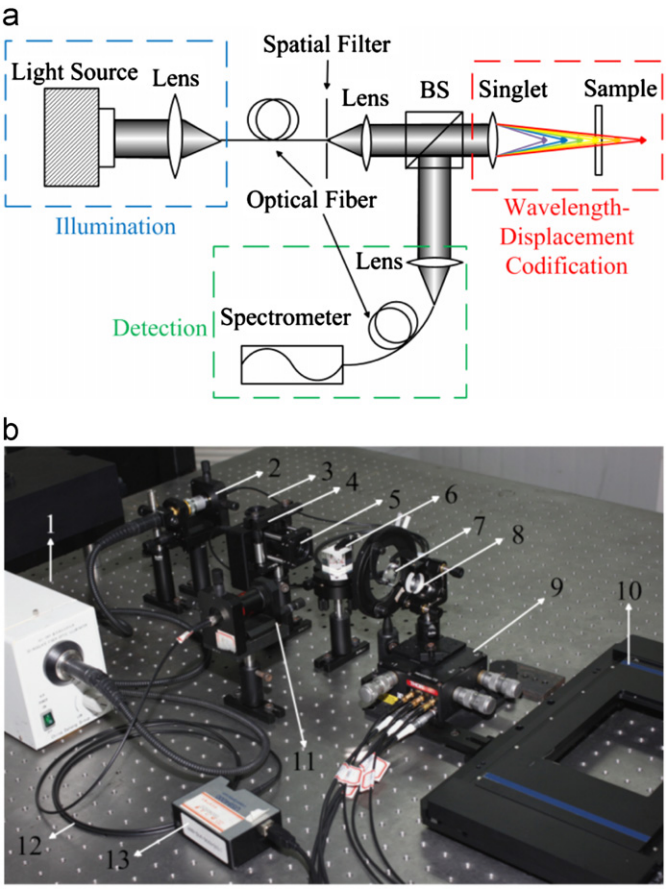


**Fig. 1.** (a) Schematic diagram of chromatic confocal system; (b) Real system: (1) light source; (2) 10× objective lens (NA=0.25); (3) optical fiber ($d$=200 μm); (4) configurable spatial filter; (5) collimating lens; (6) beam splitter; (7) singlet lens ($f$=30 mm, $d$=15 mm, BK7 glass, NA=0.133 using beam diameter of 8 mm); (8) reflecting mirror; (9) Thorlabs NanoMax-TS; (10) PILine M-686K026 Piezo Motor Stage; (11) 5× objective lens (NA=0.15); (12) optical fiber ($d$=62.5 μm); (13) USB4000 Fiber Optic Spectrometer.