Optics & Laser Technology 82 (2016) 87–93

Contents lists available at ScienceDirect

Optics & Laser Technology

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

Full length article

High precision radially-polarized-light pupil-filtering differential confocal measurement

Yun Wang, Lirong Qiu*, Weiqian Zhao

Beijing Key Lab for Precision Optoelectronic Measurement Instrument and Technology, School of Optoelectronics, Beijing Institute of Technology, Beijing 100081, PR China

ARTICLE INFO

Article history:
Received 4 July 2015
Received in revised form
1 February 2016
Accepted 8 February 2016
Available online 7 March 2016

Keywords:
Confocal
Radially-polarize
Pupil-filter
Measurement.

ABSTRACT

A new method, high precision radially-polarized light pupil-filtering differential confocal measurement (RPDCM), is proposed to improve the 3D measurement resolution of confocal system. SPDCM uses the property that the radially-polarized-light can produce a strong longitudinal field component after being focused by a high numerical aperture objective to reduce the lateral size of the focus spot, and relies on the pupil-filtering technique to optimize the pupil function of the optical system by the designed pupil filter, which therefore improves the lateral resolution of confocal system, and it uses the differential confocal technology to improve the axial measurement resolution of the confocal system, thereby improves the 3D measurement resolution of the confocal system. Based on RPDCM, we developed a high precision radially-polarized light pupil-filtering differential confocal setup, and use it to verify the effectiveness of RPDCM by experiments. The theoretical analysis and experimental results show that the RPDCM can reach the lateral and axial measurement resolutions of 150 nm and 1 nm, respectively, which are an improvement of 20–32% and 3.7 times compared with a confocal system.

1. Introduction

In semiconductor processing, precise manufacturing and other industries, the surface profile and microstructure of the sample must be measured precisely. Scanning Tunneling Microscope (STM), Atomic Force Microscope (AFM), near-field scanning optical microscope (NSOM) and other techniques can perform 3D surface measurement with high accuracy, and their precision can reach 0.1 nm [1–4], but they have such disadvantages as the complex operation process and strict requirements for the sample and environment, so their applications in the field of surface profile measurement are greatly limited.

Because of its unique axial response capability, confocal microscopy (CM) is widely used to characterize very small 3D structures and perform surface profile measurement [5–7], and it has the following advantages over STM, AFM and NSOM. (1) It has a long working distance to make the operation easy; (2) there is no need for sample pre-processing or a vacuum operation process, and there is no strict requirement for the sample or the environment; and (3) it causes no damage to the sample due to the noncontact with the sample during the process. However with the development of semiconductor processing and precise manufacturing industries, confocal microscopy system cannot meet the requirements of high precision in a 3D measurement. Therefore, overcoming the diffraction limit to improve the 3D measurement precision of the system has become an important research aspect in the surface profile measurement field.

To improve the axial measurement ability, Evangelos et al. proposed a method to improve focusing accuracy by combining interference technology with the confocal optical path [8], but its optical path was complicated and vulnerable to disturbance. Matthew S. Muller proposed a method that combines structured light illumination and synchronized Complementary Metal Oxide Semiconductor (CMOS) rolling shutter detection [9], to improve the CM axial measurement ability by 2.75 times, but it used dual-line illumination and caused the reduction of the lateral resolution. Wei Gong and Sheppard improved the axial precision of confocal systems by using the apertures to modulate the illumination light shape [10,11], but this method may cause the loss of light intensity and a decrease in the lateral resolution.

For non-fluorescent labeled industrial sample, the radially-polarized light tightly focusing technology combined with pupil filtering technology is an important research aspect to improve the lateral resolution in international. The optical pupil filtering technique allows the transverse dimensions of the focal spot to be

* Corresponding author.
E-mail address: qiugrass@126.com (L. Qiu).

http://dx.doi.org/10.1016/j.optlastec.2016.02.005
0030-3992/© 2016 Published by Elsevier Ltd.

compressed by the radially-polarized beam under high numerical aperture illumination [12]. In 2008, Haifeng Wang et al. originally proposed a feasible way to improve the lateral resolution of an optical system by combining a radially-polarized beam with pupil filtering technology [13], which compressed the lateral size of the focal spot to 0.43λ. In 2011, Kozawa et al. modulated a confocal system illuminating beam by a radially polarized plate and a six-area pupil filter [14], which was combined with an oil immersed high numerical aperture objective lens to compress the focal spot lateral size to 0.5λ. In 2013, Hanming Guo et al. used the phase pupil filter technology and radially polarized light to successfully compress the lateral size of the focal spot to 0.41λ [15]. In 2014, Wangzi Ma achieved a needle of 0.27λ in lateral size by focusing an azimuthally polarized and phase modulated beam [16]. However, all of the above-mentioned methods expanded the axial size of the focal spot and reduced the axial resolution of the system while the lateral size of the focal spot is compressed.

Some researchers proposed an annular pupil to compress the lateral and axial sizes of the focal spot at the same time. Jun Miyazaki et al introduced the annular pupil technology for laser diode pump probe microscope [17] to compress the lateral and axial sizes of the focal spot simultaneously, but it caused an increase in the side lobe of the focal spot and a loss in the light intensity of more than 60%. Liangxin Yang et al. used a radially polarized beam and a narrow-band annular pupil to compress the focal spot [18], and obtained a focal spot of 0.00711λ^2 in size by a large numerical aperture objective lens, but more than 80% of the light intensity was lost. These methods can improve the lateral and axial measurement ability at the same time, but may cause the serious loss of light intensity, so they are greatly limited in practical application.

To improve the 3D measurement ability of CM, we propose a new radially-polarized light pupil-filtering differential confocal technology, which combines the idea of compressing the focal spot size and improving the sensitivity of detection. It relies on the tight focusing of radially-polarized light and the beam modulation effects of pupil filtering technology to improve the lateral resolution of CM, uses the differential confocal technology to improve the axial response sensitivity of CM [19,20] and consequently improves the CM axial measurement precision even if the axial size of the focal spot is expanded, and thereby improving the 3D measurement resolution of CM. The method can improve the lateral resolution and axial measurement precision at the same time without loss of light intensity, so it provides a feasible method to improve the 3D measurement ability of CM. It could have wide application in the field of micromachining, semiconductor and microelectronics manufacturing.

2. Measurement principle

By combining the differential confocal axial focusing principle and radially-polarized light tightly focusing technology with the pupil-filtering technique, we propose the high-precision radially-polarized pupil-filtering laser differential confocal measurement (RPDCM), and its principle is shown in Fig. 1.

A short wavelength laser beam emitted from the laser diode travels through the beam expander and the S-P wave plate to be shaped into a uniformly distributed radially-polarized-beam. Then it travels through BS1 and is modulated into a radially polarized structured beam by the pupil filter F. The beam is focused by objective L_o, and the focal spot used to illuminate the sample is smaller than the Airy disk. The laser beam reflected back from the test sample is reflected by BS1 and then focused by the collecting lens Lc. The convergence beam is divided into two beams by BS2 and they are received by the detectors D1 and D2. Pinholes PH1 and PH2 next to the detectors are placed before and behind the focus of Lc with the same offset d_M, and the differential signal can be got by the subtraction of signals received by D1 and D2, and be used to calculate the sample height information to produce a 3D image of the sample surface.

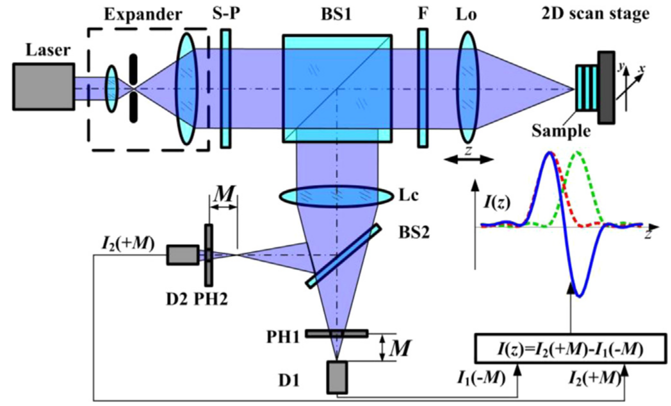

Fig. 1. RPDCM system and its axial response curve S-P is the S plate used to generate the radially polarized beam, BS1 and BS2 are beam splitters, F is a pupil filter, L_o is the objective lens, L_C is the collimating lens, PH1 and PH2 are pinholes, D1 and D2 are detectors.

RPDCM uses the differential optical structure to increase the slope of confocal axial response curve at the focus to improve the axial response sensitivity and axial measurement precision. It uses the S-P wave-plate and pupil-filter to form the radially polarized structured light and improve the lateral resolution. Therefore, combining differential technology and radially-polarized light pupil-filtering technology can improve the 3D measurement ability of CM and achieve high spatial resolution testing.

2.1. Performance of radical polarized light in DCS

When a radially polarized beam is used in a differential confocal system, the electric fields near the focus for the illumination of the high-aperture lens can be described as follows[12]:

$$E_r = \int_0^{\alpha} \cos^{1/2}\theta \times \sin 2\theta \times J_1\left(\frac{v \sin\theta}{\sin\alpha}\right) \times \exp\left(\frac{iu\cos\theta}{4\sin^2(\alpha/2)}\right) d\theta \tag{1}$$

and

$$E_z = i\int_0^{\alpha} \cos^{1/2}\theta \times \sin^2\theta \times J_0\left(\frac{v \sin\theta}{\sin\alpha}\right) \times \exp\left(\frac{iu\cos\theta}{4\sin^2(\alpha/2)}\right) d\theta \tag{2}$$

where *Er* and *Ez* are the lateral and axial component of the radially polarized light, ρ is the normalized pupil radius, and α is the numerical aperture angle of objective Lo. u and v are normalized optical coordinates, and can be written as:

$$\begin{cases} u = \dfrac{8\pi}{\lambda}\sin^2(\alpha/2) \times z \\ v = \dfrac{2\pi}{\lambda}\sin\alpha \times r \end{cases} \tag{3}$$

The object space illumination light intensity distribution is: