A novel method for nano-displacement measurement using spectral interferometry

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ABSTRACT

We demonstrate a novel method to measure nano-displacement using the spectral shifts around spectral switch points in the neighborhood of intensity minima using a Michelson white light interferometer setup in the spectral domain. As the path difference between the interfering beams is increased from zero the out put light spectrum is first red shifted, splits into two spectral lines of equal intensity, referred as a spectral switch and then is blue shifted. Around the spectral switch position, when the path delay is changed in nanoscales a dramatic change of the spectrum occurs, which was measured experimentally and found to match well with numerical calculations carried out using spectral interference law.

Keywords: Spectral Interference, nanodisplacement, spectral switch, Michelson Interferometer

1. INTRODUCTION

Optical techniques, especially interferometric techniques are widely used for accurate measurement of displacements due to their simplicity and high sensitivity compared to the other techniques. The Michelson interferometer (MI) has been used to measure small spatial displacements since its invention. Almost all interferometric measurements[1, 2] use helium-neon laser because the emitted wavelength is in the visible range. In the interferometic method, using single wavelength sources, the measurement range is limited to within a half wavelength. As a result, instead of working with single wavelength source researchers work with dual wavelength and white light source which comprises of all wavelengths in the visible range for displacement measurements. The displacement measurements were made by performing a cross correlation calculation between the experimental spectra and theoretical spectra due to the spectral modulation of white light[3]. Later absolute distance measurements were done using the white light channelled spectrum interferometer[4]

In this paper, we demonstrate an experimental method to measure nano displacement up to 1μm using the spectral shifts and spectral switches[5] around the intensity minima in a Michelson white light interferometer in spectral domain[6]. As the path difference between the arms of the MI increases from zero, the spectrum first shifts to red, splits into two spectral lines of equal intensity, referred as spectral switch and then is blue shifted. At the spectral switch position, a dramatic change of the spectrum occurs with the path difference in nanoscales. These dramatic changes of the spectrum around the spectral switch can be used to measure the nano displacements and also displacements due to temperature and pressure by suitable design of the experimental setup.

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2. THEORY OF OPERATION

The spectral interference law for the dispersion compensated MI is given by[7]

$$S(\lambda) = \frac{1}{2} S_0(\lambda)\{1 + \mathrm{Re}[\mu_{12}(\lambda)]\cos[\kappa \Delta l]\} \qquad (1)$$

Where $S_0(\lambda)$ is the lamp spectrum, $\kappa=2\pi/\lambda$ and Δl is the paths difference between the arms. Adjusting the path difference between the interfering beams, $\Delta l = 0$ so that the interference spectrum matches with the lamp spectrum, to begin with. Re $[\mu_{12}(\lambda)]$ is the real part of the complex degree of the spectral coherence $\mu_{12}(\lambda)$, which is given as

$$\mu_{12}(\lambda) = |\mu_{12}(\lambda)| \exp[i\beta_{12}(\lambda)] \qquad (2)$$

Where $|\mu_{12}(\lambda)|$ is the modulus and $\beta_{12}(\lambda)$ the phase of the complex degree of spectral coherence of the white light. For spatially coherent optical field, Re $[\mu_{12}(\lambda)] = |\mu_{12}(\lambda)| \cos[\beta_{12}(\lambda)]$. The modulus of the degree of spectral coherence $|\mu_{12}(\lambda)| =$ V, the visibility of spectral interference fringes , assumed to be equal to one and the phase of the complex degree of spectral coherence is zero. Then the Eq. (1) becomes

$$S(\lambda) = \frac{1}{2} S_0(\lambda)\{1 + \cos[\kappa \Delta l]\} \qquad (3)$$

Here $\{1+\cos[(2\pi/\lambda)\Delta l]\} = \{1+\cos(\Delta\phi)\}$ is spectral modifier function, where $\Delta\phi$ is the phase difference between the interfering beams.

3. EXPERIMENTAL DETAILS

The experimental setup, discussed in our earlier publication[6], consists of a dispersion-compensated Michelson interferometer with one of the mirror arms (M_2) mounted on a nano positioner (NanoPZ, Newport, USA) capable of a minimum step size of 10 nm as shown in Fig.1. The white light source used is a 50 W tungsten-halogen lamp coupled to an optical fiber with collimating lens and the spectral modifications at the interferometer out put are measured using fiber-coupled spectrometer (SD2000, Ocean Optics, USA). A personal computer is used to control the nano-positioner movement and for acquisition of corresponding spectral data from the spectrometer.

The spectral characteristics of the white light source are measured in the range from 300 – 1000 nm by closing one of the interferometer arms. The spectrum is fitted to give a FWHM bandwidth ($\Delta\lambda$) of 238 nm and a peak wavelength (λ_0) of 612 nm. Using these values the coherence length (l_c) of the source is calculated to be 1.57 μm. When the characteristics of the interference spectrum are similar to that of the lamp spectrum the corresponding path difference between the interfering beams is taken to be zero. The path difference between the two interfering beams can be increased in different step sizes using computer controlled nano-positioner.

4. EXPERIMENTAL RESULTS

As the path difference between the interfering beams is increased from zero in steps of 10 nm the out put light spectrum, which coincided with the lamp spectrum(for Δl=0)(Fig. 2(a)) is first red shifted, splits into two spectral lines of equal intensity, referred as a spectral switch and then is blue shifted as shown in Fig.2. The spectral switch position occurs for the path delay Δl= 280 nm (Fig.2(c)), at this position, when the path delay is changed in nanoscales, a drastic change of the spectrum from red to blue side occurs. The change of the spectrum around the spectral switch position is different for different displacements of the nanopositioner. Fig. 3(a) shows the spectra around the spectral switch for displacements 0, 10, 20,30,40,50 nm. The spectra at 0 nm is taken as our reference switch position where the two peaks have almost the same intensity. When the step size increases, the shift of the peak wavelength from red to blue around the switch position will also increase with respect to the reference switch position.

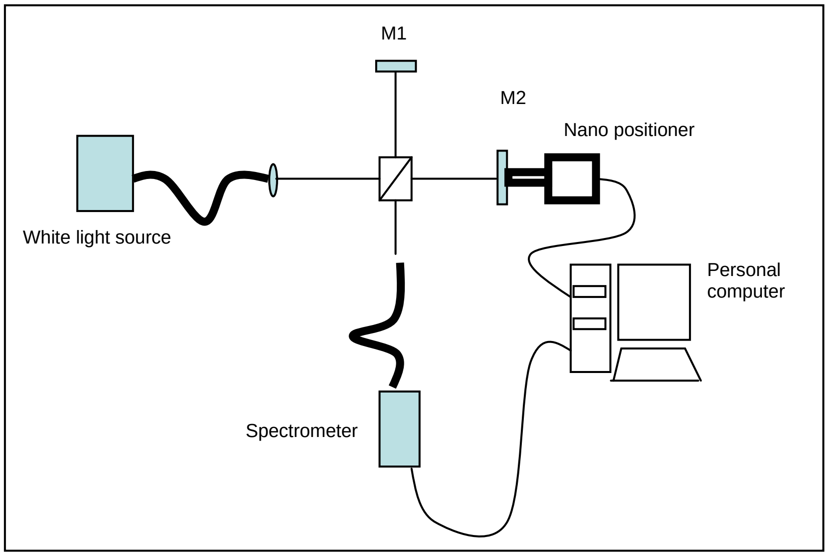

Fig. 1. Schematic of the experimental setup

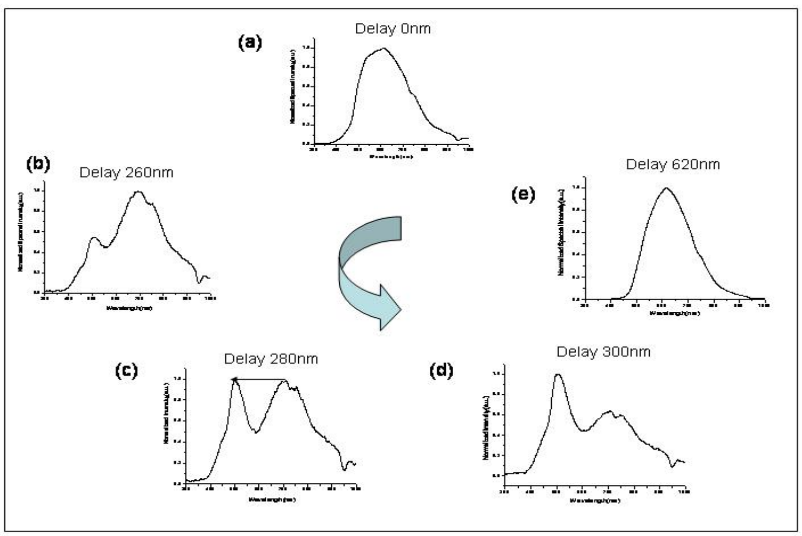

Fig. 2. Normalized spectra measured at the interferometer out put for different path delays

The switch amplitude normalized with the lamp spectrum (Fig. 2(a)) is defined as λ_n-λ_i / λ_0, where λ_n is the switching peak wavelength at different displacements, λ_i is the reference peak wavelength and λ_0 is the central wavelength of the lamp spectrum. The normalized switch amplitudes corresponding to the displacements 10, 20, 30, 40 and 50 nm are 0.339, 0.312, 0.310, 0.308 and 0.305 respectively. Fig.3 (b) shows variation of the switch amplitude with displacement. It is observed that the switch amplitude is high for small displacements implying that this method is more accurate for small displacements. The small variation from the numerical calculations can be attributed to the stability of the interferometer system. These dramatic spectral changes due to displacement can also be used to measure accurately nano scale displacements due to changes in temperature and pressure by appropriate design of the experimental setup

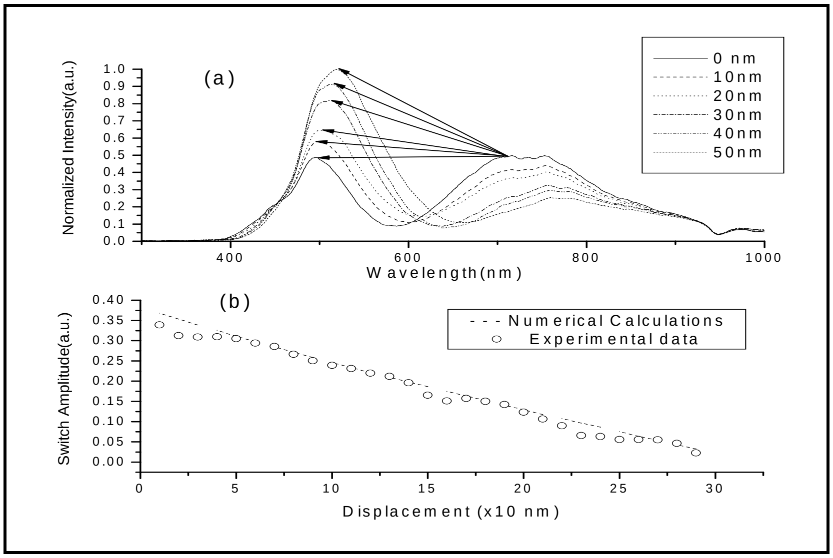

Fig. 3. (a) Spectra at the spectral switch position for different displacements (b) Switch amplitude – vs – displacement

5. CONCLUSIONS

In conclusion, we have demonstrated a novel method to measure the nano displacements using the spectral shifts spectral switches around the intensity minima in a white light MI in spectral domain. This method can be extended to measure the displacements due to changes in temperature or pressure in various applications, using appropriate design of the experimental set up.

ACKNOLEDGEMENTS

One of the others, MMB thanks University Grants Commission (UGC) for financial support

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